THE VBE-2 GOLD PROSPECT, NORTHERN LABRADOR: GEOLOGY, PETROLOGY AND MINERAL GEOCHEMISTRY

M. Skanes, A. Kerr[1] and P.J. Sylvester
Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, A1B 3X5

ABSTRACT

The VBE-2 prospect is a small stratiform or stratabound deposit located within the Tasiuyak gneiss of northern Labrador. The gold mineralization is confined to distinctive quartz–pyroxene–garnet–sulphide–graphite gneisses that contrast with the surrounding quartz–feldspar–biotite–garnet paragneisses. The host rocks form a 1- to 4-m-thick concordant unit, that is continuous over a strike length of about 250 m. This "gold horizon" is structurally underlain by a distinctive banded quartzofeldspathic paragneiss that is weakly auriferous. The best drill intersection contained 5.5 ppm Au over 2.1 m, and the thickest drill intersection contained 2.3 ppm Au over 4 m. The dominant sulphides are pyrrhotite and minor chalcopyrite, both of which contain abundant fine-grained graphite inclusions. Scanning Electron Microscope (SEM) analysis shows that löllingite $(FeAs_2)$ and arsenopyrite (FeS_2) are also present, and that löllingite is more abundant. Arsenopyrite and löllingite form composite grains that have löllingite cores and thin arsenopyrite rims, and do not contain graphite inclusions. Petrographic and SEM studies of six mineralized samples failed to locate any free gold. The gold contents of selected minerals were determined via laser ablation – inductively-coupled plasma mass-spectrometry (LA-ICPMS). Löllingite contains 19 to 27 ppm Au, but the associated arsenopyrite is gold-poor, and pyrrhotite and chalcopyrite are devoid of gold. The auriferous löllingite alone cannot explain the whole-rock gold concentrations because the proportion of löllingite, as constrained by whole-rock arsenic analyses, is far too low. Thus, it seems likely that free gold does occur at VBE-2, but has an irregular distribution, and was simply not present in our polished sections.

The host rocks at VBE-2 are considered to represent metamorphosed siliceous iron formations. The mineralization could be of true syngenetic origin, or it could represent epigenetic mineralization that preceded regional metamorphism and intense deformation. Whatever its precise origins, this gold mineralization provides a possible "deposit model" for exploration in other parts of the Tasiuyak gneiss.

INTRODUCTION

There are very few known gold occurrences in Labrador, despite its geographic immensity and geological diversity, and only one has ever been tested by drilling. This was a serendipitous discovery in the wake of another, more famous, serendipitous discovery – it was found by prospectors seeking nickel-bearing gossans south of the Voisey's Bay discovery. The VBE-2 prospect is important because it is within the Tasiuyak gneiss (Figure 1), a belt of mostly unexplored metasedimentary rocks that extends from Labrador all the way to Baffin Island. Despite this, and other interesting attributes, the mineralization remains undescribed outside unpublished assessment reports.

The area was visited by the second author in 1998, and drill core from the mineralized intervals was examined and

sampled. In 2002, a B.Sc. thesis project by the senior author was initiated to provide more systematic information. The objectives were to describe the mineralization and its host rocks, and ascertain the exact mode of occurrence of gold. The resulting thesis (Skanes, 2003) emphasized mineral geochemical studies, notably of sulphide and arsenide minerals. This report summarizes the main findings of the thesis project.

REGIONAL GEOLOGY

REGIONAL GEOLOGICAL SETTING

The VBE-2 prospect is located inland about 40 km southwest of the village of Nain (Figure 1), and straddles the borders of NTS map areas 14 D/1 and 14 D/8. It is only about 9 km due south of Discovery Hill and the Ovoid
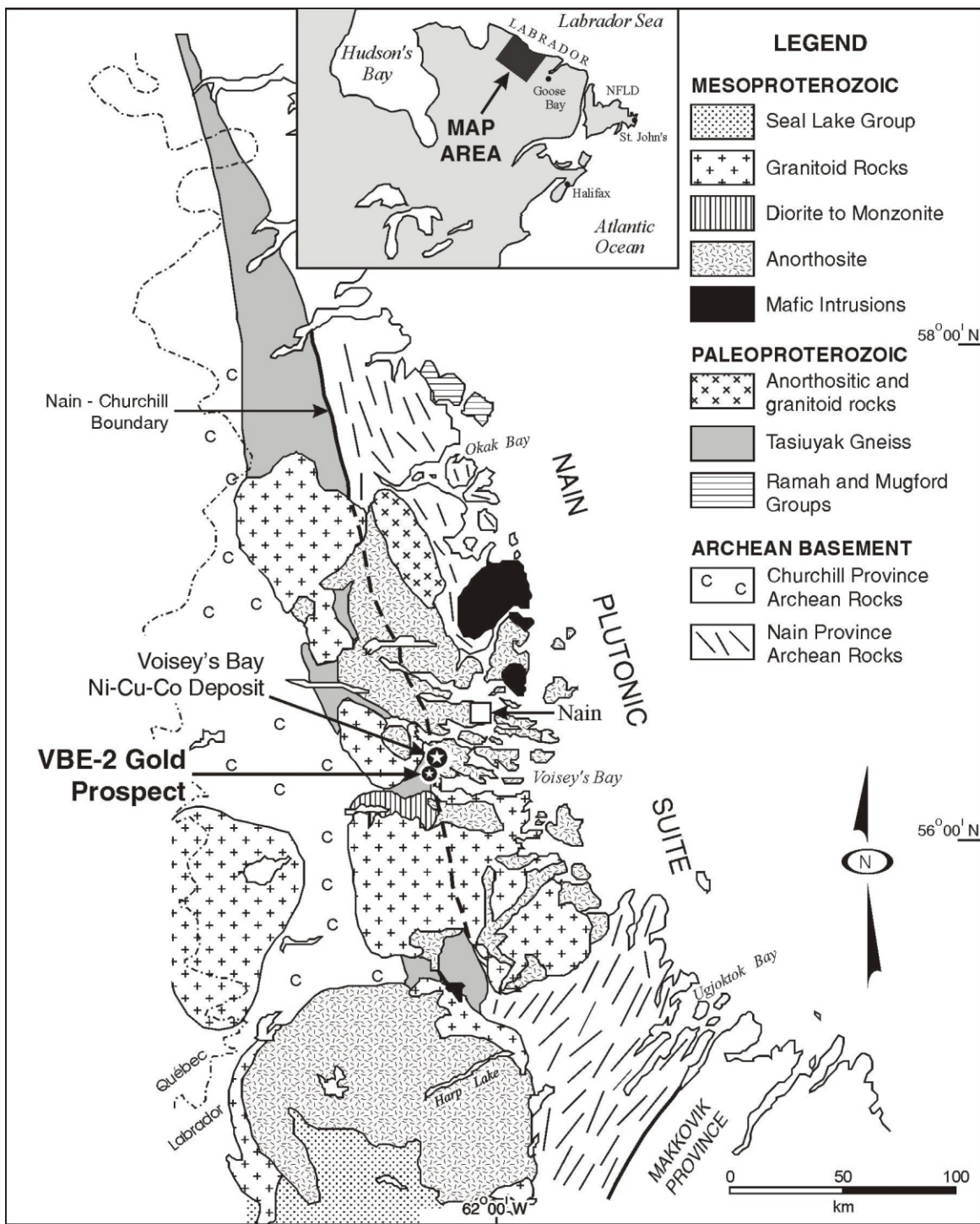
---

[1] Mineral Deposits Section

Figure 1. *Regional geology of northern and central Labrador, and the location of the VBE-2 gold prospect.*

Deposit at Voisey's Bay (Figure 1). The original claim blocks were amongst the multitude staked following the Voisey's Bay discovery. The area is part of a barren region on the flank of Makhavinekh Mountain (elevation 600 m), to which easy access is possible only by helicopter.

The VBE-2 prospect is located within the Churchill Province of the Canadian shield, west of its tectonic boundary with the Archean Nain Province (Figure 1). This part of the Churchill Province is dominated by amphibolite- to granulite-facies paragneisses of pelitic to psammitic compo-

sition (the Tasiuyak gneiss) and reworked Archean orthogneisses in the west (Wardle *et al.*, 1990, 2002; Figure 1). To the east, the Nain Province consists of upper amphibolite- to granulite-facies gneisses of 3800 to 2800 Ma age, locally overlain by Paleoproterozoic supracrustal rocks (Bridgewater and Schiøtte, 1990). The Nain–Churchill boundary region forms part of a north–south-trending orogenic belt termed the Torngat Orogen, which is believed to have formed through collision of the Nain Province with the Archean block now located to the west (Hoffman, 1990; Bertrand *et al.*, 1993). The most prominent component of the Torngat Orogen is the Tasiuyak gneiss, which can be traced along strike for more than 1300 km (Taylor, 1979; Hoffman, 1990). This is dominated by pelitic to psammitic paragneiss and associated diatexite, but also contains lenses of tonalitic, mafic, and ultramafic composition.

The protolith for the Tasiuyak gneiss was most likely a shale and greywacke sequence (Wardle *et al.*, 2002). Detrital zircons (Scott and Gauthier, 1996) suggest a Paleoproterozoic depositional age between 1940 and 1895 Ma, and Nd isotopic data indicate a mixed Archean and Paleoproterozoic source (Jackson and Hegner, 1991; Kerr *et al.*, 1993). In Labrador, the Tasiuyak gneiss was subjected to strong sinistral transpression, that created a 10- to 15-km-wide belt of strongly mylonitic granulite-facies rocks known as the Abloviak shear zone (Korstgård *et al.*, 1997). The Abloviak shear zone was active from 1844 to 1823 Ma, and was initiated following collision of the Nain and interior Churchill cratons (Bertrand *et al.*, 1993). Paleoproterozoic plutons in both domains are dated at ca. 1740 Ma (Bertrand *et al.*, 1993), and the two provinces certainly formed a single coherent continental crustal block at this time.

Following a long period of quiescence, the Nain–Churchill boundary zone was invaded by huge volumes of mafic to silicic magmas between 1350 and 1290 Ma, that formed the Nain Plutonic Suite. These include mafic intrusions, anorthosites, dioritic rocks and potassic granites, collectively representing an anorogenic environment associated with plume-related crustal rifting (Ryan, 1997). Anorthositic and granitic members of the Nain Plutonic Suite lie within a few kilometres of the VBE-2 prospect, and possibly underlie it at depth. A nearby ca. 1333 Ma mafic intrusion, the Voisey's Bay intrusion, is the host to the world-class Voisey's Bay Ni–Cu–Co sulphide deposits (e.g., Li *et al.*, 2000).

LOCAL GEOLOGY

The VBE-2 area is located within a wedge of Tasiuyak gneiss sandwiched between the Makhavinekh Lake granite pluton to the northwest, the Voisey's Bay granite pluton to the east, and the Cabot Lake diorite pluton to the south. The

area around the prospect (Figure 2; after Cavalero and Mersereau, 1997a) consists of a moderately to steeply west-dipping sequence of white- to brown-weathering, fine- to medium-grained, foliated to banded quartz–feldspar–garnet–biotite paragneisses. Within these monotonous rocks, there are bands of rusty-weathering graphite- and sulphide-bearing paragneiss, some of which form mappable units (Ryan and Lee, 1989; Figure 2). There are also units of metaquartzite that are generally thinner and less continuous. Three units, of rusty-weathering graphite- and sulphide-bearing gneiss, up to 100 m thick, form prominent ridges in the western part of the area (Figure 2). These rocks are only weakly anomalous in base metals, and contain no gold (Mersereau, 1996; Cavalero and Mersereau, 1997a). About 750 m to the east, there is a thinner and less-obvious gossaned zone that is similarly concordant with the gneissic foliation and layering. This unit contains gold mineralization, and is termed the "gold horizon" in assessment reports (Cavalero and Mersereau, 1997a, b). It is a distinctive unit of sulphide- and graphite-rich quartz–pyroxene–garnet gneiss, generally less than 5 m thick, which is in sharp contact with quartzofeldspathic paragneiss to the west. The gold
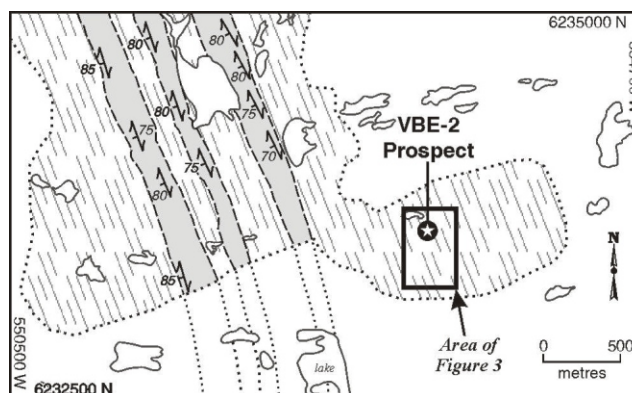
LEGEND

RZ: Rusty-weathering graphite- and sulphide-bearing paragneiss

Tasiuyak gneiss: Quartz-feldspar-garnet-biotite paragneiss

SYMBOLS

Approximate boundary of mapping ....

Gneissic foliation ....

Figure 2. *Generalized geology of the VBE-2 claim block, showing the locations of rusty, graphitic, sulphide-bearing units within the Tasiuyak gneiss, and the location of the VBE-2 prospect. After Cavalero and Mersereau (1997a, b).*

45

horizon is flanked to the east (i.e., structurally underlain) by a sulphide-bearing, banded quartzofeldspathic paragneiss that is locally weakly anomalous in gold. This is, in turn, flanked to the east by quartzofeldspathic paragneisses that resemble those to the west.

PREVIOUS INVESTIGATIONS

The area was covered by a large-scale reconnaissance mapping program by the Geological Survey of Canada (Taylor, 1979). The Tasiuyak gneiss was examined in more detail during an investigation of contact metamorphism in the vicinity of the Nain Plutonic Suite (Berg, 1977); the area was later mapped by the Newfoundland Department of Mines and Energy (Ryan and Lee, 1985, 1989), and a further study of regional and contact metamorphism in Tasiuyak gneiss was completed as a thesis by Lee (1987). This involved some samples collected within a few kilometres of the VBE-2 prospect. Prior to 1995, there was essentially no mineral exploration work in this area.

SUMMARY OF MINERAL EXPLORATION PROGRAMS

The mineral rights to this area were acquired by International Canalaska Resources Ltd. and Columbia Yukon Resources Ltd. in 1995, largely on the basis of proximity to Voisey's Bay. Reconnaissance exploration, including prospecting, rock, soil and stream-sediment sampling, and airborne geophysical surveys, were conducted in 1995 (Mersereau, 1996). The initial targets were the prominent rusty zones in the west of the area (Figure 2), which formed obvious conductors due to a high graphite content, but gave poor base-metal values (Mersereau, 1996). The airborne surveys also identified a conductive zone with a weak magnetic response associated with the gold horizon. Subsequent sampling in 1996 discovered the gold mineralization, with grab samples containing up to 19 ppm Au, and locally elevated As, Ni, Co and Cu levels (Cavalero and Mersereau, 1997a). Ground geophysical surveys conducted over the gold zone traced it over about 300 m, via its conductive and magnetic response.

A diamond-drilling program was completed on the VBE-2 prospect in early 1997, consisting of nine holes totaling 850 m. These tested the gold horizon over a 275-m strike length, to a maximum depth of 110 m (Cavalero and Mersereau, 1997b). Eight of the drillholes revealed gold mineralization in a sulphide-rich, graphite-bearing quartz–pyroxene–garnet gneiss, and confirmed that the gold is hosted by a well-defined concordant unit. The auriferous zones ranged from 0.9 to 4 m thick. The best grade result was 2.1 m of 5.5 ppm Au, and the thickest intersection was 4 m of 2.3 ppm Au. Within the gold horizon, thinner high-grade

intervals contained 10 to 24 ppm Au. The gold values were much lower in the footwall banded gneiss, which typically contained <0.5 ppm Au. Mineralized drill core was removed for storage in Nain, and was eventually donated to the Department of Mines and Energy core library. The property has been dormant since 1997.

GEOLOGY AND MINERALIZATION

This section is based upon direct examination of core from selected drillholes and on limited field work by the second author, and assessment reports by Cavalero and Mersereau (1997a, b). Only the mineralized sections and immediately adjacent rocks from drillholes VBE2-2 to VBE2-6 were available for study. VBE2-1, VBE2-7 and VBE2-8 also contained gold mineralization, but were unavailable. Unmineralized core from all holes remains at the prospect site. Table 1 lists analytical data for gold and selected elements for core samples collected by the second author in 1998; assay results for a much larger database of surface and core samples are contained in Cavalero and Mersereau (1997a, b). Gold was reanalyzed in four samples by a second laboratory using a different method, and gave similar values for our samples (Table 1).

SURFACE GEOLOGY OF THE GOLD ZONE

The geology in the prospect area is depicted in Figure 3, together with the locations of the drillholes (after Cavalero and Mersereau, 1997b). The surface outcrops consist mostly of medium-grained, grey to pale-brown paragneiss in which the most obvious minerals are quartz, feldspar, biotite and garnet. The rocks range from massive and foliated to variably banded, and commonly contain concordant "seams" of quartz and feldspar. Rocks of this general type are typical of the Tasiuyak gneiss throughout northern Labrador, and are referred to below as "typical Tasiuyak gneiss". Foliations and layering strike north-northwest and dip steeply (60° to 70°) to the west. The gold horizon is exposed on the west side of a narrow gully, together with an underlying banded gneiss unit that also contains sulphides. This unit is here termed the "footwall banded gneiss" (Figure 3). About 40 m west of the gold horizon, another rusty, graphitic unit outcrops within typical Tasiuyak gneiss; this is referred to as the "upper graphitic gneiss" because it was intersected in the hanging wall of the gold horizon. A south-plunging isoclinal fold was mapped between the gold horizon and the upper graphitic gneiss, but there is no sign that the gold horizon itself is repeated by this structure. It is thus either an intrafolial fold closure that was detached from its limbs during deformation, or a minor disharmonic fold that has little effect upon the gold horizon. Mineral lineations plunge southward, with a magnitude similar to that of the fold axis.

Table 1. Selected trace-element data for drill-core samples from the VBE-2 gold prospect

Drillhole	Sample	Depth (m)	Unit	As (ppm)	Au(ppm) [INAA]	Au(ppm) [FA-ICP]	Co (ppm)	Cu (ppm)	Ni (ppm)	Zn (ppm)
VBE2-2	AKC 952	56.6	APG	610	1.14	1.39	13	311	36	101
VBE2-3	AKC 948	50.9	GH	3360	6.70	7.20	33	496	117	157
VBE2-3	AKC 950	55.2	FBG	19	0.09	n/a	42	584	126	206
VBE2-3	AKC 951	59.2	FBG	2.2	<0.01	n/a	12	86	32	119
VBE2-4	AKC 921	48.8	GH	480	0.34	n/a	10	395	51	159
VBE2-4	AKC 922	49.1	GH	5490	4.05	4.54	48	529	156	79
VBE2-4	AKC 923	64.6	FBG	1.9	<0.01	n/a	14	102	26	114
VBE2-5	AKC 918	64.6	GH	223	0.68	n/a	9	373	40	220
VBE2-5	AKC 919	72.6	FBG	2.2	0.06	n/a	16	213	48	140
VBE2-5	AKC 920	38.4	UGG	4.8	<0.01	n/a	37	363	132	174
VBE2-6	AKC 914	32.1	UGG	5.1	<0.01	n/a	41	396	151	148
VBE2-6	AKC 915	33.9	UGG	1	0.02	n/a	29	544	93	148
VBE2-6	AKC 916	57.1	GH	2530	5.34	6.79	21	34	82	94
VBE2-6	AKC 917	63.4	FBG	1	<0.01	n/a	18	81	55	151

Notes:

Units: UGG–Upper graphitic gneiss; GH–Gold horizon; FBG–Footwall banded gneiss; APG–Auriferous paragneiss.

Au was determined for all samples by Instrumental Neutron Activation Analysis (INAA) at Becquerel Laboratories and was repeated for four anomalous samples by Fire Assay Extraction - Inductively-coupled plasma emission spectroscopy (FA-ICP) at Bondar Clegg Laboratories.

As determined by Instrumental Neutron Activation Analysis (INAA) at Bequerel Laboratories.

Co, Ni, Cu and Zn determined by Inductively-coupled plasma emission spectrometry (ICP-ES) at the Department of Mines and Energy.

n/a – not analyzed

The gold zone has a true thickness of about 2 to 3 m in outcrops, and exhibits a sharp hanging-wall contact with typical Tasiuyak gneiss. It consists of dense, dark-coloured, foliated, medium-grained rocks that contain obvious quartz, pyroxene and garnet, together with variable amounts of sulphides and graphite. Large garnet porphyroblasts are locally present, and compositional layering is locally evident. The dominant sulphide is pyrrhotite, but minor chalcopyrite and a silver-grey mineral visually identified as arsenopyrite are visible locally. The footwall banded gneiss is not well-exposed, but consists of a granular, dark-grey, strongly foliated gneiss containing small garnets. It is graphitic, sulphide-bearing and rusty-weathering, but is generally less strongly gossaned than the gold horizon proper.

All drillholes were collared west of the gold horizon and drilled to the east to intersect it in the subsurface. The parameters for the drillholes, indicated in Figure 3, are listed by Cavalero and Mersereau (1997b), and tabulated by Skanes (2003). The salient features of individual drillholes are recounted below and emphasis is placed upon those that were examined directly.

DRILLHOLE VBE2-1

This drillhole from the north end of the prospect (Figure 3; Figure 4a) is described by Cavalero and Mersereau (1997b). The upper section of the hole, to 47.6 m, consists of typical Tasiuyak gneiss, as described below from other
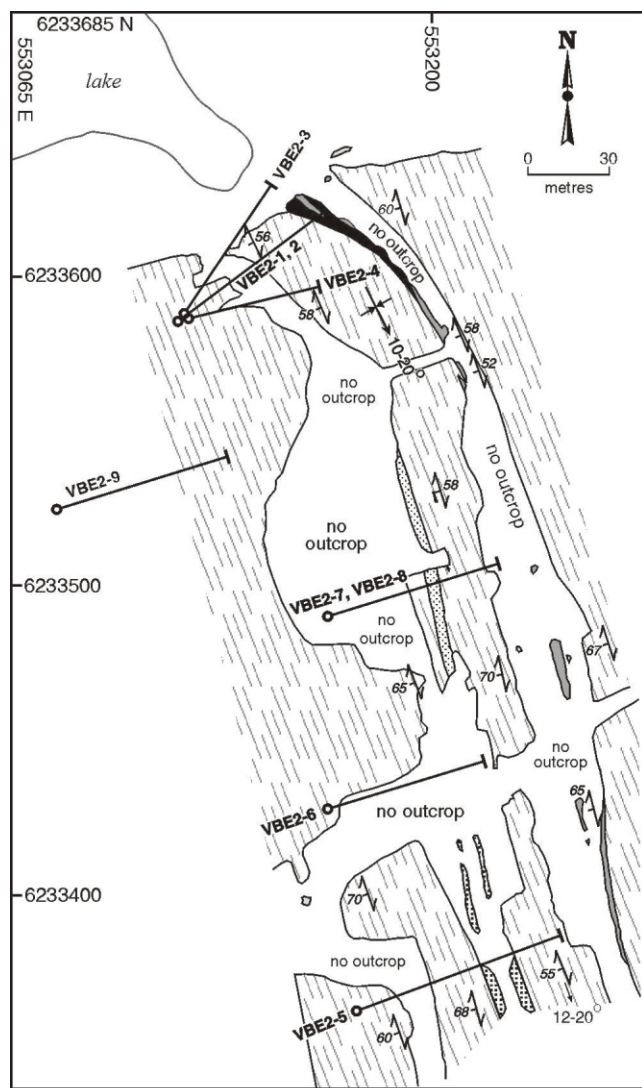
Figure 3. *Surface geology in the area of the VBE-2 gold prospect, and the locations of diamond-drill holes completed in 1997. After Cavalero and Mersereau (1997b).*

holes. A "mottled alteration zone" was described within the upper section; the logs suggest that this is mostly characterized by retrogression of garnets, although chloritic zones and fracturing were also noted. A strongly fractured zone within this section was interpreted as a fault. The gold horizon occurs from 47.3 to 51.4 m, and is underlain by the footwall banded gneiss that extends to 57.1 m. Both units are described in more detail below. The lower section of the hole consists of typical Tasiuyak gneiss. The gold horizon yielded 3.9 ppm Au over 2.3 m (upper section) and 0.5 ppm Au over 1.3 m (lower section). The footwall banded gneiss contained 0.1 to 0.4 ppm Au (Cavalero and Mersereau, 1997b).

DRILLHOLE VBE2-2

Only 5 m of core from this hole were available for study. The upper section of the hole, to 55.9 m, consisted of typical Tasiuyak gneiss (Cavalero and Mersereau, 1997b). Below 55 m, this is a monotonous pale-grey quartz–feldspar–biotite–garnet paragneiss, that is similar to material described below from more complete drillholes. A "mottled alteration zone" is described within the hanging-wall gneisses, apparently similar to, and continuous with, its equivalent in VBE2-1 (Figure 4a). A banded unit, containing graphite and disseminated sulphides in darker biotite-rich bands, occurs from 55.9 to 57.8 m, but this does not obviously resemble the rocks of the gold horizon as seen in other drillholes (*see below*). This is underlain by a narrow zone of intense fracturing interpreted as a fault, below which there is again typical Tasiuyak gneiss akin to the hanging-wall rocks. The footwall banded gneiss that occurs in all other holes is not reported from VBE2-2. The banded sulphide-bearing unit yielded 3.5 ppm Au over 0.9 m (Cavalero and Mersereau, 1997b); a small sample of this contained 1.14 ppm Au (Table 1). Cavalero and Mersereau (1997b) suggest that the lower part of the gold zone and the footwall banded gneiss are displaced by a fault, and thus were not intersected (Figure 4a). However, the offset suggested in the drill section (Figure 4a) is partly schematic.

DRILLHOLE VBE2-3

This drillhole contains three discrete units including the gold horizon, and the latter contains at least two variants (Figure 4b). The uppermost part of the hole (to 46.9 m) was
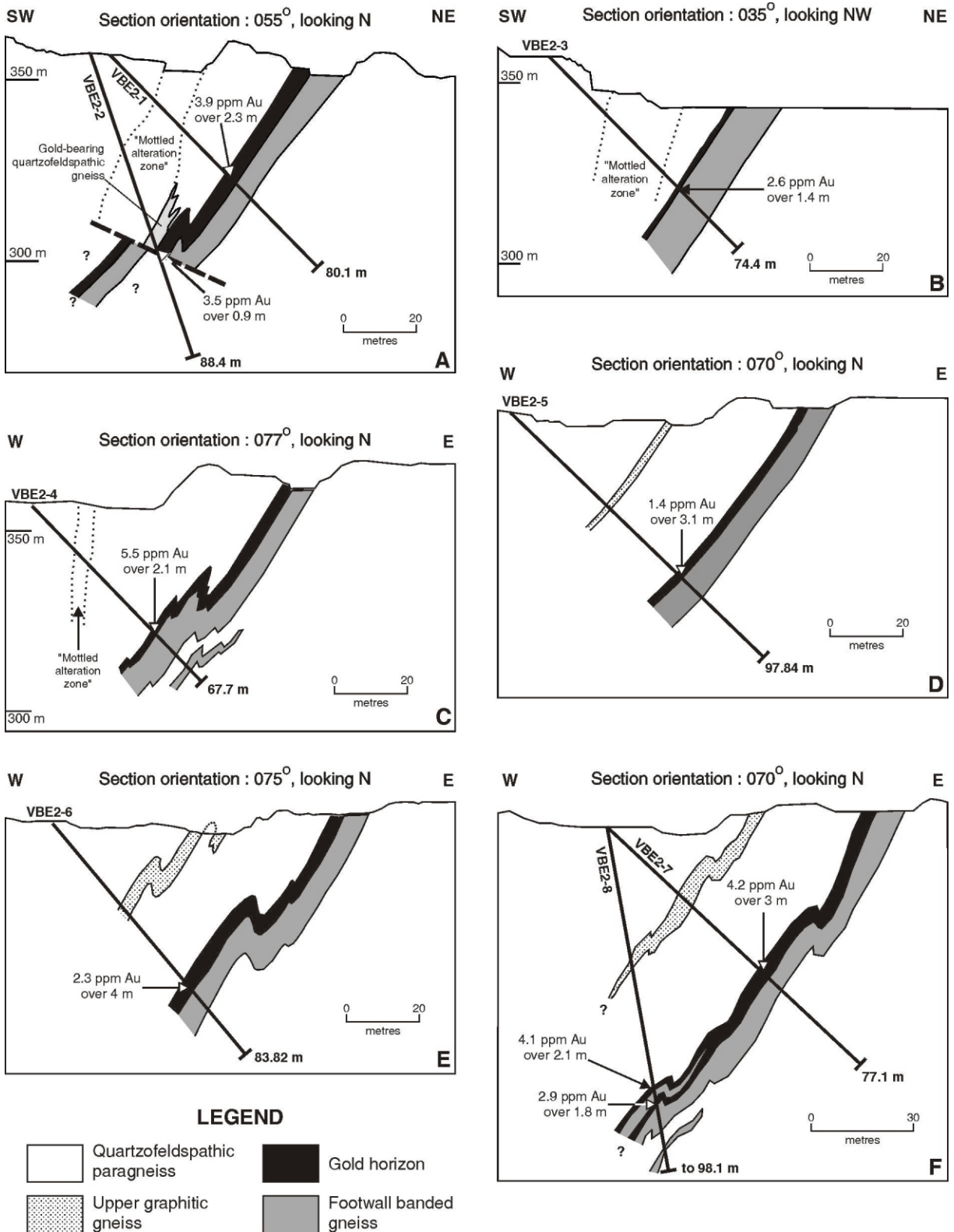
Figure 4. *Cross-sections through the VBE-2 gold prospect, illustrating the inferred subsurface distribution of rock types. For location and orientation of sections, see Figure 3. a) North end of prospect, holes VBE2-1, VBE2-2. b) North end of prospect, hole VBE2-3. c) North end of prospect, hole VBE2-4. d) South end of prospect, hole VBE2-5. e) Central part of prospect, hole VBE2-6. f) Central part of prospect, holes VBE2-7, VBE2-8. All sections modified after Cavalero and Mersereau (1997b).*

not available for study, but from descriptions appears to be identical to the section from 46.9 to 49.6 m, which is typical Tasiuyak gneiss, i.e., a light-grey quartz–feldspar–biotite–garnet paragneiss. Cavalero and Mersereau (1997b) again note a "mottled alteration zone", characterized by retrogression of garnets, within the hanging wall. The gold horizon occurs from 49.6 to 51.2 m, and includes an upper quartz–garnet–pyroxene–graphite–sulphide gneiss, underlain by material dominated by quartz, garnet and sulphides. The sulphides are mostly pyrrhotite, which forms blotchy to semi-massive material surrounding the silicates, and the associated graphite defines the fabric. Silver-grey arsenopyrite is locally prominent, particularly in the lower part of the intersection, and Cavalero and Mersereau (1997b) report minor chalcopyrite. Below the gold horizon, from 51.2 to 62.6 m, the footwall banded gneiss was intersected. This is a dark grey-blue, well-banded quartz–feldspar–garnet–biotite gneiss that contains minor sulphide in the darker layers, and prominent pink to lilac garnet. The lower section of VBE2-3, below 62.6 m, consists of pale-grey paragneiss identical to the hanging-wall rocks. The gold zone in VBE2-3 yielded 2.6 ppm Au over 1.4 m (Cavalero and Mersereau, 1997b), and a small sample from it contained 6.7 ppm Au (Table 1). The footwall banded gneiss contained from <0.1 ppm Au to 0.4 ppm Au (Cavalero and Mersereau, 1997b); two small samples from this unit both contained <0.1 ppm Au (Table 1).

DRILLHOLE VBE2-4

Drillhole VBE2-4 resembles VBE2-3, in that it contains 3 discrete units, and there are two variants within the gold horizon (Figure 4c). The uppermost section of core examined from this hole is typical Tasiuyak gneiss, consisting of grey-and-pink quartz–feldspar–garnet–biotite (± graphite) gneiss. Cavalero and Mersereau (1997b) report a narrow "mottled alteration zone", spatially associated with a fractured zone interpreted as a fault. The gold horizon occurs from 48 to 49.5 m, and contains two variants, but these are not as distinct as in VBE2-3. The upper part is a dark-grey quartz–pyroxene–garnet–sulphide–graphite gneiss, whereas the lower section is richer in garnet, but still pyroxene-bearing. Both subunits contain pyrrhotite-dominated sulphide mineralization and graphite, with rare arsenopyrite and chalcopyrite. Below the gold horizon, the footwall banded gneiss forms the interval from 49.5 to 58 m, and closely resembles its equivalent in VBE2-3. It is underlain by typical Tasiuyak gneiss (58 to 61.5 m). Footwall banded gneiss occurs again between 61.5 and 64 m (Figure 4c). The lowermost section of the hole, below 64 m, consists of pale-grey Tasiuyak gneiss identical to the hanging-wall rocks. Folding indicated in the drill section (Figure 4c) was suggested on the basis of surface geology (Cavalero and Mersereau, 1997b).

The gold horizon in VBE2-4 yielded 5.5 ppm Au over 2.1 m, including a 0.7 m section of 10.6 ppm Au (Cavalero and Mersereau, 1997b). Two small samples contained 0.3 ppm Au and 4 ppm Au respectively (Table 1). The footwall banded gneiss is more auriferous than in VBE2-3, containing from <0.1 ppm Au to about 1 ppm Au; higher gold values typically occur in the upper part, immediately below the gold horizon (Cavalero and Mersereau, 1997b). A small sample of footwall banded gneiss contained no detectable gold (Table 1).

DRILLHOLE VBE2-5

Drillhole VBE2-5 is located at the southern end of the prospect area (Figure 3), and contains four discrete units. These are "typical" Tasiuyak gneiss, the upper graphitic gneiss, the gold horizon, and the footwall banded gneiss (Figure 4d). The first 63.4 m of the hole intersected typical Tasiuyak gneiss, most of which was not examined. Cavalero and Mersereau (1997b) do not describe any "mottled alteration" in this hole. The upper graphitic gneiss occurs from 37 to 38.6 m, and also contains disseminated sulphides, particularly in its lower section. Aside from the presence of graphite and sulphides, it resembles the surrounding gneiss. The gold horizon is relatively thick and occurs between 63.4 and 67.3 m. As in the other holes, it consists of a quartz–pyroxene–garnet–graphite–sulphide gneiss, but no internal subdivision into pyroxene- and garnet-rich variants is seen. The pyrrhotite-rich sulphides are disseminated to blotchy, and occur as inclusions in garnet and pyroxene, in addition to surrounding silicates. Sulphides appear to be more abundant in pyroxene-rich bands. The gold horizon passes downward into the footwall banded gneiss (67.3 to 73.8 m), which closely resembles its equivalent in other drillholes. Below 73.8 m, typical Tasiuyak Gneiss continues to the end of the hole.

The gold horizon in VBE2-5 is relatively low grade, yielding only 1.4 ppm Au over 3.1 m; the footwall banded gneiss generally contains <0.3 ppm Au (Cavalero and Mersereau, 1997b). Small samples of these units contained 0.7 ppm Au and <0.1 ppm Au respectively (Table 1). The lower part of the upper graphitic gneiss contained 0.2 ppm Au (Cavalero and Mersereau, 1997b), but there was no detectable gold in our sample (Table 1).

DRILLHOLE VBE2-6

Drillhole VBE2-6 is located near the centre of the prospect (Figure 3), and contains the same four units as VBE2-5, i.e., typical Tasiuyak gneiss, the upper graphitic gneiss, the gold horizon, and the footwall banded gneiss. The arrangement of units is closely similar to VBE2-5 (Figure 4e). The first 56.5 m of the hole mostly intersected typ-

ical Tasiuyak gneiss (Cavalero and Mersereau, 1997b). The upper graphitic gneiss occurs from 29.7 to 33.6 m, and is a dark-grey quartz–feldspar–biotite–garnet gneiss, with variably recrystallized quartz and abundant graphite and sulphide. The underlying typical Tasiuyak gneiss also contains extensively retrogressed garnets for a few metres below the upper graphitic gneiss; this may represent the "mottled alteration" described from other holes (*see above*). The gold horizon is present from 56.5 to 60.5 m, and is represented by a dark-grey quartz–pyroxene–garnet–sulphide–graphite gneiss. Large garnets, up to 2 to 3 cm in diameter, are present locally, but the pyroxenes are finer grained and possibly recrystallized. Pyrrhotite-rich sulphide mineralization surrounds the silicates, but also occurs as inclusions in garnet, associated with quartz and biotite; arsenopyrite is locally visible, as is very minor chalcopyrite. The lower section of the gold horizon (below 58.2 m) contains more garnet, less pyroxene and less sulphide (and graphite) than the upper section. From 60.5 to 67.1 m, the footwall banded gneiss is present, and is closely similar to equivalents in other holes. Typical pale-grey Tasiuyak gneiss underlies the footwall banded gneiss, and continues to the end of the hole. Folding indicated on the drill section is based upon the surface geology and is partly schematic (Cavalero and Messereau, 1997b).

The gold horizon in VBE2-6 is thick, but of variable grade. The complete intersection yielded 2.3 ppm Au over 4 m, inclding 0.6 m of 5.1 ppm Au (Cavalero and Mersereau, 1997b). A small sample of sulphide-rich material contained 5.34 ppm Au (Table 1). The upper graphitic gneiss and the footwall banded gneiss both contained <0.01 ppm Au (Cavalero and Mersereau, 1997b; Table 1).

DRILLHOLE VBE2-7

This drillhole, located in the centre of the prospect, is described by Cavalero and Mersereau (1997b). It resembles VBE2-5 and VBE2-6 in that it contains an upper graphitic gneiss within the hanging wall, and intersected both the gold horizon and the underlying footwall banded gneiss (Figure 4f). The gold horizon yielded 4.2 ppm Au over almost 3 m, which includes a short section of very high-grade material, containing 24 ppm Au over 0.3 m. The gold content of the footwall banded gneiss ranges from <0.1 ppm Au to 0.7 ppm Au (Cavalero and Mersereau, 1997b). The upper graphitic gneiss contained no detectable gold.

DRILLHOLE VBE2-8

This drillhole was collared at the same location as VBE2-7, and is described by Cavalero and Mersereau (1997b). Overall, it resembles VBE2-7, with which it can be correlated (Figure 4f). The gold horizon in this hole is in two sections, separated by rocks that are described as similar to the footwall banded gneiss. The upper mineralized interval yielded 4.1 ppm Au over 2.1 m, including a 0.3-m high-grade section containing 18 ppm Au. The lower mineralized interval yielded 2.9 ppm Au over 1.8 m (Cavalero and Mersereau, 1997b). The footwall banded gneiss typically contains 0.1 ppm Au to 0.7 ppm Au, and the upper graphitic gneiss contained no detectable gold (Cavalero and Mersereau, 1997b). Folding indicated in the drill section (Figure 4f) is based upon surface geology and is partly schematic (Cavalero and Mersereau, 1997b).

DRILLHOLE VBE2-9

This drillhole was collared about 100 m to the west (Figure 3) in an attempt to intersect the gold horizon at depth. It intersected typical Tasiuyak gneiss, diabase dykes, and some gneisses that Cavalero and Mersereau (1997b) describe as similar to the footwall banded gneiss. No gold mineralization was detected.

SUMMARY OF GEOLOGICAL RELATIONSHIPS

Drillholes VBE2-1 to VBE2-8 reveal a similar sequence of rock types, which has a consistent "stratigraphic" arrangement (Figure 5). This is dominated by an upper sequence of pale-grey quartz–feldspar–biotite–garnet gneiss, and a lower sequence of identical material. These rocks are typical Tasiuyak gneisses identical to most of the surface outcrops. Sandwiched between these monotonous gneisses are the gold horizon and the underlying footwall banded gneiss. The latter is present in all holes except VBE2-2, where it may have been displaced by faulting (Figure 4a). The gold horizon varies from about 1 m to about 4 m in thickness and (in hole VBE2-8) appears to be interlayered with the footwall banded gneiss, suggesting that the two are closely related. The gold horizon is dominated by quartz–pyroxene–garnet–sulphide–graphite gneiss, and in three of the holes it appears to contain two variants; an upper pyroxene-rich section and a lower garnet-rich section. In other holes, the arrangement is less systematic, and garnet- and pyroxene-rich varieties appear locally to be interlayered. The footwall banded gneiss is a distinctive dark blue-grey banded gneiss that contains graphite- and sulphide-bearing bands, and pink to lilac garnet. It typically forms a unit between 7 and 10 m thick, that is locally interlayered with typical Tasiuyak gneiss and/or the gold horizon. In the southern and central part of the prospect, there is also a thin graphitic and sulphide-bearing interval within the hanging-wall sequence, typically located some 20 to 25 m above the gold horizon. However, the gold content of this upper zone is negligable.
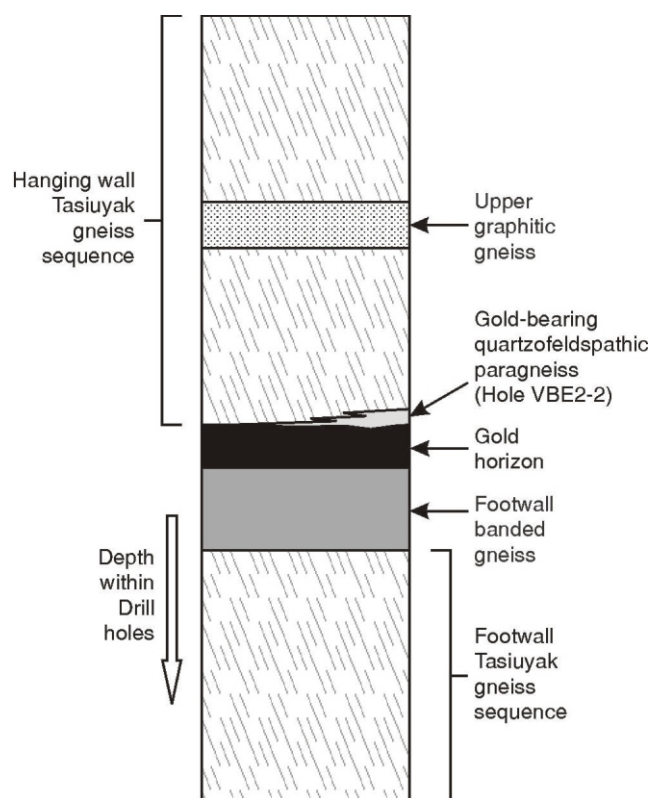
Figure 5. *Schematic illustration of the sequence of rock units indicated by most of the drillholes at the VBE-2 prospect. This is not considered to represent a true stratigraphic sequence.*

It is not likely that the arrangement depicted in Figure 5 actually represents a stratigraphic sequence, because the gneisses have been intensely deformed and folded. It is more likely a "pseudostratigraphy" defined by a transposed compositional layering that perhaps originated as different sedimentary rock types. Analytical data presented by Cavalero and Mersereau (1997b), and also in Table 1, suggest that the distribution of gold is controlled by this pseudostratigraphy. The quartz–pyroxene–garnet–sulphide–graphite gneiss of the gold horizon is generally the only rock type that contains significant gold (i.e., >1 ppm Au). The only exception to this is in hole VBE2-2, where gold is apparently hosted by a sulphide-bearing quartzofeldspathic gneiss. The footwall banded gneiss is commonly weakly auriferous, containing up to 0.9 ppm Au, but generally contains 0.4 ppm Au or less. Typical Tasiuyak gneisses, and the upper graphitic gneiss, contain essentially no gold. Analyses listed in Table 1 confirm that gold is present in intervals reported by Cavalero and Mersereau (1997b), but there are some significant differences in the Au values. Such contrasts almost certainly reflect the difference between continuous split core samples up to 1 m in length used by Cavalero and Mersereau (1997b) and the 10 to 15 cm split or quartered core samples used in this study. Generally, the data of Cavalero and

Mersereau (1997b) provide a better guide to the presence and grade of the mineralization, because their sampling was more representative. However, the generally similar results produced by re-analysis of four samples (Table 1) indicate that our data are reproducible although the samples are small.

PETROLOGY

This section summarizes the silicate mineralogy and textures of the units described above, based upon a more detailed treatment (Skanes, 2003). The sulphide and arsenide minerals present in samples from the gold zone are discussed separately. Mineral proportions quoted below for the gold horizon refer to its silicate component only.

HANGING-WALL QUARTZOFELDSPATHIC PARAGNEISS (TYPICAL TASIUYAK GNEISS)

These medium-grained rocks consist mostly of quartz, plagioclase, and porphyroblastic garnet and lesser amounts of biotite, sillimanite, and graphite. Dark-grey to black biotite-rich laminae define a layering on a scale of millimetres to centimetres which, together with recrystallized quartz ribbons, define a strong fabric. Sillimanite, graphite and minor sulphides are also aligned with this fabric, and lamellar twinning in plagioclase locally shows undulose extinction. The fabric wraps around the garnet porphyroblasts, which are variably relict. Most garnets are pseudomorphed by symplectic intergrowths of cordierite and orthopyroxene, in turn surrounded by orthopyroxene–plagioclase coronae. This reaction texture is observed in other units discussed below, and was described in detail by Lee (1987) who suggested that it records a reaction between quartz and garnet related to contact metamorphism. The original garnets grew in the latter stages of regional metamorphism, as they contain inclusions of quartz, sillimanite and locally plagioclase. The quartz inclusions have reacted with the garnet, as described above.

UPPER GRAPHITIC GNEISS

This medium-grained, dark-grey, banded unit is in general closely similar to the typical Tasiuyak gneiss described above. It consists mostly of quartz, feldspar, garnet, cordierite, biotite and sillimanite, and differs mostly by its increased graphite and sulphide content. It also appears to be richer in biotite. Garnet porphyroblasts have reacted with quartz to produce cordierite–orthopyroxene and orthopyroxene–plagioclase symplectites, as described above. Biotite-rich zones show more extensive corona development on garnets compared to biotite-poor zones. The sulphides are associated with graphite, and graphite commonly forms a rim around sulphide grains.

GOLD HORIZON

The fine- to coarse-grained sulphide-bearing gneisses of the gold horizon are the most complex and variable rocks examined during this study. In some senses, every sample from the gold horizon is different, and it is suspected that this unit is both vertically and laterally variable. Core logging suggests that there are pyroxene-rich and garnet-rich variants, and that in at least some cases, the latter form the lower part of the horizon. However, the present database does not confirm that this is a general pattern.

Quartz–Pyroxene–Garnet Gneiss

This variant consists dominantly of quartz (~65%), pyroxene (~30%) and lesser garnet (~5%). It also contains ovoidal grains of apatite, and minor fine-grained clinopyroxene. Quartz grains are commonly fractured, and fractures are filled by graphite and sulphide. Orthopyroxene grains are typically subhedral to anhedral and elongated with the fabric. Garnet grains form "trains" aligned with the fabric, and contain inclusions of quartz, orthopyroxene and rare sulphide. The garnets do not show the reaction textures and coronas that characterize other gneisses. Sulphides form larger grains aligned with the fabric, whereas graphite is disseminated and similarly aligned. Sulphides and graphite are locally semi-massive.

Quartz–Garnet–Pyroxene (± Bastite) Gneiss

This variant consists mostly of quartz, coarse-grained garnet, fine- to medium-grained orthopyroxene, graphite and sulphide. Quartz generally makes up about 50 percent of the rock, and garnet is more abundant than orthopyroxene. Minor amounts of apatite and clinopyroxene are also present. Large poikiloblastic garnets contain inclusions of quartz, graphite, sulphide and orthopyroxene. The strong fabric wraps around the large garnets. Although the mineral proportions are different, these rocks resemble the quartz–pyroxene–garnet gneiss (*see above*). Some of the garnets have reacted with quartz to produce cordierite–orthopyroxene symplectites, which form an "atoll" around the porphyroblasts. However, reaction textures are not observed around quartz inclusions within the garnets. Reaction of the original garnets appears to be less prevalent in quartz-rich samples. Orthopyroxene has been variably altered to "bastite", i.e., a mixture of serpentine and magnesian chlorite. This alteration is strongest around larger fractures, suggesting that it results from fluid interaction. Skanes (2003) distinguished a quartz–garnet–bastite gneiss as a separate variant, but this is probably just a strongly altered counterpart of the quartz–garnet–pyroxene gneiss, and the two are here grouped together.

Pyroxene–Garnet–Quartz Gneiss

This variant contains the least amount of quartz, and is dominated by pyroxenes. Orthopyroxene is dominant, and most of the clinopyroxene appears to have exsolved from orthopyroxene. Small grains of possible primary clinopyroxene were observed. A fabric is present in the rock, but is not as well-defined as in other variants described above. One sample contains spectacular "kinked" pyroxenes, which have deformation-related twinning. Some orthopyroxene crystals are large enough to include quartz and garnets, and the latter also contain inclusions of quartz and biotite. Coarse-grained poikiloblastic garnets show localized reaction to orthopyroxene–cordierite symplectites, as previously described. As in most samples from the gold zone, sulphides and graphite are abundant, and locally semimassive.

Garnet–Quartz Gneiss

This rock type contains at least 50 percent coarse-grained garnet, which contains inclusions of quartz, biotite, sulphide and graphite. The remainder of the rock consists of quartz, sulphides and graphite. A fabric, defined mostly by sulphides and graphite, wraps around the larger garnet grains. No orthopyroxene was observed, although patches of bastite suggest that minor amounts were present prior to alteration.

Auriferous Quartzofeldspathic Gneiss

In drillhole VBE2-2, gold mineralization occurs in a quartzofeldspathic gneiss that is obviously different from the other gold horizon rock types. This rock type consists of quartz, plagioclase, garnet and biotite, with lesser amounts of sulphide and graphite. It displays a millimetre-scale banding, defined largely by the abundance of biotite, graphite and sulphides. Sulphide and graphite are observed primarily in the quartz- and feldspar-rich bands. Plagioclase is saussuritized and garnets are retrogressed to chlorite along fractures and grain boundaries. This rock type more closely resembles the upper graphitic gneiss (*see above*) or the footwall banded gneiss (*see below*) than other samples from the gold horizon.

FOOTWALL BANDED GNEISS

This distinctive unit is consistently present beneath the gold horizon (Figure 4a-f). It is typically a dark-grey to blue, well-banded gneiss composed mostly of quartz, feldspar, garnet, biotite and sillimanite. Graphite is present throughout, and commonly helps to define the fabric, but varies only slightly in amount. Minor sulphides are also present, and are commonly associated with graphite. Primary and variably

recrystallized quartz is observed throughout the gneiss. Plagioclase is the dominant feldspar, but K-feldspar is also present, and locally shows perthitic exsolution textures. Garnet porphyroblasts have everywhere reacted with quartz to produce orthopyroxene–cordierite and plagioclase–orthopyroxene symplectites, as described from other units. This reaction is commonly advanced to complete, and little primary garnet remains in the unit. Orthopyroxene in the outer coronae is commonly altered to bastite and chlorite. Fine-grained disseminated biotite and coarse-grained sillimanite mostly define the fabric, which wraps around relict garnets. Variations in the proportion of biotite, garnet and sillimanite define the banding.

This unit has many similarities to the upper graphitic gneiss, as seen in the hanging-wall sequence, but is much more strongly banded, and richer in biotite and sillimanite. It is also richer in sulphides and graphite than most rocks in the hanging-wall sequence.

FOOTWALL QUARTZOFELDSPATHIC GNEISS (TYPICAL TASIUYAK GNEISS)

Quartzofeldspathic paragneisses located structurally below the gold horizon and footwall banded gneiss appear identical in drill core to those of the hanging-wall sequence. They were not examined in thin section by Skanes (2003), but surface samples from these rocks are closely similar to the gneisses located above the gold horizon (A. Kerr, unpublished data, 2003). They are typical Tasiuyak gneiss.

SULPHIDE MINERALOGY

The pyroxene- and garnet-rich gneisses of the gold horizon typically contain 5 to 35 percent sulphides and graphite. In field and drill-core samples, it is obvious that the dominant sulphide is pyrrhotite, but chalcopyrite is locally visible to the naked eye. Several samples from the gold horizon also contain a silver-grey, prismatic mineral that was identified visually in core as arsenopyrite. No visible gold was reported by Cavalero and Mersereau (1997b). In order to better understand the sulphide mineralogy and the habitat of the gold, polished sections were investigated under reflected light, and by scanning electron microscopy (SEM). Detailed descriptions, including photomicrographs, are presented by Skanes (2003).

REFLECTED-LIGHT MICROSCOPY

Petrography confirmed that the dominant sulphide mineral is pyrrhotite. It occurs as fine-grained disseminations, medium- to coarse-grained "blotchy patches" and locally as semi-massive material. Most of the pyrrhotite appears to be interstitial to silicates, and it locally surrounds the silicates.

Pyrrhotite is invariably peppered with myriad graphitic inclusions, with a maximum size of ca. 0.5 mm. Graphite is also present as a discrete phase, forming larger grains, and commonly encloses smaller pyrrhotite grains. Chalcopyrite is associated with and intergrown with pyrrhotite, but is much less abundant, typically representing <5% of the total sulphides. Chalcopyrite also contains abundant tiny graphite inclusions.

The most distinctive opaque mineral has a bright white colour under reflected light, and lacks the graphitic inclusions that dust pyrrhotite and chalcopyrite. This occurs in virtually all samples of the gold horizon, but generally in small amounts (<10% of total sulphides). The optical properties are consistent with those of arsenopyrite. However, SEM work (*see below*) demonstrates that most such grains are actually made up of two minerals, i.e., arsenopyrite (FeAsS) and löllingite (FeAs$_2$), which are generally optically indistinguishable. These composite grains locally appear to include pyrrhotite, but are more commonly surrounded by pyrrhotite, or located between pyrrhotite and silicate grains.

An exhaustive search was carried out for free gold grains in every polished section, but none could be found. Contractual petrographic examination of three mineralized samples (Vancouver Petrographics, *included in* Cavalero and Mersereau, 1997b) resulted in the tentative identification of tiny gold grains (<0.03 mm) in one sample. The location and nature of this sample is unknown. This contractual study also identified pyrite, which was not present in any of the samples examined in this study. As far as can be ascertained, the gold grains were not analyzed quantitatively.

The auriferous quartzofeldspathic gneiss from hole VBE2-2 was also investigated. The relative proportions of sulphide minerals are very similar to those of other units described above, but the amount of graphite and iron oxides is greater. "Arsenopyrite" was also identified in this rock type, and SEM work shows that this includes associated löllingite.

SCANNING ELECTRON MICROSCOPY (SEM)

Scanning electron microscopy (SEM) was conducted to augment optical work, and also to search for gold grains that were too small to be resolved optically. The instrumentation and theoretical background are described by Skanes (2003). SEM work produces backscattered electron (BSE) images, in which the brightness of mineral grains is proportional to their mean atomic mass; gold (atomic number 79; atomic mass 196.9) stands out very clearly in such images. The SEM also allows elemental spectra to be derived for individual mineral grains, allowing them to be identified and their formulae estimated.
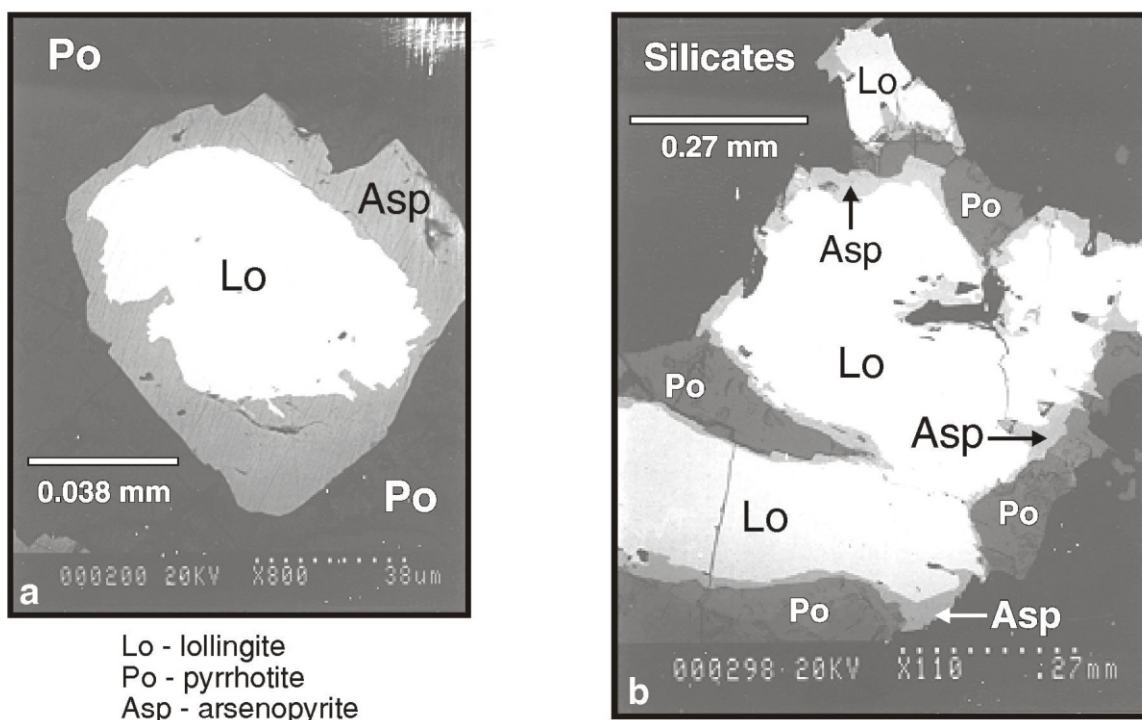
Plate 1. *Backscattered electron (BSE) images of löllingite and arsenopyrite in mineralized samples from the VBE-2 prospect. (a) Arsenopyrite rim developed on a löllingite grain enclosed by pyrrhotite. (b) Large löllingite grain with a thin arsenopyrite rim developed largely along boundaries with adjoining pyrrhotite.*

SEM studies confirmed that the dominant sulphide minerals are pyrrhotite and chalcopyrite. However, the mineral previously assumed to be arsenopyrite proved to be a mixture of arsenopyrite (FeAsS) and löllingite (FeAs$_2$), which can be resolved in BSE images by slight differences in brightness (Plate 1). BSE images show that löllingite is more abundant than arsenopyrite, and that arsenopyrite forms rims or overgrowths on löllingite (Plate 1). The two minerals are readily distinguished by their elemental spectra, as löllingite lacks a significant sulphur peak. Arsenopyrite never occurs alone, but is always associated with löllingite. In detail, it appears that arsenopyrite rims are developed on löllingite where it is adjacent to pyrrhotite, and are generally absent where löllingite is adjacent to silicates. Exceptions to this pattern probably reflect the presence of adjacent pyrrhotite outside the plane of the section (Plate 1). These textures closely resemble those described by Tomkins and Mavrogenes (2001) from the Challenger Deposit, South Australia, in which they suggest that arsenopyrite is produced by a reaction between löllingite and pyrrhotite. This is discussed further in a later section.

All bright grains were tested to check for the presence of gold, but no free gold was found in any sample. Similarly, no discernable gold peaks are present in the elemental spectra for sulphide or arsenide minerals. However, because the gold and sulphur peaks are very close in the energy spectra, small amounts of gold can be hard to detect in sulphides using SEM. Further tests for gold were conducted using a semiquantitative procedure that compares the BSE responses for two elements in the scanned mineral. No evidence for gold was found in chalcopyrite or pyrrhotite. Arsenopyrite locally showed a small gold response, but results were inconsistent and commonly unrepeatable. The only consistent indications of gold were from löllingite, but these results are not readily convertible into actual gold contents. However, these data, coupled with the lack of free gold grains, suggest that some "invisible gold" is present in löllingite.

In a quartz–pyroxene–garnet gneiss from the gold horizon, some very small bright grains were observed on the edge of a löllingite grain. These were initially suspected to be gold, but their elemental spectra suggest significant amounts of Ag, Cd, Te, S, Fe and As. The identity of this mineral is unknown.

MINERAL GEOCHEMISTRY

As discussed above, petrographic studies and SEM work failed to identify free gold grains, but suggested that gold could be present in the mineral löllingite. Three samples from the gold horizon were thus selected for laser-ablation inductively-coupled plasma mass spectrometry (LA-

ICPMS). This method allows for the *in-situ* analysis of trace elements in individual mineral grains. The general procedures are discussed elsewhere (Jackson *et al.*, 1992; Sylvester, 2001) and the specific details of analysis at Memorial University are recounted by Skanes (2003). Two types of analyses were completed; single-spot analyses process material from one location only, whereas line raster analyses continuously process material from a "traverse" across a mineral with the laser beam. The latter approach provides a method to search for cryptic gold inclusions in minerals. The results of LA-ICPMS analyses are presented by Skanes (2003); the following summary uses scatter diagrams (Figure 6) to illustrate the most important findings.

The results confirm the presence of gold in löllingite. Average löllingite gold concentrations in three samples range from 19.5 ppm Au to 27.1 ppm Au. Löllingites also have elevated Te, Sb and Pt compared to other minerals, but lower Ag and Cd (Skanes, 2003; Figure 6). Electron microprobe analyses reported by Skanes (2003) also indicate that they have elevated Ni, up to 2 wt% (Figure 6). The narrow arsenopyrite rims were more difficult to analyze than the löllingite cores, and the database is thus much smaller. They are gold-poor compared to löllingites, having an average value of 0.66 ppm Au. However, they have similar Te contents, higher Se contents and lower Sb contents (Figure 6). Chalcopyrites contain very little gold (<0.3 ppm), but have elevated Ag (2 to 7 ppm) and Cd (26 to 120 ppm) compared to other minerals (Skanes, 2003). Pyrrhotites have very low gold contents (<0.1 ppm), and also low Te, Sb and Pt (Skanes, 2003, Figure 6).

Line raster analyses were conducted across composite arsenopyrite–löllingite grains to check for extreme variations in gold content that might suggest the presence of submicroscopic gold inclusions. The results imply that the gold contents of individual löllingite grains are relatively constant, which argues against the presence of discrete inclusions.

SUMMARY AND DISCUSSION

Gold mineralization at the VBE-2 prospect is far from completely understood, and the origins of mineralization or the exact mode of occurrence of gold are not clear. The following section briefly highlights some key points, and discusses some outstanding problems that could be addressed through further research.

NATURE AND ORIGINS OF MINERALIZATION

Gold mineralization at the VBE-2 prospect is restricted to a thin unit of garnet- and pyroxene-rich siliceous gneisses that contain sulphide and graphite. The distinctive unit

intersected beneath the gold horizon, termed the footwall banded gneiss, is also weakly auriferous, but generally contains <0.5 ppm Au. The quartzofeldspathic paragneisses that dominate the hanging-wall and footwall sequences are barren, and a sulphide zone within the hanging-wall sequence, termed the upper graphitic gneiss, is also devoid of gold. The only example of quartzofeldspathic paragneiss that contains significant gold is the single sample from hole VBE2-2. An equally important feature of the prospect is a lack of discordant, crosscutting structures such as quartz veins or alteration zones. There is also no sign of any hydrothermal alteration or widespread retrogression of the high-grade metamorphic assemblages that characterize the host rocks. The "mottled alteration" described by Cavalero and Mersereau (1997b) from some drillholes appears to mostly reflect contact metamorphic transformation of garnet, which is a regional feature throughout the area, revealed by petrographic studies, and the previous work by Berg (1977) and Lee (1987).

The above observations strongly suggest that the gold at VBE-2 was present before regional metamorphism and deformation, which probably occurred before 1820 Ma (Bertrand *et al.*, 1993). This permits models in which gold mineralization is syngenetic, i.e., formed at the same time as the original sedimentary host rocks, or epigenetic, i.e., introduced in some post-deposition but pre-deformation event. Cavalero and Mersereau (1997b) favoured a syngenetic model, and suggested that VBE-2 represented a metamorphosed auriferous sulphide-facies iron formation. The siliceous and iron-rich compositions of the gold horizon gneisses (A. Kerr, unpublished data, 2003), are consistent with this interpretation. However, it could still be argued that gold was introduced by post-depositional hydrothermal processes, and that the iron-rich rocks simply represented a favourable host for its precipitation. The high graphite contents of the gold horizon and footwall banded gneiss suggest that their protoliths were also rich in organic material, and perhaps deposited in an anoxic environment.

Iron-formation-hosted gold deposits in less-deformed and metamorphosed areas are divisible into stratiform and non-stratiform types (Kerswill, 1993). Stratiform deposits are associated with laterally continuous units of cherty sulphide-facies iron formation, and generally lack associated large-scale alteration systems. They may contain arsenic, but gold–arsenic correlations are less evident than gold–sulphur correlations. Non-stratiform deposits show a spatial association between gold mineralization and crosscutting structures such as quartz veins and shear zones, and more evidence of hydrothermal alteration and replacement of iron-rich minerals such as magnetite. Gold–arsenic correlations are more common in such deposits. Stratiform types are considered to be syngenetic, whereas non-stratiform
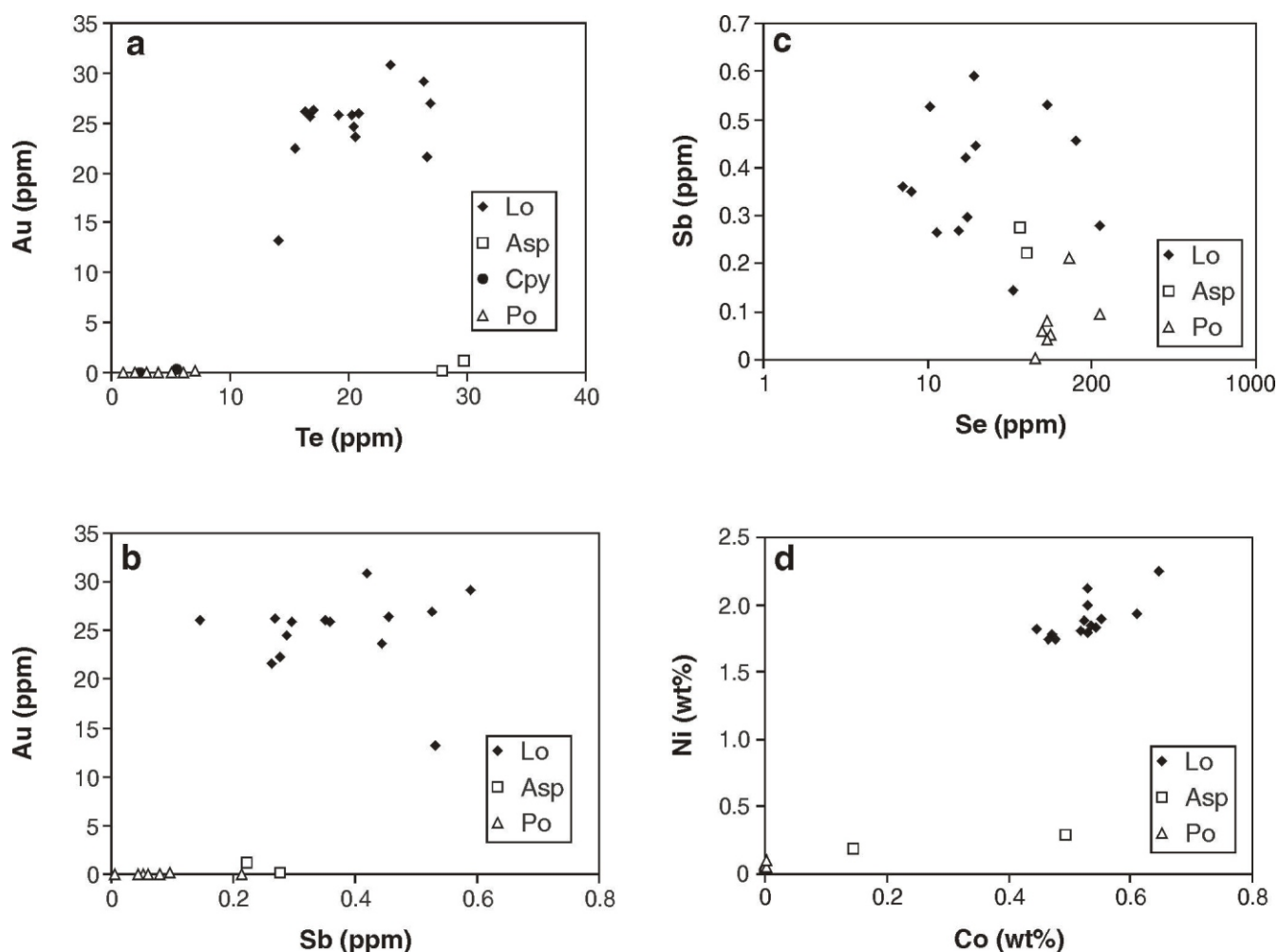
Figure 6. *Scatter diagrams illustrating trace element compositions of minerals analyzed by laser ablation - inductively-coupled plasma mass spectrometry (LA-ICPMS). (a) Au versus Te. (b) Au versus Sb. (c) Sb versus Se. (d) Ni versus Co. Ni data were obtained by electron microprobe analyses conducted adjacent to the laser ablation pits.*

types are considered to be epigenetic, and part of the mesothermal gold "clan" (Kerswill, 1993). The VBE-2 prospect has attributes of both stratiform and non-stratiform types, and is not readily classified in this framework. It could either represent a syngenetic style of mineralization associated with seafloor hydrothermal activity, or a younger epigenetic mineralization in which the iron-rich gneisses localized precipitation of gold in association with arsenic. If the latter model is preferred, it must be assumed that subsequent high-grade metamorphism and deformation obliterated any evidence of originally discordant structures, because the present geometry is clearly stratiform.

SULPHIDE AND ARSENIDE MINERALOGY AND GEOCHEMISTRY

The principal arsenic-bearing mineral in the VBE-2 prospect is löllingite ($FeAs_2$), rather than arsenopyrite

(FeAsS). Arsenopyrite is generally minor, and typically forms rims on löllingite grains. Löllingite contains significant gold, up to 27 ppm, but arsenopyrite contains negligable gold, and no gold whatsoever was found in pyrrhotite or chalcopyrite. The results indicate that at least some of the gold in the VBE-2 prospect occurs as "invisible" gold, i.e., it forms submicroscopic, colloidal-size particles that are below SEM resolution (<1 μm), or it is present in solid solution (e.g., Genkin *et al.*, 1998; Tomkins and Mavrogenes, 2001). Invisible gold is reported from both arsenopyrite and löllingite in other gold deposits (e.g., Cook and Chryssoulis, 1990; Genkin *et al.*, 1998). In general, gold-bearing arsenopyrite is more common in deposits at low metamorphic grades (e.g., greenschist facies), whereas gold-bearing löllingite is more common in deposits at higher metamorphic grades (e.g., amphibolite and granulite facies) (Barnicoat *et al.*, 1991). This is consistent with experimental work on the stability fields of the two minerals, which shows that

57

arsenopyrite breaks down to löllingite and pyrrhotite with increasing temperature (Tomkins and Mavrogenes, 2001, *and references therein*).

The textural relationships between arsenopyrite and löllingite at VBE-2 closely resemble those described from some other gold deposits in high-grade metamorphic settings (e.g., Barnicoat *et al.*, 1991; Neumayr *et al.*, 1993). The presence of auriferous löllingite grains that have arsenopyrite rims in such deposits has been used to argue that gold was introduced synmetamorphically, and that löllingite formed directly from a fluid, rather than by breakdown of pre-existing arsenopyrite. A recent experimental study of the behaviour of gold during prograde and retrograde metamorphism, applied to the Challenger gold deposit in South Australia (Tomkins and Mavrogenes, 2001) is of interest in this context. This study showed that invisible gold in arsenopyrite is expelled during prograde metamorphic reactions, and partitioned into löllingite. During retrograde reaction of löllingite with pyrrhotite to form arsenopyrite, gold remains within löllingite, and does not enter arsenopyrite. Tomkins and Mavrogenes (2001) suggest that progressive destruction of löllingite will eventually cause free gold to exsolve, because the gold solubility threshold of löllingite is exceeded. They suggest that textures akin to those we have documented at VBE-2 are developed by the prograde metamorphism of pre-existing gold deposits in which gold was originally associated with arsenopyrite, followed by variable retrogression. The occurrence of arsenopyrite where löllingite is adjacent to pyrrhotite, seen commonly at VBE-2, implies that arsenopyrite formed in this manner. Such a model is consistent with other evidence suggesting that mineralization at VBE-2 occurred prior to metamorphism, but it does not discriminate between syngenetic and epigenetic origins. At face value, the apparent absence of free gold at VBE-2 implies that retrograde reactions between löllingite and pyrrhotite did not proceed far enough to liberate it. However, an evaluation of the "gold budget" for individual samples, as discussed below, suggests that this conclusion is incorrect.

CALCULATION OF A GOLD BUDGET

LA-ICPMS analyses indicate that löllingites at VBE-2 contain up to 27 ppm Au. However, these concentrations simply cannot account for the gold measured in whole-rock analyses. Petrographic work suggests that the total proportion of löllingite and arsenopyrite in auriferous samples is less than 5%. The proportion of löllingite is quantitatively constrained by whole-rock arsenic analyses (Table 1). Pure löllingite contains about 73 weight % As, so a rock sample that contained only 1% löllingite would have 0.73% As, or 7300 ppm As. In the case of VBE-2 samples, the actual löllingite content would be less than 1%, because some of this arsenic is present in arsenopyrite. The difference, however, is small because arsenopyrite is far less abundant, and contains only 46 weight % As. Table 1 shows that gold-bearing samples contain a maximum of 5490 ppm As, in sample AKC-922, which contained 4 ppm Au. The maximum löllingite content of this sample is thus only 0.75%. Assuming that the lollingite contains 27 ppm Au, as indicated by LA-ICPMS, this sample should contain no more than 0.2 ppm Au. To put it another way, the whole-rock analysis of 4 ppm Au requires that the löllingite contain about 560 ppm Au, rather than 27 ppm Au. Consideration of all mineralized samples from VBE-2 (Table 1) leads to the same conclusion, i.e., the whole-rock gold analyses cannot be explained by auriferous löllingite, unless the estimates of löllingite gold content are much too low. Experiments by Tomkins and Mavrogenes (2001) produced synthetic löllingites containing 330 to 540 ppm Au, but the Au contents of natural löllingites were similar to those reported here. Cook and Chryssoulis (1990) did not analyze löllingites, but indicate that most auriferous arsenopyrites contain less than 100 ppm Au.

The simplest solution to this problem is that free gold is present at VBE-2, but was not observed. Clearly, one tiny speck of pure Au would easily balance the gold budget; in the case of sample AKC-922, a single grain, about 0.15 mm in diameter would satisfy the gold budget for the sample (Skanes, 2003). As noted previously, a consultant study quoted by Cavalero and Mersereau (1997b) did identify one very small possible gold grain. The lack of visible gold in our samples remains a significant problem, but there are two possible explanations. The first is that the distribution of free gold is irregular, and no polished section actually intersected any grains, i.e., free gold was not observed because of bad luck. However, the reproducibility of our gold analyses (Table 1) does not suggest an extremely irregular distribution of gold in the samples. The second is that free gold is present in the form of submicron particles that were not detected by either SEM or LA-ICPMS methods. The results of a single line raster analyses of auriferous löllingite suggest that its Au content is relatively constant (Skanes, 2003), which argues against the latter option. However, more rigorous testing is required to rule out this possibility. The work of Tomkins and Mavrogenes (2001) suggests that the boundary region between löllingite and retrograde arsenopyrite shows higher invisible gold contents, and is generally the initial site of gold exsolution. This would probably be the best place to search for submicroscopic gold inclusions.

MINERAL EXPLORATION IMPLICATIONS

The gold horizon at VBE-2 is generally thin, but some individual intersections have apparent widths up to 4 m. The gold grades are variable, but are locally 4 to 7 ppm Au, and

individual assays reported by Cavalero and Mersereau (1997b) range up to 24 ppm Au. The gold horizon has been tested by drilling over a strike length of only 275 m, and mineralization remains open to the north and south. A single deeper hole drilled in search of a downdip extension was unsuccessful, but does not rule out the presence of mineralization at depth, as there may be structural complications. As outlined above, it appears that free gold should be present in the mineralization, even though it has so far proved very difficult to detect. There thus appears to be scope for further exploration in this area.

Regardless of its precise origins, or the exact mode of occurrence of gold, the VBE-2 prospect is significant because it is located within the Tasiuyak gneiss, a regionally extensive unit that contains no other known gold occurrences. The Tasiuyak gneiss coincides with several diffuse gold anomalies defined by stream-sediment geochemical data (e.g., Swinden *et al.*, 1991). The VBE-2 prospect now provides a possible "deposit model" that could guide future exploration in these rocks. Parts of the Tasiuyak gneiss were explored following the Voisey's Bay discovery, but emphasis was placed upon larger gossan zones, such as those located to the west of VBE-2. These proved to be devoid of significant Ni, Cu, Co and Zn, and those that were checked contained no gold; however, not all such gossans were actually tested for gold. Furthermore, the VBE-2 gossan zone is a relatively small and inconspicuous feature compared to the larger sulphide-rich zones in the Tasiuyak gneiss, suggesting that similar zones could perhaps have been overlooked during regional exploration programs focused upon base metals.

ACKNOWLEDGMENTS

REFERENCES

Barnicoat, A.C., Fare, R.J., Groves, D.I. and McNaughton, N.J.
  1991: Syn-metamorphic lode-gold deposits in high-grade Archaean settings. Geology, Volume 19, pages 921-924.

Berg, J.H.
  1977: Dry granulite mineral assemblages in the contact aureoles of the Nain Complex, Labrador. Contributions to Mineralogy and Petrology, Volume 64, pages 33-52.

Bertrand, J.M., Roddick, J.C., Van Kranendonk, M.J. and Ermanovics, I.
  1993: U–Pb geochronology of deformation and metamorphism across a central transect of the Early Proterozoic Torngat Orogen, North River map area, Labrador. Canadian Journal of Earth Sciences, Volume 30, pages 1470-1489.

Bridgewater, D. and Schiøtte, L.
  1990: The Archean gneiss complex of northern Labrador; a review of current results, ideas and problems. Bulletin of the Geological Society of Denmark, Volume 39, pages 153-166.

Cavalero, R.A. and Mersereau, T.G.
  1997a: Technical report on the 1996 exploration and drilling results from the VBE-2 claim group. Unpublished assessment report by Northeast Exploration Services Ltd. for International Canalaska Resources Ltd., 20 pages. File 14D/0252

  1997b: Technical report on the 1997 exploration drilling results from the VBE-2 claim group. Unpublished assessment report by Northeast Exploration Services Ltd. for International Canalaska Resources Ltd., 52 pages. File 14D/0179

Cook, N.J. and Chryssoulis, S.L.
  1990: Concentrations of "invisible gold" in the common sulfides. Canadian Mineralogist, Volume 28, pages 1-16.

Genkin, A.D., Bortnikov, N.S., Cabri, L.J., Wagner, F.E., Stanley, C.J., Safonov, Y.G., McMahon, G., Friedl, J., Kerzin, A.L. and Gamyanin, G.N.
  1998: A multidisciplinary study of invisible gold in arsenopyrite from four mesothermal gold deposits in Siberia, Russian Federation. Economic Geology, Volume 93, pages 463-487.

Hoffman, P.F.
  1990: Subdivision of Churchill Province and extent of the Trans-Hudson Orogen. *In* The Early Proterozoic Trans-Hudson Orogen of North America. *Edited by* J.F. Lewry and M.R. Stauffer. Geological Association of Canada, Special Paper 37, pages 15-40.

Jackson, G. and Hegner, E.
   1991: Evolution of Late Archean to Early Proterozoic crust based on Nd isotopic data for Baffin Island and northern Quebec and Labrador. Geological Association of Canada, Programs and Abstracts, Volume 16, page A59

Jackson, S.E., Longerich, H.P., Dunning, G. R. and Fryer, B.J.
   1992: The application of laser ablation microprobe-inductively coupled plasma-mass spectrometry (LAM-ICP-MS) to in-situ trace element determinations in minerals. Canadian Mineralogist, Volume 30, pages 1049-1064.

Kerr, A., Fryer, B. J., Wardle, R. J., Ryan, B. and Bridgwater, D.
   1993: Nd isotopic and geochemical studies in the Labrador shield: progress report and preliminary data from the Torngat Orogen. Lithoprobe Report 36, pages 108-119.

Kerswill, J.A.
   1993: Models for iron-formation-hosted gold deposits. *In* Mineral Deposit Modeling. *Edited by* R.V. Kirkham, W.D. Sinclair, R.I. Thorpe and J.M. Duke. Geological Association of Canada, Special Paper 40, pages 171-199.

Korstgård, J., Ryan, A.B. and Wardle, R.J.
   1997: The boundary between Proterozoic and Archean blocks in central West Greenland and northern Labrador. *In* Evolution of the Lewisian and Comparable Precambrian High Grade Terrains. *Edited by* R.G. Park and J. Tarney. Geological Society of London, Special Publication 27, pages 247-259.

Lee, D.V.
   1987: Geothermometry and petrologic history of a contact metamorphosed section of the Tasiuyak Gneiss, west of Nain, Labrador. Unpublished B.Sc. Thesis, Department of Earth Sciences, Memorial University of Newfoundland, St. John's, Newfoundland, 111 pages.

Li, C., Lightfoot, P.C., Amelin, Y. and Naldrett, A.J.
   2000: Contrasting petrological and geochemical relationships in the Voisey's Bay and Mushvau intrusions, Labrador, Canada: Implications for ore genesis. Economic Geology, Volume 95, pages 771-801.

Mersereau, T.G.
   1996: Geological, geophysical and geochemical report on the 1995 exploration programme, VBE-1 and VBE-2 properties, claim blocks 0787M and 0785M, Labrador. Unpublished assessment report by Northeast Exploration Services for International Canalaska Resources Ltd., 28 pages. File LAB 1233

Neumayr, P., Cabri, L.J., Groves, D.I., Mickucki, E.J. and Jackman, J.A.
   1993: The mineralogical distribution of gold and relative timing of gold mineralization in two Archean settings of high metamorphic grade in Australia. Canadian Mineralogist, Volume 31, pages 711-725.

Ryan, B.
   1997: The Mesoproterozoic Nain Plutonic Suite in eastern Canada, and the setting of the Voiseys Bay Ni–Cu–Co sulphide deposit. Geoscience Canada, Volume 24, pages 173-187.

Ryan, B. and Lee, D.
   1985: Gneiss–anorthosite–granite relationships in the Anaktalik Brook–Kogaluk River area (NTS 14D/1, 8), Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 79-88.

   1989: Geological map, Makhavinekh Mountain. Newfoundland Department of Mines and Energy, Geological Survey.

Scott, D.J. and Gauthier, G.
   1996: Comparison of TIMS (U-Pb) and laser ablation microprobe ICP-MS (Pb) techniques for age determination of detrital zircons from Paleoproterozoic metasedimentary rocks from northeastern Laurentia, Canada, with tectonic implications. Chemical Geology, Volume 131, pages 127-142.

Skanes, M.S.
   2003: Petrography and sulphide-arsenide chemistry of an iron-formation-hosted gold deposit at the VBE-2 property, Labrador. Unpublished B.Sc. Thesis, Department of Earth Sciences, Memorial University, St. John's, Newfoundland, 91 pages.

Swinden, H.S., Wardle, R.J., Davenport, P.H., Gower, C.F., Kerr, A., Meyer, J.R., Miller, R.R., Nolan, L., Ryan, B. and Wilton D.
   1991: Mineral exploration opportunities in Labrador: A perspective for the 1990s. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey, Report 91-1, pages 349-390.

Sylvester, P.
   2001: A practical guide to platinum-group element analysis of sulphides by laser-ablation ICPMS. *In* Laser

Ablation-ICPMS in the Earth Sciences: Principles and Applications. *Edited by* P. Sylvester. Mineralogical Association of Canada, Short Course Volume 29, pages 203-211.

Taylor, F.C.
1979: Reconnaissance geology of a part of the Precambrian Shield, northeastern Quebec, northern Labrador and Northwest Territories. Geological Survey of Canada, Memoir 393.

Tomkins, A.G. and Mavrogenes, J.A.
2001: Redistribution of gold within arsenopyrite and löllingite during pro- and retrograde metamorphism: application to timing of mineralization. Economic Geology, Volume 96, pages 525-534.

Wardle, R.J., James, D.T., Scott, D.J. and Hall, J.
2002: The southeastern Churchill Province: synthesis of a Paleoproterozoic transpressional orogen. Canadian Journal of Earth Sciences, Volume 39, pages 639-663.

Wardle, R.J., Ryan, B. and Ermanovics, I.F.
1990: The Eastern Churchill Province, Torngat and New Quebec Orogens: an overview. Geoscience Canada, Volume 17, pages 217-221.