A Fluid Inclusion and Stable Isotopic Investigation of the Boston Lode-Gold Deposit, Hope Bay Volcanic Belt, Nunavut

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Abstract — The Boston deposit is a recently discovered Archean lode-gold deposit located approximately 700 km northeast of Yellowknife, in the southern portion of the Hope Bay volcanic belt. Primary H2O-CO2-NaCl fluid inclusions associated with gold mineralization at Boston are of low salinity (4.6 ± 1.4 eq. wt.% NaCl, n = 182) and contain pure CO2. Homogenization temperatures of liquid-phase inclusions average 270° ± 33°C (n = 141), but some fluid inclusion assemblages contain coexisting liquid- and vapor-phase inclusions that homogenize near critical conditions, suggesting phase separation. In these groups, liquid-phase inclusions homogenized at 299° ± 25°C (n = 24), and vapor-phase inclusions homogenized at 338° ± 28°C (n = 18). These temperatures overlap within error, and a median temperature of ~320°C is taken as representative of trapping conditions within the veins. An approximate pressure of 2–3 kbar was estimated from fluid inclusion isochores at this temperature.

Stable isotopic compositions of carbonate minerals from the mineralized zones range from –4.7‰ to –3.1‰ in δ13C, and from 11.2‰ to 12.8‰ in δ18O; quartz ranges from δ18O = 12.8‰ to 14.9‰; and pyrite ranges from δ34S = 2.1‰ to 3.5‰. The δ18O_{H2O}, δ13C_{CO2}, and δ34S_{H2S} values of the fluid calculated from these minerals at 320°C are 6‰–9‰, –2.4‰ ± 0.6‰, and 1.5‰ ± 0.5‰, respectively, and are intermediate between metamorphic and magmatic compositions. A unique source for the fluids cannot, therefore, be constrained from these data.

Petrographic and geochemical data for the Boston deposit are consistent with data from other Archean lode-gold deposits worldwide, implying that the Boston deposit formed in a similar environment and from similar types of fluids. These results suggest that the Hope Bay volcanic belt may represent a major new mesothermal gold belt in this part of Nunavut.

Key Words: Fluid inclusions, Stable isotopes, Hope Bay volcanic belt, Nunavut, Lode-gold deposit.

Sommaire — Le gîte Boston a été récemment découvert à environ 700 km au nord-est de Yellowknife dans la partie sud de la ceinture volcanique de Hope Bay, il s’agit d’un gîte d’or filonien d’âge Archéen. Les inclusions fluides primaires de H2O-CO2-NaCl associées à la minéralisation aurifère du gîte Boston présentent une faible salinité (4.6 ± 1.4 eq. pds.% NaCl, n = 182) et contiennent du CO2 pur. La température d’homogénéisation des inclusions à phase liquide est en moyenne de 270° ± 33°C (n = 141), mais certains assemblages d’inclusions contiennent des phases liquides et gazeuses coexistantes qui s’homogénéisent dans des conditions quasi critiques, suggérant qu’elles résultent d’une séparation de phase. Dans ces groupes, les inclusions de phase liquide s’homogénéisent à 299° ± 25°C (n = 24) et les inclusions de phase gazeuse s’homogénéisent à 338° ± 28°C (n = 18). Ces températures se recoupent à l’intérieur des limites de l’erreur de mesure, et nous considérons qu’une température médiane de ~320°C est représentative des conditions de piégeage dans ces veines. Les isochores permettent d’estimer une pression d’environ 2–3 kbar à cette température.

La composition des isotopes stables des carbonates dans les zones minéralisées s’étend de –4.7‰ à –3.1‰ pour δ13C et pour de 11.2‰ à 12.8‰ pour δ18O; les valeurs de δ18O pour le quartz varient de 12.8‰ à 14.9; et les valeurs de δ34S dans la pyrite vont de 2.1‰ à 3.5‰. Les valeurs de δ18O_{H2O}, δ13C_{CO2}, et δ34S_{H2S} du fluide calculé à partir de ces minéraux à une température de 320°C est de 6‰–9‰, –2.4‰ ± 0.6‰, et 1.5‰ ± 0.5‰ respectivement, reflétant des conditions intermédiaires entre des compositions métamorphiques et magmatiques. Il n’est donc pas possible d’identifier une source unique pour ces fluides à partir de ces données.

Les données pétrographiques et géochimiques du gîte Boston sont similaires à celles d’autres gîtes d’or filonien ailleurs dans le monde, ce qui implique que le gîte Boston s’est formé dans un environnement similaire à partir des mêmes types de fluides. Ces résultats suggèrent que la ceinture volcanique de Hope Bay pourrait être un important nouveau district d’or mésothermal dans cette partie du Nunavut.

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Key Words: Fluid inclusions, Stable isotopes, Hope Bay volcanic belt, Nunavut, Lode-gold deposit.

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Introduction

The Boston mesothermal quartz-carbonate vein lode-gold deposit is located in the Slave structural province, in the southern portion of the Hope Bay volcanic belt (NTS map sheet 76 O/9). The Hope Bay volcanic belt was first mapped by the Geological Survey of Canada in 1962 (Fraser, 1964). The Boston deposit was the first major quartz-carbonate vein lode-gold deposit recognized in the Hope Bay belt and is also the largest, with a measured and indicated resource of 1.387 million tonnes at a grade of 15.4 g/t gold, and an additional inferred resource of 2.574 million tonnes at a grade of 10.9 g/t gold (Miramar Mining Corp. press release, Jan. 22, 2004). Other gold deposits have been discovered in the northern portion of the belt; however, presently the Boston deposit remains isolated in the southern portion of the belt.

This paper reports on the nature of the fluids responsible for lode-gold mineralization and hydrothermal alteration in the Boston deposit, using fluid inclusions and stable isotopic analysis. The structure, composition, and paragenesis of the Boston deposit are also summarized, and the potential for the discovery of additional lode-gold resources within the Hope Bay volcanic belt is evaluated.

Regional Geology

The Boston deposit occurs within the Hope Bay volcanic belt, which is located in the northeastern corner of the 2.7 to 2.5 billion-year-old Slave structural province. The Hope Bay volcanic belt is part of the Bathurst block, which formed 1.97 to 1.92 Ga ago as the result of collision between the Slave and Rae provinces (Hoffman, 1989). The Bathurst block is defined to the southwest by the Bathurst fault and to the northwest by the Thelon tectonic zone. Granitoids make up over 60% of the exposed Archean rocks within the Bathurst block (Thompson, 1997). The northern part of the block, which hosts the Boston deposit, consists mainly of volcanic rocks, granite to granodiorite plutons, and a heterogeneous gneiss (Gebert, 1993). The southern portion of the block consists predominantly of sedimentary rocks, pink gneiss, migmatite, and granitoids (Gebert, 1990a).

The Hope Bay volcanic belt is a 90 km-long by 15 to 20 km-wide north-trending greenstone belt (Fig. 1) lying within the northern portion of the Bathurst block. The geology of the Hope Bay volcanic belt was first outlined by Fraser (1964) as part of a government-sponsored mapping project, and has since been described in detail by Gebert (1989a,b, 1990a,b, 1992, 1993), LeClair (1990a,b, 1991, 1992), and Clark (1996). It has also been described in numerous unpublished BHP company reports, the most comprehensive being the “Hope Bay Project—Exploration Overview, 1999” (BHP, 1999). Thompson (1996, 1997) also described the geology of the granitoid rocks that border the belt. U-Pb zircon ages for most of the major rock types in the belt have been determined by Bevier and Gebert (1991) and Hebel (1999).

The Hope Bay volcanic belt is made up primarily of pillowd tholeiitic basalt, basaltic andesite, and iron-rich tholeiite with interfingered intermediate-to-felsic volcanic rocks and sedimentary rocks (Gebert, 1993). The mafic volcanic rocks appear to belong to a single pre-2.7 Ga event that has been cut locally by ultramafic intrusions forming sills up to 200 meters thick (BHP, 1999). The entire Archean assemblage experienced regional metamorphism to lower greenschist facies and locally amphibolite facies (Thompson, 1997) between approximately 2.63 and 2.58 Ga (Isachsen et al., 1991).

The eastern margin of the Hope Bay volcanic belt is bounded by a series of granodiorite, tonalite, and gabbro intrusions, which were emplaced approximately 2.67 Ga ago (Bevier and Gebert, 1991). A 2.65-Ga heterogeneous gneissic terrane, possibly turbiditic in nature, and several granitoid intrusions define the southeastern margin of the belt (Hebel,
To the west, the Hope Bay volcanic belt is bounded by granodioritic to granitic rocks with a U-Pb zircon age of 2.61 Ga (Bevier and Gebert, 1991). These rocks contain xenoliths of foliated mafic volcanic rocks and provide a minimum age for the peak of regional metamorphism in the Hope Bay volcanic belt (Bevier and Gebert, 1991).

### Structural Geology of the Hope Bay Volcanic Belt

The Hope Bay volcanic belt, like most Archean greenstone belts, is structurally complex. The following summary is based largely on observations made by BHP geologists working in the belt during the 1990s (summarized in BHP, 1999) and more recently by geologists working for the Miramar Mining Corporation (Sherlock and Sandeman, 2004).

Several episodes of deformation have affected the Hope Bay volcanic belt since its formation. The first phase (D1) occurred sometime following the deposition of turbidites ca. 2.66 Ga, but before the peak of regional metamorphism and the onset of regional plutonism at 2.63 Ga in the Slave structural province (Davis and Bleeker, 1997). This early stage of deformation (D1) is locally represented by a weakly developed fabric; however, generally its effects are hard to recognize and it is poorly understood.

The second episode of deformation (D2) is related to the peak of regional metamorphism in the Hope Bay greenstone belt and corresponds to the peak of compressional deformation in the Slave structural province, between 2.63 and 2.60 Ma (van Breemen et al., 1992; Relf, 1992; Davis et al., 1994). Compressional deformation resulted in flattening of rock units, folding, and the development of a regionally extensive, generally north-trending and subvertically dipping foliation that appears to parallel to the edges of the belt (Gebert, 1993). Xenoliths of strongly foliated volcanic rock have been noted within a group of granitic rocks to the west of the Hope Bay volcanic belt with a U-Pb zircon age of 2.61 Ga (Bevier and Gebert, 1991). The granitic suite has been affected by subsequent episodes of deformation and must, therefore, have been emplaced shortly after the peak of regional metamorphism but before the onset of the next period of deformation in the Hope Bay greenstone belt.

The third episode of deformation (D3) to affect the Hope Bay volcanic belt is associated with retrograde metamorphism that accompanied the emplacement of granitic plutons to the west of the belt between 2.61 and 2.58 Ga (Padgham and Fyson, 1992; Bleeker and Villeneuve, 1995). During this time, there was a shift from pure compressive deformation to oblique compression and shearing. Deformation is marked locally by the development of crenulation cleavage and regionally by the development of northeast-striking, southeast-dipping folds and belt-scale flexures (Gebert, 1993, Sherlock and Sandeman, 2004). In the vicinity of shear zones, foliation that developed in response to D3 deformation locally overprints the more regionally extensive compression related fabric. Within the Boston deposit, gold-bearing quartz-carbonate veins and associated hydrothermal alteration have been strongly affected by D3 deformation, and appear to have been emplaced prior to its onset, sometime during the D2 deformaational event.

Late brittle faulting followed late shearing as the fourth episode of deformation (D4) to affect the Hope Bay volcanic belt. Some of the northwest and north-northwest trending valleys and lakes that occur throughout the belt have been attributed to late faulting. However, the nature of these faults is poorly understood due to the lack of marker units that can be used to determine sense of motion. Several deflections occur along the borders of the Hope Bay volcanic belt, some of which appear to be related to this late faulting event (Gebert, 1993). All lithologies, including the auriferous veining associated with lode-gold mineralization in the Boston deposit, have been subjected to various amounts of offset by these late faults.

### Exploration History of the Hope Bay Volcanic Belt

The Hope Bay volcanic belt was first mapped in 1962 by the Geological Survey of Canada, as part of a 1:506,880-scale reconnaissance mapping project called “Operation Bathurst”. During the sixties and seventies, a number of gold and silver showings were discovered in the belt by Roberts Mining Company, Radioore Uranium Mines, Hope Bay Mining Company, and Perry River Nickel Mines. A small, high-grade silver mine was operated by Hope Bay Mining Company in the northern portion of the belt during the summers of 1973 and 1974, with a total production in excess of 100,000 ounces of silver.

Between 1977 and 1983, Noranda Ltd. conducted a base-metal exploration program over the entire belt. As part of this exploration, Noranda flew 2,809 line kilometers of airborne input EM and magnetic surveys. This was followed by geological mapping and ground magnetic/HLEM surveys over anomalies. In 1983, several holes were drilled to test the best EM anomalies, but no areas of economic mineralization were discovered.

In 1987, Abermin Corporation restaked all the known gold showings in the belt. In 1988, Abermin conducted several traverses and staked the Spyder claims over a large carbonate-altered shear zone in the southern portion of the belt. This shear zone was later restaked by the Broken Hill Proprietary Company Limited of Canada (BHP) as part of the Boston claim group in May of 1991.

In 1988, BHP began ground exploration in the Hope Bay volcanic belt and commenced drilling on the Boston property in 1992. From 1992 to 1998, the company completed several consecutive diamond-drilling programs, and in 1996 and 1997 a decline was driven between two of the three main mineralized zones at Boston to a depth of 200 m, allowing for underground drilling and bulk sampling.

In 1999, as part of a worldwide company restructuring, BHP sold all interests in the Hope Bay volcanic belt to a fifty-fifty joint venture between Miramar Mining Corporation and
Hope Bay Gold Corporation, which have since merged. Miramar Mining Corporation has been exploring in the Hope Bay belt since 1999, and to date has identified several deposits including the Boston, Doris, Naartok, Perrin, and Suluk deposits, with a combined gold resource in excess of 6 million ounces (Miramar Mining Corp.: http://www.miramarmining.com). At present, ongoing diamond drilling and property evaluation programs are being conducted by Miramar over several claim groups.

Deposit Geology

Structural Setting

The Boston lode-gold deposit occurs in close proximity to the major north–south-trending structure. This structure, termed the Boston fault zone by geologists working for BHP during the 1990s (Fig. 2), coincides with the axis of a large-scale south-plunging fold, which incorporates the package of metasedimentary and metavolcanic rocks hosting the Boston deposit. The Boston fault zone is also part of a larger north–south-trending structure, the Hope Bay fault, which runs down the center of the Hope Bay volcanic belt. Using lithological contacts and facing directions (graded bedding and bedding-cleavage relationships in the sedimentary rocks and pillow shelves in the mafic volcanic rocks), Sherlock and Sandeman (2004) concluded that the geometry of the fold hosting the Boston deposit is either that of a steeply plunging synformal anticline or an overturned anticline.

The earliest fabric present in the Boston area is bedding (S0), which was recognized within the sedimentary rocks and from pillow shelves within the mafic volcanic rocks hosting the Boston deposit (Sherlock and Sandeman, 2004). A penetrative fabric (S1) is locally identifiable parallel to bedding within the sedimentary rocks, and was interpreted as a transposition foliation by Sherlock and Sandeman (2004).

The dominant fabric (S2) recognized within the Boston deposit has an orientation of 022º/86ºE (BHP, 1999). This foliation is broadly axial-planar to the F2 fold structure that dominates the Boston area and is most likely related to the regional compression-related fabric (D2) present throughout the Hope Bay volcanic belt. An additional fabric (S3), observed within the vicinity of the Boston fault zone, has an orientation of 052º/78ºE (BHP, 1999). This fabric developed in response to localized northeast-striking, southeast-dipping folding (F3) that accompanied D3 deformation. The intersection of S2 and S3 defines a strong intersection lineation, trending approximately 200º and plunging 50º to 70º to the south (BHP, 1999).

Sherlock and Sandeman (2004) found that there was no apparent difference in the orientation of D3 fabrics within auriferous high-strain zones and barren unaltered rocks surrounding the Boston deposit, suggesting that mineralized veining at Boston formed sometime during D2-related deformation within the Hope Bay greenstone belt. The mineralized veins were then boudinaged, folded, and rotated into the well-developed S2-S3 intersection lineation by subsequent D3 deformation. Deformation associated with D3 structures may also account for a major flexure that occurs in the trend of the Boston fault zone in the vicinity of the Boston deposit (Sherlock and Sandeman, 2004).

The Boston deposit has been affected by at least three generations of post-mineralization faulting (BHP, 1999). Thrust faults with an orientation of approximately 195º/75ºW have been identified underground, which may displace blocks up to 40 m (hanging wall to the west). Veining is commonly dragged into these faults where they may be associated with a narrow zone of fault gouge.

The second fault set to affect the Boston deposit has an orientation of approximately 090º/35ºS. The amount of displacement associated with these faults does not appear to be as great as in the first fault set (<30 cm).

A final fault set with an orientation of approximately 070º/87ºSE can be seen cutting all veins and lithologies. Movement appears to be dextral strike-slip with an associated displacement of approximately 7 to 10 m.

Host Lithologies

Outcrop is limited in the area surrounding the Boston deposit, and as a result the following descriptions rely heavily on observations made underground, and on petrographic and geochemical examinations of surface and underground drill core. The observations of Sherlock and Sandeman (2004) and of numerous BHP geologists working in the belt during the 1990s (summarized in BHP, 1999) were also taken into account. For simplicity, igneous and sedimentary rock terminology is used where describing the various lithologies hosting the Boston deposit, except where the distinction between metamorphic and hydrothermal alteration is necessary.

Mafic Volcanic Rocks: Mafic volcanic rocks are the most common lithology in the Boston area. Several suites of massive or pillowed basaltic lava flows underlie the Boston claims and make up much of the outcrop in the surrounding area. Locally, volcanic textures and structures such as flow top breccias, varioles, pillow selvages, and amygdales filled with calcite and epidote are preserved (Sherlock and Sandeman, 2004). Compositionally, the mafic volcanic rocks range from tholeiitic basalt to basaltic andesite and iron-rich tholeiite (Locock, 1998).

The least hydrothermally altered examples of basalt are found outside of the main fault zone, and as an isolated wedge of basalt within the fault zone. Basaltic rocks tend to be massive and fine grained, resembling a dark, forest-green, chloritic phylite. This rock type is characterized by a typical lower greenschist facies metamorphic mineral assemblage. Original igneous minerals are rarely observed, with the possible exception of plagioclase. Magnesian chlorite (clinochlore) is the dominant metamorphic mineral in the basaltic rocks, making up over 60% of most samples. Abundant quartz and small amounts of rutile, epidote, and actinolite are also typically present. A significant amount of
fine-grained calcite occurs in most samples, and irregular calcite-filled fractures are locally abundant.

**Mafic Intrusive Rocks:** Discontinuous gabbroic units up to 200 m thick are common throughout the mafic volcanic package. However, it is unclear whether the gabbroic units represent distinct intrusions (possibly feeders to the overlying pillow flows) or the slowly cooled centers of thicker volcanic flows. The gabbroic units have higher abundances of potassium, rubidium, and barium than the basaltic units, and are commonly also richer in iron and titanium (Locock, 1998).

Hydrothermally unaltered samples of gabbro tend to be darker gray-green in color than the dark forest-green basalts. Mineralogically, the gabbroic units have the same lower greenschist facies mineral assemblage as the basalts, consisting of clinochlore, quartz, rutile, and coarse-grained plagioclase. A significant amount of epidote also occurs in some samples.
Ultramafic Intrusive Rocks: An ultramafic unit, possibly of picritic composition (Locock, 1998), occurs in close association with mineralization occurring within the B₃ zone (the mineralized zones occurring within the Boston deposit are discussed in more detail below). This unit probably intruded as a sill sometime prior to deformation and mineralization; however, the contacts between this unit and the surrounding pillow basalts are generally not well defined.

In hand sample, this unit is typically medium- to fine-grained and has a distinctive bright turquoise-green color and a distinctive metamorphic mineral assemblage due to a higher iron and magnesium content. Samples typically consist of ferroan dolomite and ferroan magnesite, quartz, paragonite, muscovite, clinochlore, and rutile.

Sedimentary Rocks: Sedimentary rocks in the Boston area range from massive turbiditic graywacke to fine-grained argillite. Unaltered samples of the graywacke are composed of relict quartz and plagioclase grains in a fine-grained matrix of quartz, clinochlore, and muscovite. Minor amounts of paragonite and rutile also occur in most samples. Bedding and fining-upwards sequences are occasionally preserved in the turbiditic sediments, and have been used as evidence for folding in the Boston area (Sherlock and Sandeman, 2004).

Fine-grained argillite occurs within both the turbiditic and basaltic units. Argillite units are typically dark gray to black in color and contain interstitial graphite, and clots and bands of diagenetic pyrite. Pyrite grains typically display inclusions and overgrowths of sphalerite and pyrrhotite. The graphite content of the argillite beds increases significantly in areas of intense shearing and faulting, and along sedimentary-volcanic interfaces. Overprinting episodes of deformation have resulted in the development of crenulation cleavage and tight folding in some samples.

Intermediate Intrusive Rocks: A 0.5- to 3.0-m-wide, beige colored, fine-grained andesitic dike occurs in the vicinity of the Boston deposit. The dike dips subvertically and is located between the B₂ and B₃ zones; it is hydrothermally altered but unmineralized. Alteration assemblages consist of quartz, calcite, ferroan dolomite, clinochlore, muscovite, paragonite, and residual Ca-plagioclase. Minor amounts of magnetite are present in some samples, and fine- to medium-grained pyrite cubes occur locally.

The dike appears to postdate mineralization and is not as strongly deformed as the surrounding wall rocks or mineralized zones. However, the presence of hydrothermal alteration suggests that it was emplaced before the end of hydrothermal activity within the Boston deposit (late to post D₂).

Hydrothermal Alteration

A distinct hydrothermal alteration mineral assemblage overprints metamorphic assemblages adjacent to mineralized veins within the Boston deposit. All affected lithologies show a trend to intense carbonation (calcite is replaced by ferroan dolomite and/or ankerite) and replacement of metamorphic chlorite by hydrothermal sericite. Plagioclase is completely replaced by paragonite and/or muscovite, even in weakly altered samples. A substantial amount of rutile also occurs in most samples.

Deformation subsequent to mineralization and alteration has resulted in the development of strong foliation fabrics (S₂ and S₃) in the mafic volcanic rocks. Paragonite, muscovite, chlorite, and rutile tend to be aligned parallel to foliation and define the orientation of this fabric.

In the areas that have experienced the strongest hydrothermal alteration and deformation, rocks are strongly banded and very dark gray-brown in appearance. No features of the pre-alteration protoliths remain, making it difficult to determine rock type and to pinpoint the position of lithological contacts in the field. Strongly altered basaltic and gabbroic rocks typically consist of millimeter-scale, foliation-parallel bands of paragonite, muscovite, and rutile alternating with centimeter-scale, commonly massive bands of carbonate and quartz. Dravite is common in the most advanced stages of alteration close to auriferous veins. Thicker bands of quartz-carbonate alteration are commonly boudinaged and may contain short, quartz-carbonate-filled, extension-related fractures or ladder veins, which are discussed in detail in the next section. In some cases, siderite is also present within very highly altered rocks in the Boston deposit. Minor phlogopite has also been identified in some samples.

The strongly altered rocks adjacent to auriferous quartz-carbonate veins are typically enriched in sulfide minerals. Pyrite and lesser amounts of arsenopyrite, and chalcopyrite form a halo of sulfide alteration, which can extend up to 15 cm into the wall rocks on either side of these veins. In some cases, sulfide minerals make up over 40% of the wall rock adjacent to mineralized quartz-carbonate veins. A large proportion of the gold resource in the Boston deposit forms as inclusions within, or as fracture-fill and thin coatings on the surface of, sulfide grains in this halo.

Mineralized Zone

Individual mineralized zones developed parallel to S₂ foliation, along the contacts between alternating packages of greenschist facies basalt, gabbro, and sedimentary rocks within what is believed to be a steeply plunging synformal or overturned anticline (Sherlock and Sandeman, 2004). Three subparallel zones of auriferous quartz-carbonate veining are recognized: the B₂, B₃, and B₄ zones (B₁ terminology was abandoned after the B₁ zone was found to be a continuation of B₂ mineralization; Fig. 3). Although the mineralized veins have been observed within all rock types and are believed to crosscut stratigraphy at depth, the strongest veining appears to have developed along the contacts between competent mafic rocks and ductile sedimentary units. Within the Boston deposit, vein intensity in each of the mineralized zones
increases significantly as lithological contacts are approached.

**B₂ Zone:** The B₂ zone has a known strike length of approximately 900 m, a width of 25 to 50 m, and a depth extent of at least 1,000 m. B₂ mineralization occurs within a package of moderately to strongly altered and deformed mafic volcanic rock at or near the sediment-volcanic contact (Fig. 3). Veining in the B₂ zone consists of less than one-metre- to several-metre-thick quartz-carbonate fissures that plunge steeply to the southwest, roughly parallel to the intersection of S₂ and S₃ foliation (Fig. 4). These veins have experienced several episodes of ductile deformation and tension-related fracturing since their formation. As a result, the thickness of mineralized portions of the B₂ zone can fluctuate considerably over very short distances.

A significant proportion of the gold (Fig. 5) in the B₂ zone occurs with pyrite, arsenopyrite, and chalcopyrite in a sulfidation halo that extends up to fifteen centimeters into the wall rock immediately adjacent to the quartz-carbonate veins. Visible gold has also been observed in association with strongly altered wall-rock fragments and sulfide minerals within the quartz-carbonate veins that make up the B₂ zone, and as free gold within microfractures in the B₂ veins (Fig. 5c,d).

**B₃ Zone:** The B₃ zone runs parallel to and approximately 10 to 40 m east of the B₂ zone (Fig. 3), within basaltic and more competent gabbroic and ultramafic rocks occurring within the mafic volcanic package. The B₃ zone has a known strike length of 900 m and an average width of 30 to 50 m.

Quartz-carbonate veins in the B₃ zone tend to be more irregular and discontinuous than veins in the B₂ zone due to the resilient nature of the mafic and ultramafic host rocks. This gives veining in the B₃ zone a brittle or stockwork-like appearance. In the B₃ zone, several overprinting sets of foliation-parallel and foliation-crosscutting veins have resulted in intense wall-rock alteration and sulfidation. Gold typically occurs with sulfide minerals in the hydrothermally altered wall rocks surrounding the quartz-carbonate veins in this zone (Fig. 5a,b). Gold has also been observed as free grains in association with strongly altered wall-rock fragments and within microfractures in the B₃ veins. Numerous flat veins also occur throughout the B₃ zone.

**B₄ Zone:** The B₄ zone is located to the east of the B₃ zone, at or near the contact between graphitic sediments and basalts, much like the B₂ zone to the west (Fig. 3). Veining in the B₄ zone appears to be more discontinuous than the B₂ or B₃ zones, although individual veins can be several meters wide locally.

Mineralization within the B₄ zone is similar to the B₂ zone, with significant amounts of wall-rock sulfide-gold mineralization occurring around shear-parallel quartz-dolomite veins. Coarse-grained gold has also been observed in microfractures within the quartz-dolomite veins in the B₄ zone.

**Vein Paragenesis**

Several overprinting vein sets occur within the Boston deposit, including at least five episodes of quartz-carbonate veining. Different vein types were identified both underground and from diamond drill core, and can be distinguished on the basis of appearance, mineral assemblage, crosscutting relationships, and intensity of deformation. The relationships between the three main vein types in the B₂ zone are illustrated in Figure 4.

**Main-Stage Quartz-Carbonate Veins:** Main-stage quartz-carbonate veining in the Boston area has resulted in the formation of fissure or sheeted veins in the B₂, B₃, and B₄ zones (Fig. 4). These veins are directly related to gold deposition, intense hydrothermal alteration, and sulfide enrichment of the wall rocks, and range from several centimeters to several meters thick. They form three sets of highly deformed quartz-carbonate veins that are aligned parallel to the trend of the Boston fault zone and plunge steeply to the southwest. Ferroan dolomite and/or ankerite typically line the margins of the veins, with a mixture of carbonate and quartz filling the center. Radiating needles and stringers of dravite tourmaline, coarse-grained pyrite, chalcopyrite, and arsenopyrite, and slivers of strongly altered wall rock also commonly occur within these veins. Gold
Fig. 4. Paragenesis of main-stage quartz-carbonate veins, ladder veins, and flat veins in the Boston deposit (modified after Hodgson, 1989, and Hurst, 1935, for mineralized veining in the Hollinger mine, Timmins, Ontario). (a) Crack-seal formation of main-stage quartz-carbonate veins (1a, 1b, 1c, etc.). (b) Ladder veins (2) form within the main-stage veins in response to compression perpendicular to the walls of the main-stage veins. (c) Flat veins (3) crosscut the main-stage veins. (d) Continued deformation results in folding of the flat veins and boudinage of the main stage veins. (e) Typical deformed main-stage quartz-carbonate fissure vein and associated flat veins from the B₂ zone (hammer is approximately 40 cm long).
occurs as inclusions and fracture fillings within pyrite, arsenopyrite, and chalcopyrite grains associated with strongly altered wall-rock stringers in these veins, just as it does in the hydrothermally altered wall rock adjacent to the veins. Stringers of strongly altered wall rock became incorporated into the veins during vein growth as a result of repeated fracturing and resealing at or near the contact between previously formed veins and the wall rock (Fig. 4; Hodgson, 1989).

Postmineralization deformation resulted in both the brittle fracturing and ductile boudinage and tight folding of all main-stage quartz-carbonate veins in the B₂, B₃, and B₄ zones. Quartz and carbonate within the main-stage quartz-carbonate veins, and within the most intensely altered wall rocks immediately adjacent to these veins, has been deformed and recrystallized. Quartz also typically displays strong undulose extinction and has sutured grain boundaries. Variable degrees of cataclastic deformation and recrystallization have also been observed in sulfide minerals within and surrounding the main-stage quartz-carbonate veins. These observations are consistent with development of the main stage quartz-carbonate veins and associated wall-rock alteration parallel to S₂ during D₂, with subsequent deformation occurring during D₃.

**Phantom Veinlets (Brecciation):** Numerous phantom veinlets, outlined by trails of fluid inclusions, occur within the main-stage quartz-carbonate veins in the B₂, B₃, and B₄ zones. The phantom veinlets are difficult to see in hand sample and thin section because they are mineralogically similar to, and have been deformed and recrystallized along with, the main-stage quartz-carbonate veins that host them. Phantom veinlets create a stockwork array of irregular and crosscutting veinlets with no obvious preferred orientation, and appear to have formed in response to fracturing during main-stage quartz-carbonate vein formation. In the B₂ and B₄ zones, free gold occurs in association with some phantom veinlets. The gold within these veinlets may have been remobilized into the veins or it may have been deposited within the phantom veinlets due to rapid drops in fluid pressure accompanying hydraulic fracturing during D₂ deformation and main-stage quartz-carbonate vein emplacement.
**Ladder Veins:** Ladder veins are common within quartz-carbonate veins and the strongly dolomite-enriched wall rock within the Boston deposit. The quartz-carbonate-filled "rungs" of the ladders are typically only a few millimeters to centimeters thick, up to half a meter long, and typically terminate abruptly at unit boundaries. In the Boston deposit, the ladder veins appear to have formed in response to vertical stretching within the main-stage quartz-carbonate veins and strongly dolomitized portions of the wall rock. The ladder rungs are roughly horizontal and would have formed at right angles to the minimum compressive stress associated with compression-related D₂ and D₃ deformation (Fig. 4c). Continued deformation resulted in recrystallization of the quartz-carbonated-filled rungs after their formation.

Within a compressional environment, ladder veins will form areas of dilation, and as a result the ladder veins in many Archean lode-gold deposits are mineralized (Groves and Foster, 1991). However, within the Boston deposit, the ladder veins tend to be subeconimic and, therefore, must have been emplaced very late to post D₂, subsequent to the formation of the main-stage quartz-carbonate veins and gold deposition.

**Flat Veins:** Isolated flat veins also formed perpendicular to the minimum compressive stress associated with D₂ and D₃ deformation. However, these veins are not confined to a specific rock type and have been observed crosscutting all lithologies and vein types in the Boston deposit (Fig. 4c–e). Flat veins are also much thicker (several to tens of centimeters thick) and more laterally extensive (several meters long) than the ladder veins. Internal layering parallel to the vein walls, and elongation of quartz and carbonate perpendicular to the vein walls has been observed within many flat veins, indicating that these veins formed as a result of several consecutive opening and vein-filling events (Robert and Poulsen, 2001). Locally, slabs of wall rock have also become incorporated into the flat veins during vein propagation and dilation. In the most strongly deformed portions of the Boston deposit, the flat veins have been folded into sigmoidal shapes by subsequent D₃ deformation (Fig. 4d,e).

Like the ladder veins, flat veins within the Boston deposit do not contain economically significant concentrations of gold, and are not generally associated with wall-rock alteration or sulfide enrichment.

**Late Brittle Veins (Rebrecciation):** Throughout the Boston deposit, thin, irregular veinlets with no apparent preferred orientation occur both within and outboard of the main-stage quartz-carbonate veins, cutting across all of the other vein types. These late veinlets generally contain clear, relatively undeformed quartz and carbonate, and are always barren. Petrographically, these veinlets appear to have formed very late in the life of the hydrothermal system under conditions dominated by brittle deformation (likely syn- to post-D₃).

**Sample Selection and Analytical Methods**

During the 1997 and 1998 field seasons, vein and wall-rock samples were collected from surface showings and drill core both proximal and distal to the Boston deposit. Drifting on two of the three main mineralized zones, B₂ and B₃, allowed additional sampling underground. Numerous mineralized and barren vein sets were sampled in this way. In addition, samples of altered and unaltered wall rock were collected from surface outcrop and drill core both locally and regionally. Sample numbers, descriptions, and UTM coordinates are listed in Stemler (2000).

** Petrography, XRD, and Electron Microprobe Analyses**

Representative thin and polished sections of all of the rock types associated with the Boston deposit were prepared for petrographic analysis. In addition, X-ray diffraction (XRD) and qualitative electron microprobe analysis was used to aid in the identification of end-member minerals difficult to distinguish on the basis of petrographic analysis alone (for example, calcite, dolomite, ankerite, and siderite).

**Fluid Inclusion Analysis**

Forty doubly polished thin sections of auriferous and barren veins from the B₂, B₃, and B₄ zones were prepared for fluid inclusion microthermometry. Considerable effort was made to select samples or areas of samples that contained undeformed populations of primary fluid inclusions that could be directly related to specific vein events, whereas unconstrained or deformed clusters and trails of secondary fluid inclusions were avoided.

Microthermometric analysis was performed on a Linkam THMSG600 fluid inclusion heating/freezing stage at the University of Alberta. This stage was calibrated using Syn Flinc synthetic fluid inclusion standards to a precision of ±0.1°C at temperatures near or below 0°C, and to within 1.0°C at temperatures above 32°C.

The salinities of CO₂-rich aqueous fluid inclusions were calculated from the final melting temperatures of clathrate (in the presence of liquid CO₂) using the equation of Darling (1991). Salinities of inclusions that contained no liquid CO₂ or clathrate were calculated from final ice melting temperatures using the equation of Bodnar (1993). Isochores for selected fluid inclusion assemblages were calculated using the computer program of Brown (1989; Brown and Hagemann, 1995), and the equations of Brown and Lamb (1986, 1989).

**Stable Isotope Analysis**

**Carbonates:** Ferroan dolomite and/or ankerite were separated from fifteen samples of mineralized main-stage quartz-carbonate vein material from the Boston deposit and analyzed for their oxygen and carbon isotopic composition. Samples of vein carbonate were roughly crushed, then hand picked for purity under technical-grade ethanol using a binocular microscope. All samples were powdered to
Fluid Inclusion Observations and Results

Fluid Inclusion Types

In general, it is uncommon to find primary fluid inclusions within the deformed quartz-carbonate veins that make up the Boston deposit. The fluid inclusions within these veins typically occur along healed microfractures, as irregular three-dimensional clusters, or along recrystallized grain boundaries, and are interpreted to be secondary in origin. Such inclusions tend to be small and irregularly shaped, and many have experienced post-entrapment volume and/or compositional change. Microthermometric data from such inclusions are, therefore, of dubious value, and such inclusions were avoided where possible in this study except to characterize late fluids.

Rare, primary fluid inclusion assemblages (FIAs) were found within undeformed quartz crystals occurring within or immediately adjacent to large pyrite or carbonate grains in mineralized quartz-carbonate veins associated with the Boston deposit (Fig. 6a,b,c). The relative strength or plasticity of the pyrite or carbonate (respectively) appears to have protected the quartz and its inclusions from most of the strain associated with deformation (Guha et al., 1991). A small number of undeformed primary fluid inclusions were also observed within large carbonate grains within sheltered portions of the main-stage quartz-carbonate veins.

**Type 1 H₂O-CO₂-NaCl Inclusions:** Type 1 CO₂-bearing aqueous fluid inclusions are present as primaries and secondaries within the main-stage quartz-carbonate veins, extensional (ladder) veins, and barren quartz-carbonate veins that make up the Boston deposit (Fig. 6a–c). Primary inclusions are typically <5 to 15 μm in size, and generally have negative crystal shapes. Secondary type 1 fluid inclusions are the most prevalent fluid inclusion type in the mineralized zones, where they occur as trails and three-dimensional clusters within deformed quartz and carbonate grains.

Secondary type 1 inclusions also appear to be the dominant fluid inclusion type within the phantom veinlets that occur within the main-stage quartz-carbonate veins. Deformation and recrystallization of the phantom veinlets has resulted in small, irregularly shaped fluid inclusions with inconsistent fill ratios reflecting post-entrapment modification; no measurements were made of these inclusions.

**Type 2 CO₂-Rich Inclusions:** Type 2 CO₂-rich fluid inclusions occur as rare 5- to 15-μm inclusions within both mineralized and barren quartz-carbonate veins. Inclusion contents are dominated by CO₂ (liquid plus vapor bubble), and no liquid H₂O meniscus was visible. These inclusions mostly occur in trails or three-dimensional clusters within deformed quartz and carbonate, and are interpreted to be secondary in origin.

**Type 3 Aqueous Inclusions:** Type 3 aqueous fluid inclusions occur as trails of secondary inclusions within healed microfractures within main-stage quartz-carbonate veins and crosscutting ladder veins in all three ore zones, as well as within crosscutting brittle veinlets in the B₂ zone (Fig. 6d). These inclusions are liquid-rich, irregularly shaped, and typically <5 to 20 μm in size.
Microthermometric Results

The results of microthermometric examination of primary and secondary fluid inclusions from mineralized main-stage quartz-carbonate veins, and barren ladder veins and late brittle veins in the Boston deposit are summarized in Table 1 and illustrated in Figures 7 and 8.

Type 1 $\text{H}_2\text{O}-\text{CO}_2-\text{NaCl}$ Inclusions: Primary type 1 fluid inclusions, preserved in protected areas of minimally deformed quartz and rare carbonate, yield quite uniform microthermometric data. Melting points of the carbonic phase averaged $–56.6° \pm 0.1°C$ ($n = 165$, in 9 samples), indicating an essentially pure CO$_2$ composition. Where eutectic melting points in the aqueous phase could be observed, they ranged between $–17°$ and $–30°C$ (with an average of $–21° \pm 3°C$, $n = 26$), consistent with a dominantly $\text{H}_2\text{O}$-NaCl composition. Clathrate melting temperatures ranged between 4.8° and 9.5°C (average $= 7.6° \pm 0.8°C$, $n = 182$), yielding salinities of 1.0 to 9.3 eq. wt.% NaCl (average $= 4.6 \pm 1.4$ eq. wt.% NaCl; Fig. 7a). The carbonic phases homogenized close to the CO$_2$ critical point of 31.1°C, with approximately equal numbers homogenizing to the liquid phase as to the vapor phase (Table 1). Calculated densities of the CO$_2$ phase range from 0.27 to 0.75 g/cm$^3$, and mole fractions of CO$_2$ range from 3% to 21%.

Despite these relatively uniform low-temperature phase relationships, type 1 fluid inclusions showed important differences during final homogenization. The majority of inclusions homogenized to the liquid phase at temperatures ranging from 189° to 342°C (average $= 270° \pm 33°C$, $n = 141$; Fig. 7b). However, five samples contained type 1 fluid inclusion assemblages in which some inclusions homogenized to the vapor phase (Th$_{L-V,V} = 306°–400°C$; average $= 338° \pm 28°C$, $n = 18$; Fig. 7b). Coexisting type 1 inclusions that homogenized to the liquid phase did so at a higher average temperature (Th$_{L-V,L} = 299° \pm 25°C$, $n = 24$; Fig. 7b) than inclusions from single-phase (liquid) assemblages (Th$_{L-V,L} = 264° \pm 32°C$, $n = 117$; Fig. 7b). This behavior is interpreted to reflect conditions of aqueous–carbonic phase separation at temperatures close to 320°C (319°C is the median of the average homogenization temperatures of coexisting liquid- and vapor-phase inclusions). The physical properties of the two phases are so similar, however, that conditions near the critical point are suggested, and indeed some inclusions showed final homogenization behavior that was very near critical (i.e.,
fading of the meniscus before final expansion or contraction). Consequently, isochores calculated for these immiscible fluid inclusion assemblages using the MacFlinCor program (Brown, 1989; Brown and Hagemann, 1995) are subparallel, and their points of intersection cannot be taken as an accurate indication of pressure-temperature conditions at the time of trapping. In three cases, however, the isochores converge near 320°C at pressures of between 2 and 3 kbar. Such pressures and temperatures are consistent with the expected conditions of entrapment in mesothermal vein systems, although the data are not robust enough to make a more precise estimation.

Type 2 CO₂-Rich Inclusions: Secondary type 2 fluid inclusions appear to represent the late entrapment of a discrete carbonic vapor phase, but trapping temperature and pressure conditions are unknown. Melting points of the carbonic phase were consistently within error of the melting point of CO₂ (~56.6°C), and the fluid is therefore interpreted
Table 1. Summary of Fluid Inclusion Microthermometric Results from the Boston Gold Deposit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type 1 H2O-CO2- NaCl inclusions (primary)</th>
<th>Type 2 CO2-rich inclusions (secondary)</th>
<th>Type 3 aqueous inclusions (secondary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TmCO2⁴</td>
<td>–56.6±0.1°C (n = 2)</td>
<td>–56.5°C (n = 15)</td>
<td></td>
</tr>
<tr>
<td>Te²</td>
<td>–21°±3°C (n = 26)</td>
<td>–20° to –50°C (n = 40)</td>
<td></td>
</tr>
<tr>
<td>Tmice³</td>
<td>–2.6° to –28.6°C (n = 75)</td>
<td>–2.6° to –28.6°C (n = 75)</td>
<td></td>
</tr>
<tr>
<td>TmClath⁴</td>
<td>7.6°±0.8°C (n = 182)</td>
<td>Not Visible</td>
<td></td>
</tr>
<tr>
<td>Salinity (eq. wt. % NaCl⁵)</td>
<td>4.6±1.4 (n = 182)</td>
<td>4.3 to &gt;20.8 (n = 75)</td>
<td></td>
</tr>
<tr>
<td>THCO2(L-V)L⁶</td>
<td>28.5°±2.8°C (n = 59)</td>
<td>26.7°±3.2°C (n = 15)</td>
<td></td>
</tr>
<tr>
<td>THCO2(L-V)V⁷</td>
<td>30.0°±0.7°C (n = 15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>THL-VL⁸</td>
<td>270°±33°C (n = 165)</td>
<td>Not Visible</td>
<td>151°±46°C (n = 67)</td>
</tr>
<tr>
<td>THL-VW⁹</td>
<td>338°±28°C (n = 18)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes
¹ Melting temperature of carbonic phase.
² Eutectic melting temperature.
³ Melting temperature of ice.
⁴ Melting temperature of clathrate.
⁵ Equivalent weight percent NaCl in solution.
⁶ Homogenization temperature of carbonic phases to liquid phase.
⁷ Homogenization temperature of carbonic phases to vapor phase.
⁸ Final homogenization temperature to liquid phase.
⁹ Final homogenization temperature to vapor phase.

Stable isotopic compositions of ferroan dolomite and ankerite are tightly grouped, varying by only 1.6‰ in both δ¹³C (–4.7‰ to –3.1‰, n = 15) and δ³⁴S (11.2‰ to 12.8‰, n = 15; Fig. 9a,b). The total range in the δ³⁴S composition of quartz separated from the auriferous veins is also small, varying by only 2.1‰ (12.8‰–14.9‰, n = 16; Fig. 9c).

There is no systematic variation in carbon isotopic compositions for samples from the three mineralized zones, but oxygen isotopic compositions are slightly lower in carbonates and quartz from the B₃ zone compared to samples from the B₂ and B₄ zones (Fig. 9a,b): δ¹⁸O values of carbonates range from 11.2‰ to 12.2‰ in the B₃ zone, compared with 12.0‰ to 12.8‰ in the B₂ and B₄ zones; δ¹⁸O values of quartz range from 12.8‰ to 14.3‰ in the B₃ zone, compared with 14.6‰ to 14.9‰ in the B₂ and B₄ zones. It is not known whether these small differences are significant, but they do not appear to be reflected by average fluid inclusion temperatures from these zones, which overlap within error.

Sulfur (Pyrite)

The results of sulfur isotopic analyses of twenty samples of pyrite from barren and auriferous wall rock from within and around the Boston deposit are listed in Table 4 and illustrated in Figure 9d.

Mineralized Veins: Pyrite separated from the sulfidation haloes around gold-bearing main stage quartz-carbonate veins in the B₂, B₃, and B₄ zones has a tight isotopic range from 2.1‰ to 3.5‰ (average of 2.7‰±0.4‰, n = 8), with little variation between the three zones.

Unmineralized Veins: Pyrite was also separated from the sulfidation haloes around unmineralized quartz-carbonate veins within basalt, gabbro, and turbiditic and argillic sedimentary country rocks, and strongly altered rocks that occur in the area surrounding the Boston deposit. δ³⁴S values range from 1.6‰ to 3.4‰ with an average value of 2.4‰±0.6‰ (n = 6), which is similar to values from mineralized vein halos.

Pyrite Not Associated With Veining: Small amounts of pyrite not directly associated with veining occur locally throughout the turbiditic and argillic (graphitic) sedimentary country rocks, as vugs in the turbidites, and as foliation-parallel bands and clots in the argillic sedimentary rocks. The sulfur isotopic composition of pyrite from the graphitic argillite is between 3.4‰ and 4.7‰, with an average value of 4.2‰±0.6‰ (n = 4), slightly higher than the vein-related pyrite. In contrast, two samples of pyrite separated from vugs within the turbiditic sediments yielded lower δ³⁴S values of 0.3‰ and 0.9‰ (Fig. 9d).

Discussion

Fluid Types and Paragenesis

Auriferous Fluids: A significant portion of the gold associated with the Boston deposit occurs within inclusions...
A Fluid Inclusion and Stable Isotope Investigation of the Boston Lode-Gold Deposit, Hope Bay Volcanic Belt, Nunavut – J.U. STEMLER ET AL.

and fractures hosted by pyrite and other sulfide minerals deposited within and adjacent to main stage quartz-carbonate veins (Fig. 5). Undeformed quartz and rare carbonate grains containing primary type 1 (H₂O-CO₂-NaCl) fluid inclusions have been preserved within and adjacent to large pyrite or carbonate grains in these veins, where they were protected from post-entrapment modification either by the strength of the pyrite, or the weakness of the enclosing carbonate (which absorbed the strain). Petrographically, the quartz, pyrite, and gold appear to have been deposited during the same mineralizing event, suggesting that the fluid contained within these fluid inclusions represents the primary ore-forming fluid.

Type 1 fluid inclusions are of low to moderate salinity (1.0–9.3 eq. wt.% NaCl; average = 4.6 ± 1.4°C) and contain variable proportions of CO₂ (3–21 mol.%). The majority of these inclusions homogenized to the liquid phase, but five samples (including samples from all three of the mineralized zones) contained type 1 fluid inclusion assemblages that homogenized both to the liquid and vapor phases. We interpret these assemblages to indicate conditions of phase separation, and thus calculate that fluid pressures were between 2 and 3 kbar at an approximate temperature of 320°C (realistically ±50°C) at the time of trapping. Fluid inclusion assemblages representing single-phase (liquid) conditions show slightly lower average homogenization temperatures,
which may reflect lower actual fluid temperatures at the same pressure, or periodically higher fluid pressures, which prevented phase separation. Given the dynamic environment of shear zone-related mesothermal lode gold deposits, pressure fluctuations are expected, and have been proposed as a trigger for gold deposition by loss of volatiles (especially \( \text{H}_2\text{S} \)) to the vapor phase during low-pressure phase separation events (e.g., Sibson et al., 1988; Robert et al., 1995; Wilkinson and Johnston, 1996).

Supporting evidence of periodic phase separation is provided by the presence of type 2, \( \text{CO}_2 \)-rich fluid inclusions, trapped along secondary trails in some vein samples. These inclusions are interpreted to represent a \( \text{CO}_2 \)-rich vapor phase, presumably separated from a liquid phase at greater depth, that periodically invaded the vein system (e.g., Chi et al., 2005).

**Late Barren Fluids:** Type 3 secondary fluid inclusions occur in trails in late, barren, brittle quartz-carbonate veinlets and ladder veins that have been observed to crosscut all other vein types and host lithologies within the Boston deposit. These inclusions show a range of salinities (4.3 to >23 eq. wt. % \( \text{NaCl} \)) and homogenization temperatures (80°–236°C, with an average of 151° ± 46°C), and lack detectable \( \text{CO}_2 \). They are thus quite distinct both in timing and composition from the \( \text{H}_2\text{O}-\text{CO}_2-\text{NaCl} \) fluids, and are not thought to be involved in gold deposition.

Similar, late-stage, saline fluids have been reported from many other Archean lode-gold deposits in Canada, such as the Sigma mine, Quebec (Robert and Kelly, 1987; Boullier et al., 1998), and the Hollinger-McIntyre mine, Ontario (Smith et al., 1984). These fluids have been interpreted to reflect late invasion of basement brines, and are similarly believed to be unrelated to gold deposition in these deposits (Boullier et al., 1998).

### Table 3. Oxygen Isotope Data for Vein Quartz from the Boston Gold Deposit

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unit</th>
<th>( \delta^{18}\text{O}_{\text{H}_2\text{O}} ) (‰)</th>
<th>( \delta^{13}\text{C}_\text{CO}_2 ) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSB-046</td>
<td>Ankerite</td>
<td>14.6</td>
<td>9.4</td>
</tr>
<tr>
<td>JSB-056</td>
<td>Ankerite</td>
<td>14.8</td>
<td>8.6</td>
</tr>
<tr>
<td>JSB-057</td>
<td>Ankerite</td>
<td>14.7</td>
<td>8.5</td>
</tr>
<tr>
<td>JSB-058</td>
<td>Ankerite</td>
<td>14.7</td>
<td>8.5</td>
</tr>
<tr>
<td>JSB-059</td>
<td>Ankerite</td>
<td>14.9</td>
<td>8.7</td>
</tr>
<tr>
<td>JSB-062</td>
<td>Ankerite</td>
<td>13.5</td>
<td>7.3</td>
</tr>
<tr>
<td>JSB-062</td>
<td>Ankerite</td>
<td>13.6</td>
<td>7.4</td>
</tr>
<tr>
<td>JSB-072</td>
<td>Ankerite</td>
<td>13.9</td>
<td>7.7</td>
</tr>
<tr>
<td>JSB-070</td>
<td>Ankerite</td>
<td>12.8</td>
<td>6.6</td>
</tr>
<tr>
<td>JSB-075</td>
<td>Ankerite</td>
<td>14.3</td>
<td>8.1</td>
</tr>
<tr>
<td>JSB-083</td>
<td>Ankerite</td>
<td>14.8</td>
<td>8.6</td>
</tr>
<tr>
<td>JSB-085</td>
<td>Ankerite</td>
<td>14.7</td>
<td>8.5</td>
</tr>
<tr>
<td>JSB-082</td>
<td>Flat vein, B3 zone</td>
<td>13.8</td>
<td>7.6</td>
</tr>
<tr>
<td>JSB-082</td>
<td>Flat vein, B3 zone</td>
<td>14.0</td>
<td>7.8</td>
</tr>
<tr>
<td>JSB-077</td>
<td>Flat vein, basal</td>
<td>14.2</td>
<td>8.0</td>
</tr>
<tr>
<td>JSB-082</td>
<td>Flat vein, B3 zone</td>
<td>14.6</td>
<td>8.4</td>
</tr>
</tbody>
</table>

### Table 4. Sulfur Isotope Data for Pyrite from Vein Wall Rocks and Country Rock from the Boston Gold Deposit

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unit</th>
<th>Occurrence</th>
<th>( \delta^{34}\text{S}_{\text{pyrite}} ) (‰)</th>
<th>( \delta^{34}\text{S}_{\text{H}_2\text{S}} ) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSB-046</td>
<td>B2 vein</td>
<td>Sulfide halo (mineralized vein)</td>
<td>2.1</td>
<td>1.0</td>
</tr>
<tr>
<td>JSB-056</td>
<td>B2 vein</td>
<td>Sulfide halo (mineralized vein)</td>
<td>2.7</td>
<td>1.6</td>
</tr>
<tr>
<td>JSB-076</td>
<td>B2 vein</td>
<td>Sulfide halo (mineralized vein)</td>
<td>2.6</td>
<td>1.5</td>
</tr>
<tr>
<td>JSB-079</td>
<td>B2 vein</td>
<td>Sulfide halo (mineralized vein)</td>
<td>3.0</td>
<td>1.9</td>
</tr>
<tr>
<td>JSB-012</td>
<td>B2 vein</td>
<td>Sulfide halo (mineralized vein)</td>
<td>3.1</td>
<td>2.0</td>
</tr>
<tr>
<td>JSB-023</td>
<td>B2 vein</td>
<td>Sulfide halo (mineralized vein)</td>
<td>3.5</td>
<td>2.4</td>
</tr>
<tr>
<td>JSB-033</td>
<td>B2 vein</td>
<td>Sulfide halo (mineralized vein)</td>
<td>2.4</td>
<td>1.3</td>
</tr>
<tr>
<td>JSB-085</td>
<td>B2 vein</td>
<td>Sulfide halo (mineralized vein)</td>
<td>2.5</td>
<td>1.4</td>
</tr>
<tr>
<td>JSB-179</td>
<td>Basalt</td>
<td>Sulfide halo (barren zone)</td>
<td>3.4</td>
<td>2.3</td>
</tr>
<tr>
<td>JSB-074</td>
<td>Gabbro</td>
<td>Sulfide halo (barren zone)</td>
<td>2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>JSB-104</td>
<td>Gabbro</td>
<td>Sulfide halo (barren zone)</td>
<td>2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>JSB-150</td>
<td>Turbidite</td>
<td>Sulfide halo (barren zone)</td>
<td>2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>JSB-162</td>
<td>Graphitic argillite</td>
<td>Sulfide halo (barren zone)</td>
<td>2.5</td>
<td>1.4</td>
</tr>
<tr>
<td>JSB-126</td>
<td>Sulfide halo (barren zone)</td>
<td>1.6</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>JSB-106</td>
<td>Strongly altered rock</td>
<td>Pyrite vugs</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>JSB-135</td>
<td>Turbidite</td>
<td>Pyrite vugs</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>JSB-007</td>
<td>Graphitic argillite</td>
<td>Pyrite bands or clots</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>JSB-008</td>
<td>Graphitic argillite</td>
<td>Pyrite bands or clots</td>
<td>4.4</td>
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### Notes

2σ error = ±0.2‰.

Fluid \( \delta^{18}\text{O}_{\text{H}_2\text{O}} \) values were calculated at 320°C (18O-Water = -1.5‰) using the dolo-

tite-CO2 fractionation equation of Ohmoto and Rye (1979).

Fluid \( \delta^{13}\text{C}_\text{CO}_2 \) values were calculated at 320°C (13C-CO2 = 5.5‰) using the dolo-


All accurate to within 0.3‰.

Fluid \( \delta^{34}\text{S}_{\text{pyrite}} \) values for vein-related pyrite were calculated at 320°C (18O-H2O = -1.1‰) using the pyrite-H2S fractionation equation of Ohmoto and Rye (1979).
**δ¹⁸O_H₂O Composition of the Auriferous Fluid**

The oxygen isotopic composition of the hydrothermal fluid responsible for the deposition of quartz, carbonate, and gold within quartz-carbonate veins in the Boston deposit was calculated from quartz and carbonate mineral values using the quartz-water and dolomite-water fractionation equations of Clayton et al. (1972) and Matthews and Katz (1977), respectively. A temperature of 320°C was chosen, based on the estimated temperature of entrapment of two-phase fluid inclusion assemblages. Assuming that dolomite-water fractionation is also applicable to ankerite, the fluid in equilibrium with carbonate from the three mineralized zones was determined to have δ¹⁸O_H₂O values of 5.7‰ to 7.3‰, with an average value of 6.5‰ ± 0.5‰ (n = 15; Table 2). The fluid in equilibrium with quartz from mineralized and flat veins was determined to have δ¹⁸O_H₂O values of 6.6‰ to 8.7‰, with an average value of 8.0‰ ± 0.6‰ (n = 16; Table 3). Given the uncertainties involved in temperature estimation, and the use of the dolomite-water fractionation in lieu of a reliable ankerite-water fractionation equation, the overlap of these calculated water compositions is encouraging, and suggests that the quartz and carbonate were co-deposited from a fluid with δ¹⁸O_H₂O between 6‰ and 9‰.

Metamorphic dewatering of igneous and volcanogenic sedimentary rocks associated with greenstone belts typically produces fluids with δ¹⁸O_H₂O compositions of 5‰ to 13‰, whereas magmatic waters have δ¹⁸O_H₂O compositions of 5.5‰ to 10‰ (Taylor, 1979). The δ¹⁸O_H₂O fluid values calculated above for the Boston deposit fall within both of these ranges, and it is, therefore, impossible to distinguish between a metamorphic or magmatic source based on the oxygen isotope data alone. Either of these sources for the fluid is reasonable considering that the granodioritic intrusions west of the Hope Bay volcanic belt appear to be broadly contemporaneous with the peak of metamorphism and deformation in this area.

**δ¹³C_CO₂ Composition of the Auriferous Fluid**

Generally speaking, carbon isotopic fractionation between carbonate minerals is poorly constrained at temperatures above 200°C, but is believed to be less than 1.0‰ (Ohmoto and Rye, 1979). Therefore, it is reasonable to assume that the dolomite-CO₂ fractionation equation of Ohmoto and Rye (1979) can be used to calculate δ¹³C_CO₂ values from both ferroan dolomite and ankerite without significant error.

δ¹³C_CO₂ values calculated at 320°C from the compositions of ferroan dolomite and ankerite in main stage quartz-carbonate veins at Boston range from −3.2‰ to −1.6‰ (average = −2.4‰ ± 0.6‰, n = 15; Table 2). These values are intermediate between juvenile magmatic carbon (−5‰ ± 2‰) and CO₂ produced by decarbonizing or leaching of marine carbonate from sedimentary and igneous rocks (0.4‰ ± 2.7‰; Schidlowski et al., 1975; Ohmoto and Rye, 1979). Other authors working on Archean lode-gold deposits have reported similar δ¹³C_CO₂ values, and have concluded that the CO₂ was derived from a combination of magmatic and metamorphic sources (Rye et al., 1976; Golding and Wilson, 1983).

**δ³⁴S_H₂S Composition of the Auriferous Fluid**

Pyrite separated from sulfidation haloes adjacent to barren and auriferous quartz-carbonate veins has relatively uniform δ³⁴S values of 1.6‰ to 3.5‰ (n = 14; Fig. 9d). In lode-gold ore fluids, sulfur is generally thought to be present as the bisulfide species. According to Ohmoto and Rye (1979), under equilibrium conditions, isotopic fractionation between H₂S and HS⁻ dissolved in the hydrothermal fluid is negligible. Therefore, δ³⁴S_H₂S values of 0.5‰ to 2.4‰ (average = 1.5‰ ± 0.5‰, n = 14; Table 4) were calculated for bisulfide (H₂S) in the hydrothermal fluid at 320°C, using the pyrite-H₂S fractionation equation of Ohmoto and Rye (1979).

These values are similar to those expected from dissolution of sulfides in igneous and sedimentary rocks by circulating hydrothermal fluids (δ³⁴S = 1‰–3‰; Ohmoto and Rye, 1979), but they are also similar to typical values for magmatic fluids (0.0‰ ± 3‰; Ohmoto and Goldhaber, 1997). Consequently, the sulfur isotope data, like the oxygen and carbon data, cannot be interpreted unambiguously in terms of magmatic or metamorphic sources (e.g., Goldfarb et al., 2005).

**Deposition of Gold**

A significant portion of the gold in the Boston deposit occurs with sulfides, in particular pyrite, arsenopyrite, and chalcopyrite (Fig. 5). Gold typically occurs as inclusions within these minerals or as fracture fillings and thin coatings on the surface of sulfide grains. Sulfide alteration forms a halo that extends more than 15 cm into the wall rock on either side of auriferous veins. Sulfide deposition is interpreted to be related to an increase in pH and the release of ferrous iron that accompanies the replacement of chlorite in the wall rock by carbonate, paragonite, and muscovite. Pyrite forms when this iron reacts with HS⁻ in the fluid under slightly acidic conditions (Kishida and Kerrich, 1987). If the fluid also contains dissolved arsenic and copper, arsenopyrite and chalcopyrite may also be deposited as a result of a similar process.

The stability of the gold-bisulfide complex is related to availability of HS⁻ in the fluid (Reed, 1997; Gibert et al., 1998). Thus, removal of HS⁻ from the fluid by the deposition of sulfides in the wall rock adjacent to veins may trigger the precipitation of gold in lode-gold deposits (Kishida and Kerrich, 1987). Gold may be co-precipitated and intergrown with sulfide grains as hydrothermal alteration and sulfidation of the wall rocks continues. This mechanism is thought to have controlled gold deposition in wall rocks at the Boston deposit.

Gold also occurs as coarse grains within deformed and recrystallized phantom quartz veinlets within the main stage quartz-carbonate veins at Boston. It is possible that in this
setting, the gold was remobilized and redeposited in the phantom veinlets as a result of subsequent deformation. Alternatively, a rapid drop in fluid pressure accompanying hydraulic fracturing during formation of the main-stage quartz-carbonate veins may have triggered phase separation in the hydrothermal fluid. Carbon dioxide, H\textsubscript{2}S, and other dissolved gases would have been lost to the vapor phase, resulting in destabilization of gold-bisulfide complexes, and deposition of gold (e.g., Wilkinson and Johnston, 1996; Gibert et al., 1998). Evidence for fluid phase separation and pressure fluctuations has been noted in the fluid inclusion record, as well as the presence of both steeply dipping and flat veins (e.g., Robert et al., 1995), supporting such a depositional mechanism for vein-hosted gold.

**Comparison With Other Archean Lode-Gold Deposits**

Quartz-carbonate vein lode-gold deposits are a characteristic feature of Archean greenstone belts within granite-greenstone terrains throughout the world. Deposits of this type occur in environments characterized by low- to medium-grade metamorphic rocks, brittle to ductile deformation behavior, and compressional tectonics. Mineralized veins occur in close proximity to belt-scale shear zones, resulting in broadly linear arrays of major gold deposits or districts (Groves and Foster, 1991; Robert, 1995; de Ronde et al., 1997; Goldfarb et al., 2005). Mineralized quartz-carbonate veins may occur in any of the rock types present in a given greenstone belt, although deposits hosted by mafic volcanic and associated ultramafic igneous rocks are the most common. Within a given shear zone, mineralized veins tend to be structurally controlled, and are most abundant near the contacts between rocks of differing competency. Fluids forming these deposits are typically low-salinity (3–6 eq. wt.% NaCl), slightly reducing, H\textsubscript{2}O-CO\textsubscript{2}-rich, and near neutral pH. Temperatures of 200º to 400ºC and pressures of 0.5 to 4.5 kb are typical, and stable isotopic values range from \(\delta^{18}O_{\text{H}_2\text{O}} = 6\%_e - 9\%_e\), \(\delta^{13}C_{\text{CO}_2} = -2.4\%_e\pm 0.6\%_e\), \(\delta^{34}S_{\text{H}_2\text{S}} = 1.5\%_e \pm 0.5\%_e\) to typical lode-gold fluids.

The Boston deposit matches all of the above characteristics of typical Archean lode-gold deposits. The deposit occurs in close proximity to the Boston fault zone and is hosted by deformed, lower-greenschist facies, mafic volcanic and gabbroic rocks. The Boston fault zone is part of a larger north–south-trending structure, the Hope Bay fault, which traverses the entire length of the Hope Bay volcanic belt. The quartz-carbonate veins that make up the Boston deposit have been affected by both brittle and ductile deformation related to compression in the vicinity of the Boston fault zone, and the intensity of quartz-carbonate veinining increases significantly as the contacts between competent volcanic rocks and ductile sedimentary rocks are approached. Finally, the ore-forming fluid had similar composition (H\textsubscript{2}O-CO\textsubscript{2}-rich, 4.6 ± 1.4 eq. wt.% NaCl), temperature (~320°C), pressure (~2–3 kbar), and stable isotopic composition (\(\delta^{18}O_{\text{H}_2\text{O}} = 6\%_e - 9\%_e\); \(\delta^{13}C_{\text{CO}_2} = -2.4\%_e\pm 0.6\%_e\); \(\delta^{34}S_{\text{H}_2\text{S}} = 1.5\%_e \pm 0.5\%_e\)) to typical lode-gold fluids.

**Conclusions**

The system responsible for lode-gold mineralization and hydrothermal alteration in the Boston deposit appears to have been fluid dominated; however, alteration and mineralization are largely confined to quartz-carbonate veins and immediately adjacent wall rocks. The auriferous fluid was a low salinity (4.6 ± 1.4 eq. wt.% NaCl) H\textsubscript{2}O-CO\textsubscript{2} fluid, with an estimated trapping temperature of 320ºC at a pressure of between 2 and 3 kbar. Fluid \(\delta^{18}O_{\text{H}_2\text{O}} (6\%_e - 9\%_e), \delta^{13}C_{\text{CO}_2} (-2.4\%_e \pm 0.6\%_e), \text{and}\ \delta^{34}S_{\text{H}_2\text{S}} (1.5\%_e \pm 0.5\%_e)\) values are similar to those of other Archean lode-gold vein fluids worldwide, but are similarly difficult to evaluate in terms of the relative importance of magmatic versus metamorphic fluid input into the hydrothermal system. Granodioritic intrusions synchronous with the peak of metamorphism and deformation in the Hope Bay volcanic belt are common to the west of the Boston deposit, and it is entirely possible that, at deeper levels in the crust, a metamorphically-derived hydrothermal fluid may have incorporated carbon, sulfur, and possibly gold from an as yet undiscovered magmatic source before entering the Boston area. Alternatively, Nesbitt and Muehlenbachs (1989) suggested that deeply circulating, highly evolved meteoric water may have played an important role in the development of mesothermal lode-gold deposits. At the present time, however, we cannot further constrain the origin of the fluids responsible for gold mineralization in the Boston deposit.

The tight grouping of microthermometric and stable isotopic data from Boston suggests that gold was deposited from a fluid with relatively uniform physical and geochemical characteristics. The structural style and nature of the hydrothermal alteration, mineralization, and fluid chemistry at Boston matches conditions described in other Archean greenstone belt-hosted lode-gold deposits worldwide (Groves and Foster, 1991; Robert, 1995; de Ronde et al., 1997; Goldfarb et al., 2005), suggesting that these deposits formed in similar tectonic environments and from similar fluids.

Because of these similarities, it is concluded that there is significant potential for the discovery of additional lode-gold deposits within the Hope Bay volcanic belt. Highly mineralized greenstone belts in Archean cratons throughout the world generally contain clusters of individual gold deposits that outline giant gold mining districts or camps (larger examples include the Val d’Or district, Quebec; the Timmins district, Ontario; and the Kalgoorlie area, western Australia; Groves and Foster, 1991; Robert, 1995). Following the discovery of the Boston deposit, several additional gold deposits and prospects have been discovered at the northern end of the Hope Bay volcanic belt, in which the style of
mineralization and hydrothermal alteration resembles what has been described from Boston. However, to date the Boston deposit remains relatively isolated in the southern portion of the belt. There is no reason to suppose that future exploration along the strike of the Hope Bay volcanic belt will not reveal the presence of additional lode-gold resources in this area.

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