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THE STEEP NAP PROSPECT: A LOW-SULPHIDATION, GOLD-BEARING EPITHERMAL VEIN SYSTEM OF LATE NEOPROTEROZOIC AGE, AVALON ZONE, NEWFOUNDLAND APPALACHIANS

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ABSTRACT

The Steep Nap Prospect is a vein- and breccia-hosted, low-sulphidation style, epithermal gold–silver occurrence of late Neoproterozoic age. It is situated at the northern end of a 15-km-long hydrothermal alteration zone (the eastern Avalon high-alumina belt), within the eastern part of Newfoundland Avalonian belt. Precious-metal mineralization occurs in a nonwelded tuff unit located near the upper part of a thick, subaerial, caldera-facies volcanic succession of 580 to 570 Ma ash-flow tuffs, rhyolite domes and in-situ breccias, and coarse-grained pyroclastic breccia. The low-sulphidation mineralization, and the adjacent altered rocks of the high-alumina belt, are overlain unconformably by Lower Cambrian shales.

The prospect includes both crustiform–colloform-textured quartz–adularia–hematite veins (typically auriferous) and comb-textured quartz–hematite veins (typically barren). Early quartz–adularia-bearing, crustiform- and cockade-textured breccia carries gold. Later breccias are auriferous only where they contain fragments of crustiform veins. Textural and mineralogical data indicate that the crustiform veins and breccias formed within the precious-metal section of the host epithermal system, above the boiling level, from near-neutral-pH hydrothermal fluids. A strong positive correlation exists between elevated gold values and the presence of (1) adularia, and (2) recrystallization and replacement textures. Vein orientation data indicate that the geometrical control of the mineralized system at the Steep Nap Prospect was linked moreso to synvolcanic faulting than to the primary permeability of the host rocks.

The Steep Nap Prospect represents the first late Neoproterozoic precious-metal-bearing low-sulphidation epithermal system documented from the Appalachian Avalonian belt. The potential for similar style of mineralization within the Avalonian belt is high, particularly where caldera-facies subaerial felsic volcanic successions are thickest, and intersected by syn- to late-volcanic faults or ring fractures.

INTRODUCTION

Low-sulphidation, epithermal-style mineralization currently represents an attractive target for gold exploration worldwide, due to its potential to form world-class deposits: either high-grade, bonanza vein deposits, such as Hishikari, Japan (average grade 70 g/t Au; Izawa *et al.*, 1990; Hedenquist *et al.*, 1996) or large-tonnage, low-grade deposits, such as Round Mountain, Nevada (277 Mt at 1.2 g/t Au; Sander and Einaudi, 1990). This style of mineralization is common in Cenozoic and younger magmatic arcs of the circum-Pacific belts. Although epithermal-style alteration and gold mineralization is the prominent metallogenic characteristic of the Neoproterozoic magmatic arcs of the Appalachian Avalonian belt, most known examples of gold mineralization within it are of the high-sulphidation type

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(e.g., O'Brien *et al.*, 1998a; Dubé *et al.*, 1998). The recently discovered gold-bearing epithermal veins (Steep Nap Prospect) in the eastern Avalon high-alumina belt near Manuels, Newfoundland, represents the first unequivocal example of low-sulphidation epithermal-style precious-metal mineralization documented within the Appalachian Avalonian belt. This prospect is one of only a small number of known examples of Proterozoic low-sulphidation gold mineralization.

The following report presents a detailed description of the Steep Nap Prospect, provides evidence of its low-sulphidation affinity, and discusses the implications of this interpretation for precious-metal exploration. A brief review of low-sulphidation gold deposits is presented below, as an introduction to the ensuing description and discussion of the prospect.

STYLES OF EPITHERMAL GOLD MINERALIZATION: AN OVERVIEW

Two main types of subaerial epithermal precious-metal mineralization are recognized in the geological record: low-sulphidation (also known as adularia–sericite type) and high-sulphidation (also known as acid-sulphate or quartz–alunite–kaolinite) type (e.g., White and Hedenquist, 1995). Both form high in the earth's crust, at depths from 1 to 2 km, and are related to fluids in the approximate temperature range of 150 to 300°C (Heald *et al.*, 1987; Hedenquist *et al.*, 1996). Both are linked mainly to magmatism at convergent plate boundaries, in volcano–plutonic continental arcs and in island arcs. Mineralization is typically associated with subaerial calc-alkalic volcanic centres and related subvolcanic porphyritic intrusions of intermediate to felsic composition. Low-sulphidation deposits also occur in alkalic–shoshonitic igneous rocks, although this association is relatively uncommon (e.g., Porgera, Papua New Guinea: Richards and Kerrich, 1993) and in related sedimentary rocks (e.g., alkalic low-sulphidation subtype: Sillitoe, 1993; Richards, 1995).

Low-sulphidation precious-metal deposits form in hydrothermal systems having little direct magmatic input, where mineralization is linked primarily to the lateral flow of heated meteoric waters, above or distal to a magmatic dome (e.g., Heald *et al.*, 1987). The fluids responsible for their formation are sulphur-poor, reduced, and of near-neutral pH. Sulphide-rich and sulphide-poor sub-types of low-sulphidation mineralization have been distinguished (*see* Sillitoe, 1993 and references therein). Both high- and low-sulphidation styles of alteration and mineralization occur in the same epithermal mining district, although, overprinting relationships and/or vertical transitions between both have not been well documented and are uncommon (Sillitoe, 1993; Love *et al.*, 1998).

Setting and Character of Low-Sulphidation Style Precious-Metal Mineralization

Low-sulphidation deposits are genetically associated with, and commonly hosted by, strike-slip faults and associated jogs, splays and extensional veins, and related extensional structures (Corbett and Leach, 1998). In many cases, mineralization is associated with volcanic calderas (e.g., Round Mountain, Nevada), where it may be associated with ring fractures and related high- or low-angle faults (e.g., Round Mountain, Nevada; Sander and Einaudi, 1990). The process of caldera formation is particularly effective in providing channel-ways for younger hydrothermal fluids. Typically, low-sulphidation mineralization postdates the formation of the host rocks by at least 1 million years (Heald *et al.*, 1987). Low-sulphidation deposits commonly occur immediately above the basement to the host volcanic rocks, but may also be sited in the basement (e.g., Hishikari, Japan; Izawa *et al.*, 1990). Relatively impermeable lithology may play an important ponding role in the formation of some deposits (e.g., Hishikari, Japan; Hedenquist *et al.*, 1996).

Low-sulphidation precious-metal deposits comprise subvertical, banded and/or brecciated quartz–calcedony–adularia–sericite vein systems containing irregular zones of mineralogically similar stockwork and hydrothermal breccia; disseminations are less common (e.g., Buchanan, 1981; Heald *et al.*, 1987; Sillitoe, 1993; White and Hedenquist, 1995; Hedenquist *et al.*, 1996; Robert *et al.*, 1997; Corbett and Leach, 1998). Chalcedony and/or quartz in these veins typically display open-space crustiform, colloform, cockade and bladed textures. Manganese–carbonate (rhodocrosite), pyrite, electrum, iron-rich sphalerite, galena, arsenopyrite, silver-sulphides and sulphosalts are also present in many low-sulphidation veins. Sulphide concentrations are normally low, (<5 % volume percent), although veins near intrusions may be more sulphide-rich. Associated metals include gold, silver, arsenic, antimony, mercury, zinc, lead and selenium. Other geochemical characteristics include an anomalously high concentration of potassium, a high Ag/Au ratio, and an anomalously low concentration of copper (White and Hedenquist, 1995).

Lattice-bladed calcite and/or barite that are typically replaced by silica, are common either adjacent to, or within, the banded-breccia veins in low-sulphidation systems. Typically, hydrothermal alteration grades outward from silicification and sericite–illite/smectite (argillic) assemblages, with or without fine-grained adularia, near the veins, into a broader external zone of propylitic alteration (Figure 1). Hypogene alunite is absent from low-sulphidation systems, however, supergene alunite is commonly present in association with kaolinite and pyrite. It occurs as a result of steam-heating in the upper portion of the hydrothermal system, mainly in the hanging wall of the primary host structure

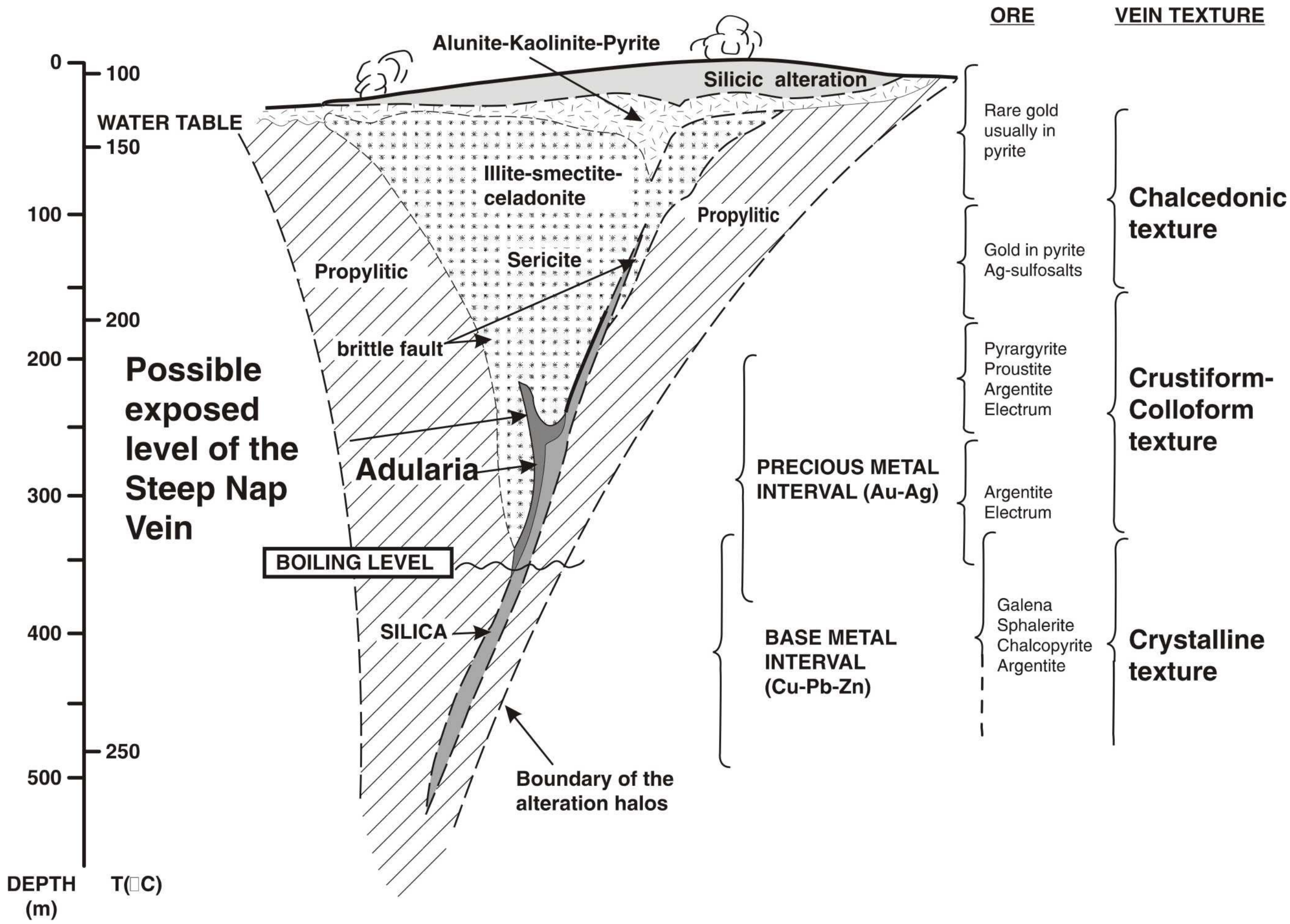

Figure 1. *Section view of a typical low-sulphidation epithermal system showing vertical zonation of metals, mineralogy, texture, and alteration halos, and the inferred location of the exposed levels of the Steep Nap Prospect. (Depth scale is shown only for reference and is not directly applicable to the Steep Nap Prospect). After Buchanan (1981) and Morrison* et al. *(1990).*

(e.g., White and Hedenquist, 1995). Large zones of strong silicification having anomalous values of arsenic and antimony may cap the gold-bearing veins (Figure 1; White and Hedenquist, 1995). The surface expression of low-sulphidation systems consists of silicic sinter, which is commonly enriched in arsenic, antimony and mercury, with or without gold and silver (e.g., McLaughlin deposit, California; Hedenquist *et al.*, 1996). Because they are highly susceptible to erosion, sinters are rarely preserved.

Typically, mineralization is vertically zoned, and grades downward, over distances of hundreds of metres, from precious-metal-rich ores into precious-metal-poor, base-metal-rich (Cu, Zn, Pb) ores (Figure 1; e.g., Buchanan, 1981; Morrison *et al.*, 1990; Hedenquist *et al.*, 1996). This metal zonation, inherent to this style of hydrothermal system, is also clearly reflected by the vein texture and mineralogy, the recognition of which is a fundamental tool in mineral exploration in low-sulphidation hydrothermal systems (Figure 1; e.g., Morrison *et al.*, 1990; Dong *et al.*, 1995).

Most known low-sulphidation deposits are of Tertiary age or younger. The rapid rate of erosion encountered in the subaerial and tectonically active settings in which such deposits are developed reduces the likelihood of their preservation in the geological record. Subsequent tectonism that may have effected more ancient examples further decreases their chance of preservation. That most are of Tertiary age may also be a function of the widespread magmatism at this time, particularly in the Andean–Cordilleran system. Lack of recognition due to structural and metamorphic overprinting may be another explanation of why such deposits are apparently rare in similar, albeit older terranes, characterized by equally prodigious magmatic activity at high crustal levels.

REGIONAL GEOLOGICAL SETTING OF THE STEEP NAP PROSPECT

The Steep Nap Prospect is located near the community of Manuels–Conception Bay South, approximately 2 km from Conception Bay tidewater, on the Avalon Peninsula of eastern Newfoundland. Gold mineralization was first discovered at Steep Nap Road in 1996 by C. Miles and T. Gosine. The property was first explored by Northstar Exploration in 1996 and 1997, and is currently held by Fort Knox Gold Resources Inc. The prospect lies near the northern end of the eastern Avalon high-alumina belt (Hayes and O'Driscoll, 1990), an extensive zone of epithermal-style hydrothermal alteration sited at the eastern margin of the late Neoproterozoic volcano–plutonic core of the Avalon Peninsula (King, 1988; O'Brien *et al.*, 1996, 1997; Figure 2). This 15-km-long by 1-km-wide alteration zone is widely known for its occurrences of pyrophyllite (including Newfoundland Pyrophyllite's Oval Pit Mine (ca. 3 Mt at <14.5 % Al_2O_3; M. Dawe, personal communication, 1997), and is host to a number of recent gold discoveries (*see* O'Brien *et al.*, 1998a,b; Figure 3). The rocks hosting the alteration are of late Neoproterozoic age (ca. 580 to 570 Ma; J. Ketchum, written communication, 1998), and embody part of the northeastern termination of the 3000-km-long Appalachian Avalonian belt (O'Brien *et al.*, 1998a). Both high-sulphidation and low-sulphidation types of alteration and mineralization are developed in the subaerial pyroclastic volcanic rocks of eastern Avalon high-alumina belt. Porphyry-related alteration is locally developed (albeit to a much lesser degree) within and along strike of the belt. Altered rocks are unconformably overlain by a thin succession of flat-lying to gently dipping, unaltered, early Paleozoic platformal sedimentary rocks, exposed at the north end of the belt.

The auriferous hydrothermal vein system exposed at Steep Nap Road is situated close to the faulted contact between the host subaerial felsic tuffs of the Harbour Main Group and the overlying sequence of primarily grey-green, subaqueous siltstone and sandstone, previously assigned to the Conception Group (e.g., King, 1988). The host rocks are unwelded and poorly sorted lithic lapilli tuffs. The tuff unit becomes coarser grained along strike, grading into a coarse-grained agglomerate and breccia, likewise rich in similar granitic and rhyolitic clasts. There, the unit locally hosts patchy potassic alteration. It is interlayered with tongues of rhyolitic material, and is intruded by pyrite–silica–sericite-altered quartz–feldspar porphyry.

At Steep Nap Road, the tuff unit that hosts the prospect is faulted against mafic pyroclastic rocks and aphanitic mafic flows to the east; these are in presumed fault contact with banded rhyolite, in situ rhyolite breccia and silica-rich hydrothermal breccia. On a regional scale, much of the volcanic succession east of the prospect (excepting the aforementioned mafic unit) consists primarily of welded and flattened eutaxitic ash-flow tuffs. These ash flows host much of the advanced argillic alteration in the area, including the major pyrophyllite zones, particularly in association with

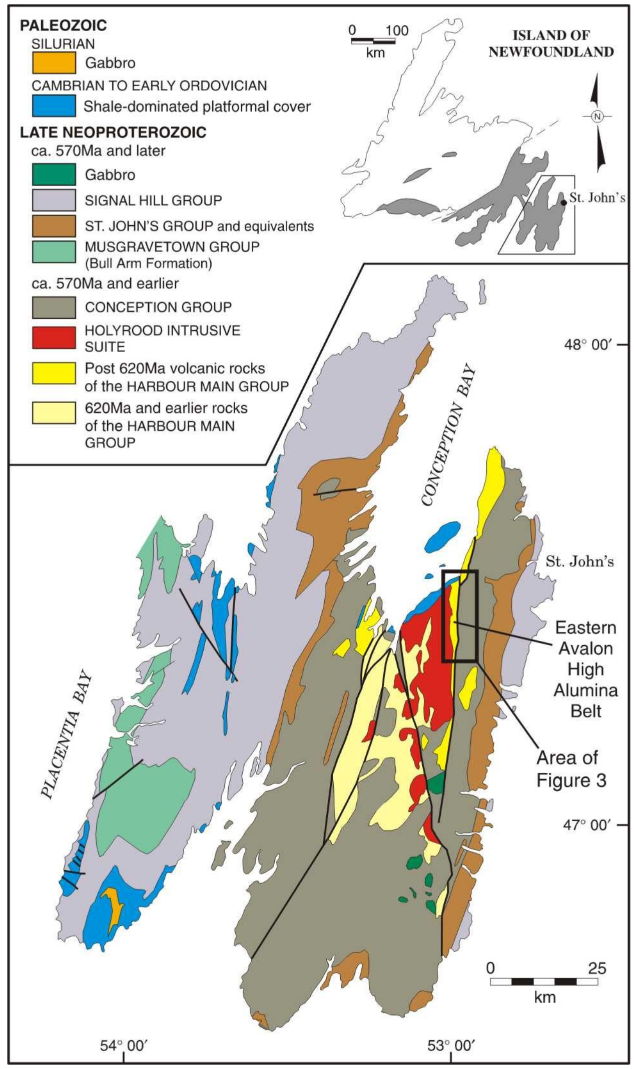

Figure 2. *Generalized geological map of the Avalon Peninsula (modified from King, 1998), showing the location of the eastern Avalon high-alumina belt. Shaded area on inset shows approximate area of "Avalonian" rocks within the Newfoundland Appalachians (from O'Brien* et al., *1996).*

pumice-rich units and zones of vapour phase recrystallization. An unwelded unit similar to that at Steep Nap Prospect hosts gold mineralization farther south in the belt at the Roadcut and Santana prospects (O'Brien *et al.*, 1997, 1998b; Fort Knox Gold Resources Inc., 1998). Deformed, post-alteration diabase intrudes silica-altered pyroclastic rocks near the western end of the Steep Nap Prospect.

Zones of pyrophyllite have been discovered immediately north of the Steep Nap Prospect (M. Dawe, personal communication, 1997) and silica–sericite–pyrite hydrothermal alteration is exposed within a few hundred metres to the south of the prospect. The main pyrophyllite-rich advanced argillic alteration zone at the Oval Pit Mine is located approximately three kilometres south of the prospect.

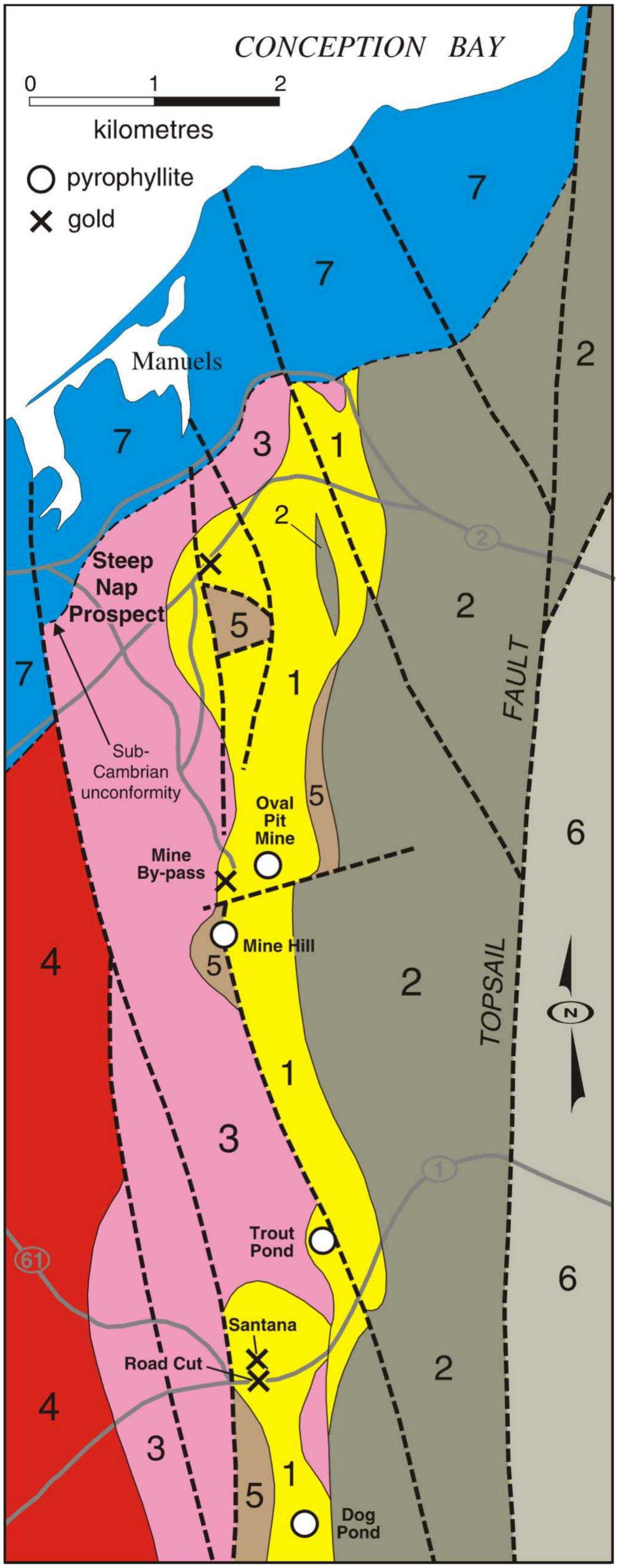

Figure 3. *Simplified distribution of the major regional elements in the northern part of the eastern Avalon high-alumina belt. Modified from O'Brien* et al., *1998a,b and Hayes and O'Driscoll (1989). Legend: 1 = eastern Avalon high-alumina belt and related rocks of the Harbour Main Group; 2 = unseparated mafic and felsic flows and sediments of the Harbour Main Group; 3 = unseparated monzonite, gabbro, granite and porphyry phases of the Holyrood Intrusive Suite, in many instances with hydrothermal alteration; 4 = mainly weakly altered (chlorite–epidote) quartz-rich biotite granite (Holyrood Intrusive Suite); 5 = sediments of uncertain stratigraphic affiliation (Black Hill sequence of Dawson, 1963); 6 = Conception Group marine sediments; 7 = Cambrian cover sequence of mainly shaly rocks.*

Boulders, subcrops and – more rarely – outcrop of similar adularian or chalcedonic–silica-bearing breccias and/or vein material, are distributed sporadically over an area of several square kilometres. Given the known glacial dispersion data (from the south), this distribution requires the presence of more than one such hydrothermal vein system in this immediate region.

THE STEEP NAP PROSPECT

The Steep Nap Prospect corresponds to a 60-m-wide roadside outcrop, within which precious-metal mineralization occurs in epithermal quartz–adularia–hematite-bearing veins and hydrothermal breccias crosscutting non-welded and poorly sorted felsic pyroclastic rocks. These massive, unsorted lapilli tuffs are lithologically homogeneous and contain rounded to angular lithic pyroclasts ranging in size from <1 to 13.5 mm; most are less than 6 cm in longest dimension. Fragments of massive or finely flow-banded white, pink and orange (potassic-altered) rhyolite are predominant within the tuffs; mafic clasts are rare. A unique feature of the tuffs is the presence of rounded, out-sized fragments of equigranular to porphyritic granitoid rocks.

More than 100 hydrothermal veins and veinlets are present in the exposed section of the prospect, many of which are depicted on Figure 4. Both crustiform and comb-textured veins are recognized; the former are typically anomalous in gold; the latter are weakly anomalous or barren. The veins are associated with several generations of hydrothermal breccia. Some of the early breccias contain anomalous gold; later breccias are typically barren, other

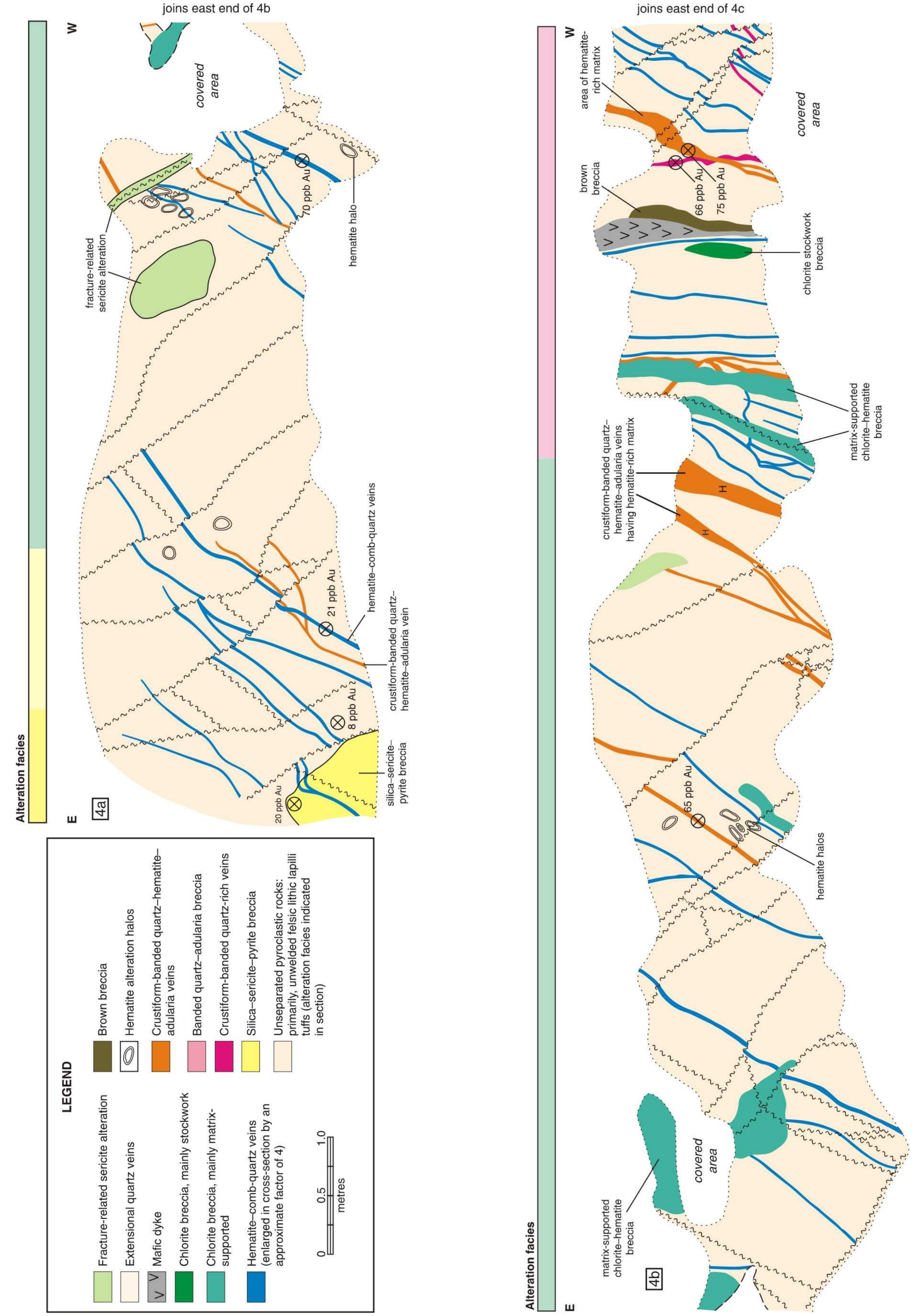

Figure 4. *Geological section across the Steep Nap Prospect.*

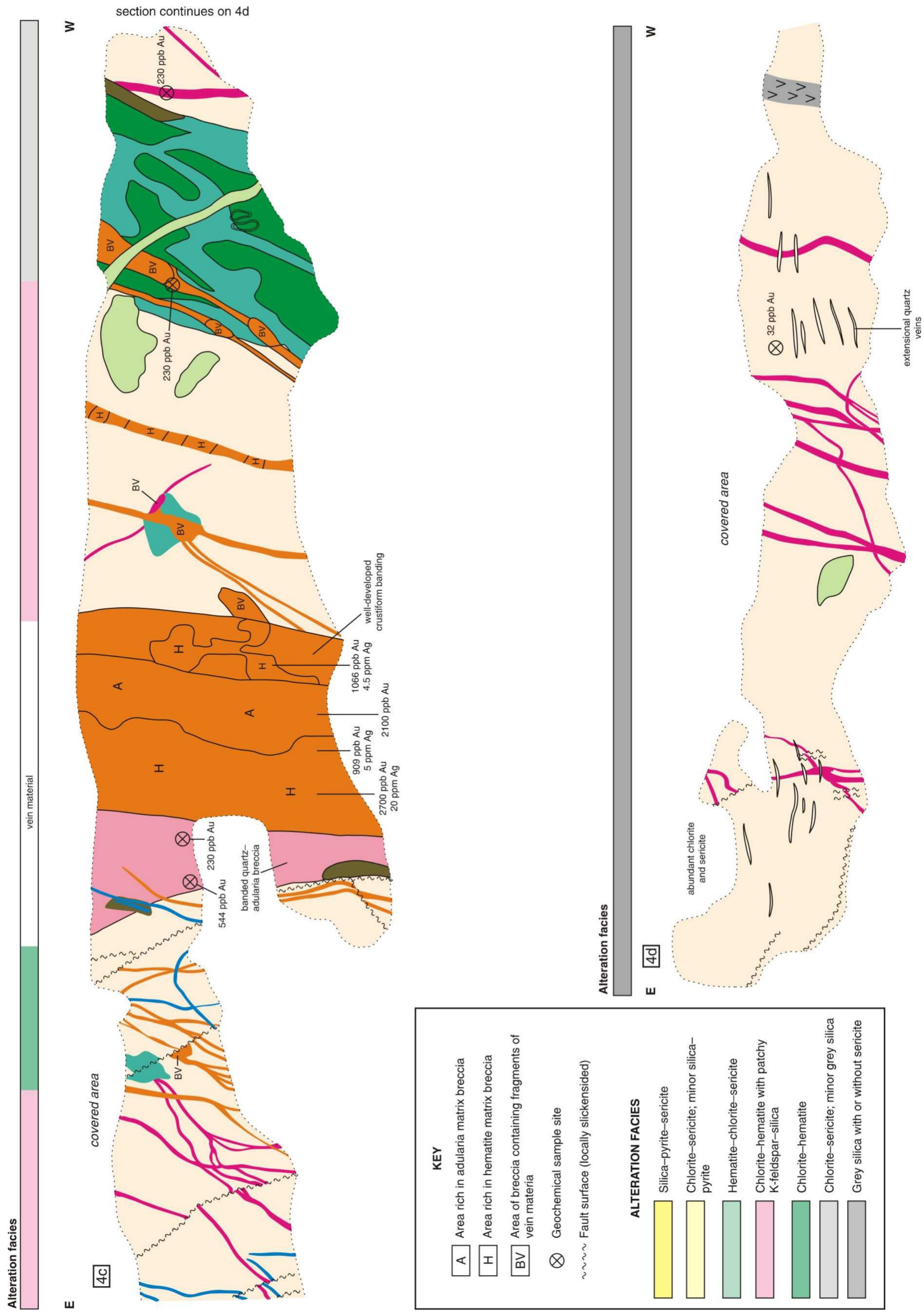

Figure 4. *Continued.*

than where they contain vein fragments. Veins trend approximately northwest–southeast to north–south, although some variation is present in detail. They are mainly steeply dipping, and range in width from 1 mm to approximately 2 m. Grab samples from the largest vein in the prospect, contain up to 2.7 g/t Au and 20 g/t Ag. The veins exposed at Steep Nap Road can be traced along strike to the southeast for at least 300 m. Anomalous gold values (from 100 ppb to 3.5 g/t) have been obtained in grab samples from outcrop and float over an area of several square kilometres (T. Gosine and C. Miles, personal communication, 1998; S. O'Brien, unpublished data). Wall rock alteration in the immediate host to the veins is typically weak and irregular, and includes chlorite, hematite, silica, K-feldspar and locally sericite. Early silica–sericite–pyrite alteration is locally preserved in the immediate area of the gold veins, and extends several hundred metres south of the prospect. Similar, albeit less intense, alteration is associated with locally developed barren pyritic hydrothermal breccia.

Based on crosscutting relationships, the various hydrothermal veins and breccias are divided into three broad groupings, each with distinct texture, mineralogy, morphology, colour and relative age. They represent various stages of hydrothermal activity that was synchronous with tectonic and hydrostatic fracturing. They are: 1) early, pyritic siliceous breccias (barren); 2) crustiform-banded quartz ± hematite ± adularia veins and breccia (auriferous); and 3) late, hematite comb-quartz veins and breccia (barren to weakly auriferous). Each is developed – to varying degrees – on a more regional scale within the northern part of the eastern Avalon high-alumina belt.

EARLY SILICA–SERICITE–PYRITE BRECCIA

The earliest hydrothermal breccias represent a volumetrically minor aspect of the Steep Nap Prospect. They are silica-rich and characterized by a dark grey to black matrix of silica, finely disseminated pyrite and minor sericite. These are clast-supported, and rich in fragments of silica–sericite–pyrite-altered, pyroclastic rocks. Fine-grained pyrite occurs primarily in the breccia matrix, and is present only as a minor component in silica-altered clasts. The breccias show only a very slight enrichment in gold (ca. 20 ppb Au). The breccia is overprinted by chlorite–hematite alteration related to the later hydrothermal vein emplacement, and by still later sericite alteration.

A similar style of variously intense silica–pyrite alteration is developed on a larger scale in volcanic rocks approximately 200 m south of the prospect. In that area, silica-altered material has pervasively flooded felsic volcanic rocks, locally resulting in the development of narrow zones of massive-silica-matrix breccia.

MINERALIZED CRUSTIFORM-BANDED ROCKS

Quartz-Rich Veins

The earliest hydrothermal veins typically contain in excess of 90 percent quartz by volume. Two variants of the quartz-rich veins are identified, based on the presence or absence of a silica-rich hematite phase. The quartz-rich veins are characterized by crustiform-banded, grey and white quartz, with or without chlorite and hematite, and contain crystalline comb-quartz near their centre (Plate 1). Although these veins attain widths up to 10 cm, most are less than 40 mm wide. The wider veins are normally planar, with pinch-and-swell development; narrower veins are multiply branched. Grab samples from the veins have returned assays up to 500 ppb gold.

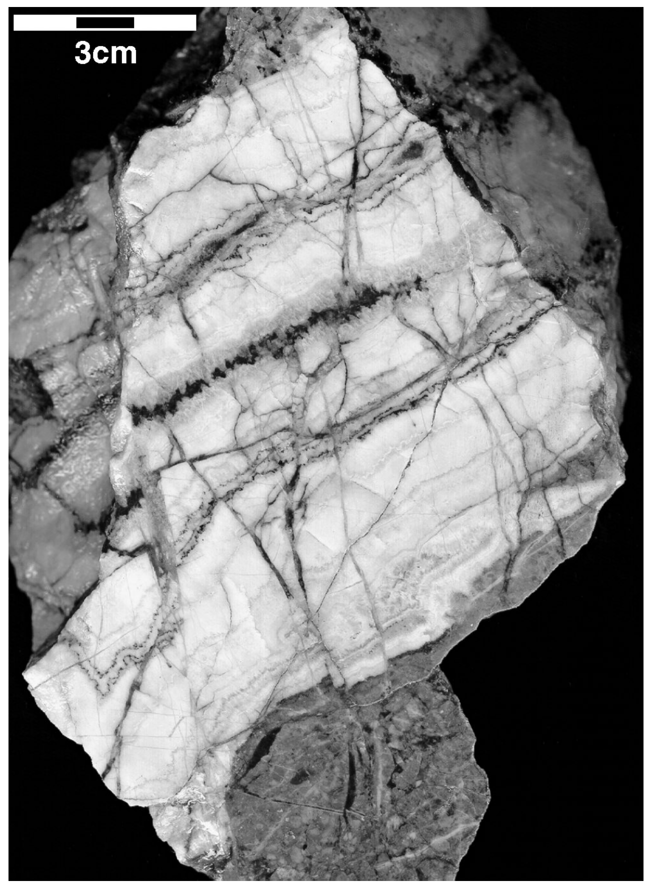

Plate 1. *Crustiform-banded quartz-rich, chlorite-bearing hydrothermal vein containing white chalcedonic and grey crystalline silica bands.*

The crustiform banding is weakly defined in most cases, and is formed by alternating layers of grey to white silica, symmetrically arranged around the vein centre. Banding is defined either by mosaic- and comb-textured

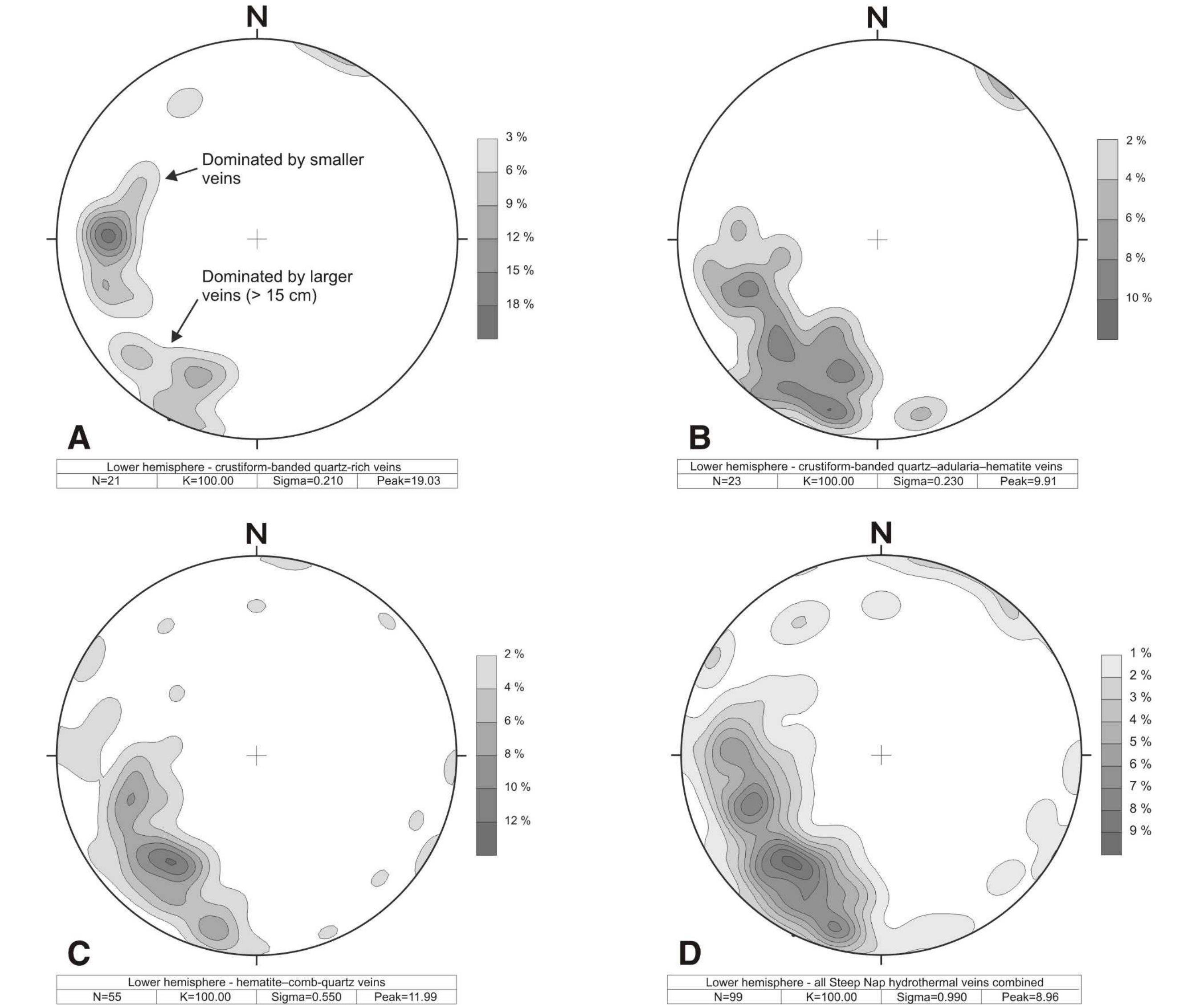

Figure 5. *Lower hemisphere stereographic plot of contoured poles to planes, showing the distribution of hydrothermal veins at the Steep Nap Prospect. A: quartz-rich crustiform veins, B: quartz–hematite–adularia-bearing crustiform veins, C: hematite comb-quartz veins, D: all hydrothermal veins.*

quartz or by very fine-grained (≤ 0.01 mm) mosaic-textured, distinctive cream-white chalcedonic silica. Locally, a sub-millimetre-scale colour banding, defined by equal proportions of chlorite and quartz, and minor hematite is preserved. Two main types of grey silica bands are identified, and these are separated on the basis of grain size and texture. The fine-grained grey quartz, like the creamy chalcedonic silica, displays strong mosaic texture, upon which, a pseudo-bladed texture has been superimposed.

Orientation data reveal two close but separate groups of orientations of the quartz-rich veins, which correspond to vein widths greater than, and less than, 15 mm (Figure 5). The mean orientation of the early silica-rich veins is 320/58 (right-hand rule).

Quartz–Hematite–Adularia Veins

A second group of veins, which crosscut the quartz-rich veins, are defined by symmetrically arranged colloform and crustiform bands of grey and white quartz, red hematite (with chlorite), and, in many cases, orange adularia (Plate 2). Typically, vein cores are defined by brick-red hematite bounded by poorly developed crystalline comb-textured quartz. The veins are of widely variable width (2 mm to 1.7 m); their orientations are similar to the earlier crustiform-

Plate 2. *Crustiform-banded quartz**n**adularia**n**hematite-bearing hydrothermal vein, containing alternating bands of chalcedonic silica and orange adularia.*

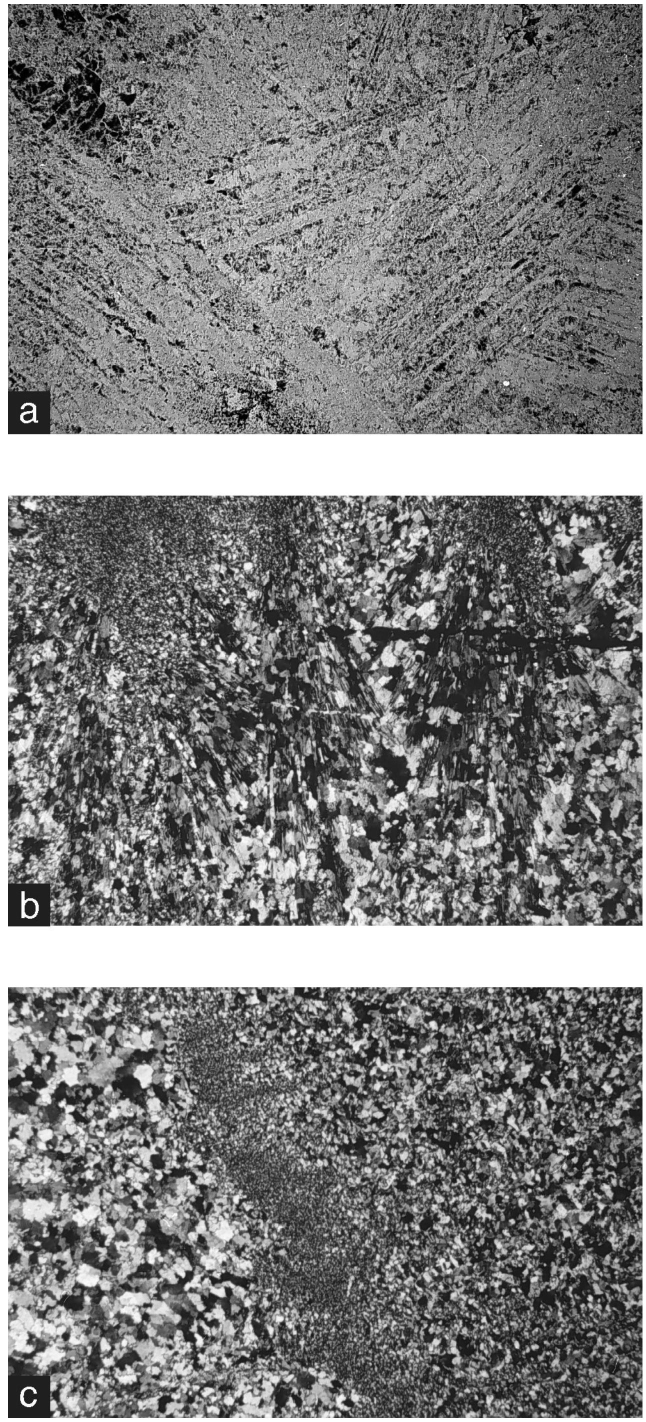

Plate 3. *Photomicrographs of i) textures characteristic of chalcedonic silica replacement of calcite and ii) recrystallization of chalcedonic silica; from main mineralized quartz**n**adularia**n**hematite vein. 3a: parallel-bladed texture, 3b: pseudo-acicular texture, 3c: mosaic texture. Field of view is approximately 6 mm.*

banded quartz-rich veins. All the veins greater than 10 cm width contain adularia.

The relative proportion of adularia to quartz within the orange bands determines their colour intensity. Colourless to milky white adularia may be present as a minor component (normally < 2 % by volume). The grey and white bands consist primarily of very fine-grained quartz, with 1 to 2 percent adularia. Colour variation in this case is a function of grain size: grey bands are defined by crystals ≤ 0.02 mm, and white bands have a grain size between 0.06 and 0.2 mm. The quartz bands also contain traces (up to 1 % combined) of very fine-grained hematite, chlorite and sericite. The red bands contain variable amounts of hematite and chlorite (40 to 60 % combined), slightly less quartz, and <10 % sericite. Less common green bands contain abundant sericite, and minor hematite and chlorite.

Ghost-bladed, parallel-bladed and pseudo-acicular textures are developed in the veins; all reflect the replacement of calcite by chalcedony (Plate 3a,b). The grey and white bands also display superbly preserved mosaic textures (Plate 3c) formed by recrystallization of chalcedonic silica. In rare cases, microscopic circular to ovoid clusters of crystalline

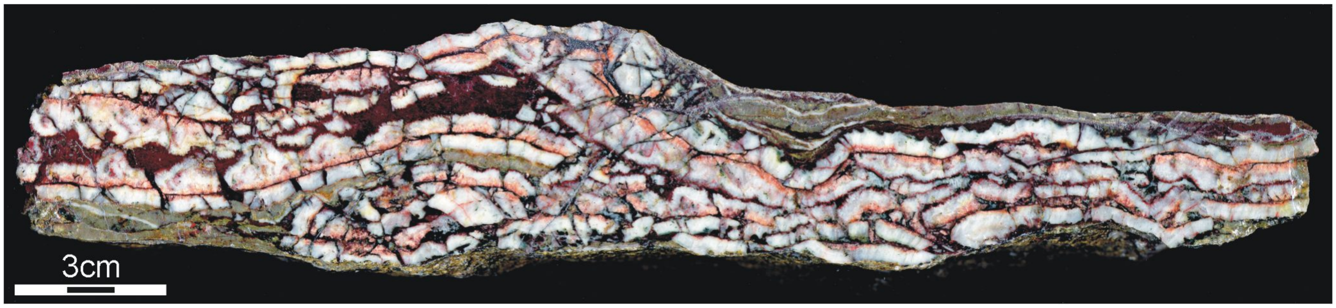

Plate 4. *Jigsaw-textured quartz–adularia–hematite-bearing hydrothermal vein.*

quartz are preserved; these represent originally open vugs, subsequently filled by silica.

The quartz–hematite–adularia veins locally contain hydrothermal breccia that is confined within the walls of the vein. Brecciation intensity is highly variable, and is greatest in adularia-bearing veins. Angular clasts of adularia and silica-rich material are set in a hematite–chlorite–silica matrix, mineralogically identical to the red bands in the surrounding veins. Similar material also forms the matrix of jigsaw-textured breccia, in which *in situ* fragmentation has occurred (Plate 4). Where internal brecciation is most intense, surrounding wall rocks are also brecciated, within a 30 cm radius of the vein. The largest veins are unique in containing both a clast-supported, adularia-matrix breccia, and a later hematite–quartz–ferroan-chlorite matrix-supported breccia. The later brecciation is commonly intense, destroying most primary vein texture. A stockwork is locally developed, in which fragments of adularia-matrix breccia occur together with vein material.

The highest precious-metal contents obtained in this study (up to 2.7 g/t Au and 20 g/t Ag) are found in a 1.7-m-wide vein having well-developed crustiform and colloform bands of adularia, quartz and, to a lesser extent, hematite (Plate 5). The silica in this vein is entirely chalcedonic in nature. The vein lacks internal symmetry, and is likely a composite of individual veins. Macroscopic cockade texture is locally preserved, and a variety of microscopic textures indicative of calcite-replacement and chalcedony recrystallization are developed.

Plate 5. *Hydrothermal vein consisting of alternating crustiform bands of quartz, adularia and hematite, cut by hematite-rich stockwork breccia (2.7 g/t Au; 20 g/t Ag).*

Quartz–Adularia Breccias

Associated hydrothermal breccias are distinguished by a distinctive white and grey, crustiform-banded silica-rich matrix, that locally contains adularia. This breccia is anomalous in gold (up to 544 ppb Au in grab samples). The breccia is situated in the immediate hanging wall of the main mineralized vein at Steep Nap Road. It is matrix-supported, having a clast-to-matrix ratio of approximately 3:2. Clasts are entirely of local pyroclastic host-rock material displaying hematite–chlorite–sericite–K-feldspar–silica alteration. These are mostly subrounded to subangular, and range in size from 1 mm to 7 cm. In some places, jigsaw texture is developed as a result of brecciation without substantial movement.

The breccia matrix is characterized by alternating, concentric crustiform bands of creamy-grey recrystallized chalcedonic silica, white crystalline silica and/or pale-orange adularia. These wrap around wall rock clasts, producing a

Plate 6. *Cockade-textured, silica-rich breccia containing clasts of silica–sericite–chlorite-altered pyroclastic host rocks in a banded matrix of recrystallized chalcedonic silica and adularia.*

Plate 7. *Typical hematite–comb-quartz vein, displaying hematite core, surrounded by quartz having euhedral terminations and pseudo-crustiform banding; the latter is formed by layers of quartz crystals growing perpendicular to the vein walls. Approximate vein width is 1.5 cm.*

cockade texture (Plate 6). The white to grey variation in the matrix silica is primarily a function of grain size. The grey bands are formed by very fine-grained (≤0.01 mm) quartz crystals having a strong mosaic texture, reflecting recrystallization of the chalcedonic silica. These bands contain up to 10 % colourless adularia. White bands consist of slightly coarser grained quartz anhedra (≤0.25 mm), whereas light-orange bands contain at least 50 % adularia, together with quartz (both ≤0.1 mm).

The breccia is likely a precursor to the main period of vein emplacement, related to fracturing associated with the initiation of the fault structure filled by adjacent quartz–adularia vein material. The initial stockwork fracturing most probably formed by a combination of tectonic brecciation and hydrofracturing related to the hydrothermal circulation.

LATE HYDROTHERMAL VEINS AND BRECCIAS

Hematite–Comb-Quartz Veins

The latest hydrothermal veins are the most widespread (on a prospect scale) and also on a regional scale. These consist of weakly banded quartz along the margins, and crystalline comb-quartz near the centre, surrounding a red (or red-to-green) hematite ± chlorite core (Plate 7). These veins do not contain chalcedonic silica and are typically between 2 and 10 mm wide; they are everywhere internally symmetrical. Their mean trend (320/65) is subparallel to that of the earlier veins, although there is wider deviation from the general trend that is evident elsewhere. The comb-quartz–hematite veins are curvilinear in detail, but in many cases, are discontinuous on outcrop scale. Those exposed in the Steep Nap Prospect have only slightly anomalous gold concentrations (<100 ppb Au), although values up to 400 ppb have been obtained from similar veins elsewhere in the northern part of the eastern Avalon high-alumina belt.

The quartz in these veins is crystalline, euhedral, and elongate perpendicular to the vein walls. In outcrop, the quartz may either be massive in appearance or display pseudo-crustiform banding. The latter texture is defined by individual growth layers of similarly oriented quartz developed parallel to the vein wall. Adjacent to the core of the veins, quartz may be intergrown with thinner dark bands defined by a hematite–chlorite–quartz mixture. The brick-red to dark-green core consists of quartz, hematite, chlorite (clinochlore) and rarely, sericite. The relative proportion of hematite and chlorite is variable and is reflected in the colour variation from red (hematite > chlorite) to green (chlorite > hematite) seen in the veins. The quartz protruding into the hematite core of the vein forms well-developed comb texture.

The hematite–comb-quartz veins crosscut both types of crustiform-banded veins. Locally, the hematite that fills the core of crustiform-banded veins has migrated into fractures that locally cut the crustiform-banded vein, the surrounding wall rock, *and* adjacent hematite–comb-quartz veins (Plate 8). These relationships are consistent with at least some of the hematite core of the crustiform bands being late, relative to the remainder of the banded vein, and coeval with the emplacement of the younger hematite–comb-quartz veins.

Plate 8. *Early crustiform quartz–adularia vein filled by late hematite–chlorite–silica material that has migrated along chlorite-haloed fractures and cut hematite comb-quartz vein.*

Fe-Oxide- and Chlorite–Hematite Breccias

Two types of breccias are associated with the hydrothermal activity that produced the hematite–comb-quartz veins: These are i) brown breccia and ii) chlorite–hematite breccia. The earlier brown breccia is a minor breccia phase characterized by its fine-grained nature and a brown Fe-oxide matrix. Other than its colour, the breccia is very similar in appearance to the post-veining chlorite breccia (*below*). The matrix includes the iron oxide akaganeite (FeO[OH]), as well as quartz and albite. The breccia crosscuts crustiform-banded silica breccia and related banded quartz-rich veins, and is itself crosscut by hematite–comb-quartz cored veins.

The later chlorite–hematite breccias represent the youngest hydrothermal phase recognized in the prospect and they contain fragments of both the crustiform-banded and comb-textured veins, and previously-altered (chlorite–silica–sericite) wall rock pyroclastic rocks. The breccia has matrix- and clast-supported components. In the former, the clasts are small (<10 cm), subangular and are set in a matrix rich in millimetre-scale wall rock fragments (Plate 9). However, more typically, the breccia is defined by bundles of chloritic fractures or more intense jigsaw-style stockwork. Clasts are essentially autochthonous relative to the wall rock. The matrix is dark green (typically) or black, and locally dark rusty red, consisting of quartz, chlorite (clinochlore), hematite, and minor orthoclase and sericite. The proportions of chlorite and hematite varies slightly throughout the breccia, resulting in colour variation from dark green (chlorite > hematite) to dark brown (hematite > chlorite). Hematite is typically deposited on the rims of clasts, whereas chlorite occupies the central portion of the matrix.

The breccia is anomalous in gold (up to 692 ppb) only where it contains clasts of crustiform-banded vein material. In contrast, a breccia sample enriched in matrix material and pyroclastic host rock clasts returned an assay of 28 ppb Au.

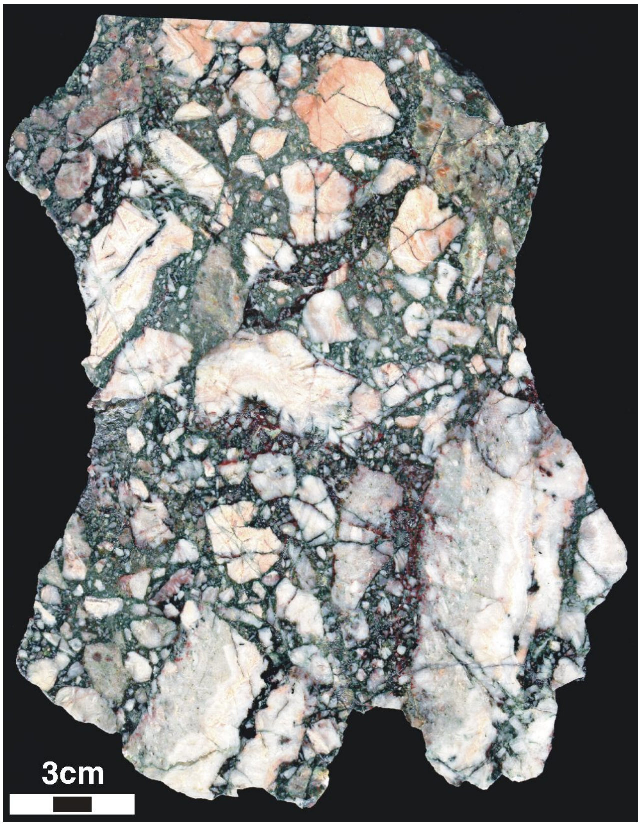

Plate 9. *Chlorite breccia containing adularia-bearing vein fragments in chlorite***n***hematite matrix.*

WALL ROCK ALTERATION

Silica–Pyrite and Grey Silica Alteration

Pyrite-rich silicic alteration is associated with silica–pyrite–sericite hydrothermal breccia exposed near the east end of the prospect. The spatial association and similarity of alteration in the breccia and in surrounding wall rock indicates that brecciation and alteration represent different manifestations of the same hydrothermal event. More intense silica alteration exposed along the powerline, approximately 200 m south of the prospect, may be related to this event.

Pyrite-free, buff to light-grey silica alteration is exposed in the western portion of the Steep Nap Prospect, where it is overprinted by chlorite-matrix hydrothermal breccia. There, the least altered rocks consist of a mixture of silica, hematite, and sericite. More intense silica alteration is encountered locally (ca. 84 % SiO_2), and the altered rocks take on a rhyolitic appearance. The silicic alteration is associated with only slightly anomalous gold (32 ppb). Its relation to the silicic K-feldspar alteration proximal to the main mineralized vein is uncertain, although the contrasting alteration styles require hydrothermal fluids of significantly different acidity.

Thin (1 to 5 mm) silica veinlets or stockwork locally crosscut the crustiform-banded veins and silica-altered host rocks. These may represent a late pulse of silica-saturated fluids generated and emplaced late in the formation of the crustiform-banded veins.

Hematite–Chlorite–Sericite–K-feldspar–Silica Alteration

The alteration assemblage hematite–chlorite–sericite–K-feldspar–silica is developed in the area of the mineralized hydrothermal veins, and is, in part, synchronous with the development of both the quartz-rich and adularia-bearing types of crustiform-banded veins. This alteration is variably intense and has an irregular, patchy distribution. In detail, the relative proportion of phases is variable, and in some instances, one or more of the phases are absent. The diverse assemblage may reflect a protracted history, and/or irregular physico-chemical conditions. Rocks affected by this alteration are cut by early quartz veins, and occur as clasts that core cockade texture in these hydrothermal veins. Similarly, altered rocks occur in the late chlorite breccias, and are affected by late chlorite fractures.

Within 3 to 4 m of the main vein at Steep Nap Road, K-feldspar and silica are developed as small (≤30 cm wide) patches. Primary pyroclastic texture has been obliterated locally, and in those instances, crystallization of K-feldspar and silica produce textures similar to that in nearby veins. The altered rock has an orange hue, and a mineralogy similar to that of the hydrothermal veins: *viz*. quartz, albite, orthoclase, and barian orthoclase. In areas of less intense alteration, the rocks can also contain up to 10 % hematite and sericite. Bright orange fragments in the pyroclastic rocks, also display evidence of K-feldspar (adularia?) and silica alteration. These fragments host a quartz–albite–barian orthoclase assemblage like that of the adularia-bearing veins and K-feldspar-altered wall rocks. The surrounding pyroclastic matrix is similarly altered, albeit in selective zones.

Chlorite (clinochlore) is the predominant alteration phase adjacent to the hanging wall of the main mineralized vein, from whence it grades outward into a hematite–chlorite assemblage. Where hematite is predominant, the rock is brown or brick-red.

Hematite Halos

Late remobilization of hematite has occurred in rocks previously affected by hematite–chlorite–sericite–K-feldspar–silica alteration. Brick-red to brown bands (10 cm width) of hematite alteration form round to oval halos (≤30 cm in diameter) around yellow-green sericite-enriched or, more rarely, orange, K-feldspar–silica-enriched centres

(Plate 10). The alteration assemblage in the sericite-enriched cores includes muscovite and brammallite ($NaAl_2[Si,Al]_4O_{10}[OH]_2$).

Plate 10. *Hematite halo containing sericite-enriched core.*

These halos are not directly related to the veining and are clearly crosscut by both the late hematite–comb-quartz veins and the auriferous crustiform-banded veins. The hematite halos are also crosscut by chloritic fractures and late chlorite breccias. The halos most likely formed in the late stages of hematite–chlorite–sericite–K-feldspar–silica alteration.

Hematite–Chlorite Vein and Fracture Halos

Late stage chlorite–hematite alteration occurs along the margins of some hematite–comb-quartz veins and chlorite–hematite-filled fractures. Alteration extends only a few centimetres into the wall rock and, depending on whether chlorite or hematite dominates, is either green or red-brown, respectively. Fractures and veinlets associated with this style of alteration crosscut both the quartz-rich veins and the crustiform-banded veins, and are themselves locally disrupted by the late chlorite-rich hydrothermal breccias and late silica veinlets. The alteration is synchronous with the emplacement of the hematite–comb-quartz veins and is likely a result of the chlorite–hematite-rich fluids in these veins and fractures reacting with the surrounding wall rock. This alteration also forms around fractures derived from the central hematite–chlorite-filled core of earlier crustiform-banded veins. Thus the alteration, like the void-filling, is likely syn- to late-veining.

POST-HYDROTHERMAL ACTIVITY

Both the altered pyroclastic host rocks and hydrothermal related veins and alteration are cut by rare mafic dykes. Dark-green diabase crosscuts buff to light-gray silica-altered rocks and is itself unaltered. The brown breccia is similarly crosscut by unbrecciated dark-brown to black diabase. The dykes contain up to 10 % hematite and chlorite and are not unlike deformed mafic dykes found elsewhere in the region that are assumed to be related to the younger Late Neoproterozoic mafic rocks along the eastern margin of the eastern Avalon high-alumina belt.

Subhorizontal extensional quartz veins are common in and around the prospect. These discontinuous veins typically contain massive euhedral white quartz (with minor green chlorite) crystals elongated perpendicular to the walls of the vein. The extensional veins crosscut veins, breccias, hydrothermally altered rocks, and post-alteration diabase. Small-scale extensional veins are preferentially developed in the area of the silica-rich crustiform veins. Very local migration of hematite into the extensional veins has occurred where they crosscut earlier hematite-bearing crustiform veins.

Late sericite (illite–muscovite) occurs as irregular apple-green patches along some fracture and fault surfaces that crosscut all other features in the prospect. This type of sericite is unlike the earlier more pervasive hydrothermal sericite alteration in that it is confined to linear fractures. Its origin is likely related to the late brittle fracturing and faulting, and related regional low-grade metamorphism.

Numerous late fractures are randomly distributed throughout the outcrop. Most of the larger slickensided surfaces display a normal sense of movement. Nowhere is displacement greater than 1 m; most have no movement. These postdate all hydrothermal features.

DISCUSSION

NATURE AND EVOLUTION OF THE HYDROTHERMAL SYSTEM

The Steep Nap Prospect displays many characteristics of a low-sulphidation (adularia–sericite) epithermal gold system. These include: i) the association of gold and silver with a high Ag/Au ratio (up to 7:1); ii) the sulphide-poor, banded crustiform- and colloform-textured quartz–adularia–hematite veins; iii) the alteration assemblage characterized by sericite–adularia–quartz–chlorite–hematite; iv) the presence of carbonate replacement textures; v) the occurrence of (recrystallized) chalcedonic and/or amorphous silica; and vi) the geological setting within a thick succession of subaerial felsic pyroclastic rocks.

The observed chronology of vein and breccia formation (Table 1), coupled with textural and compositional variations, reveal the multi-stage physical and chemical evolution of this auriferous hydrothermal system. The total duration of

Table 1. Chronology of events: Steep Nap Prospect

Post-hydrothermal activity	
16	Development of metamorphic sericite along fractures
15	Formation of barren extensional quartz veins
14	Mafic dyke emplacement
Post-precious-metal mineralization (syn-hydrothermal activity)	
13	Formation of chlorite breccia
12	Formation of hematite–chlorite vein/fracture halos
11	Emplacement of hematite–comb-quartz veins
10	Formation of brown breccia
9	Formation of hematite alteration halos
8	Emplacement of silica veinlets
7	Formation of auriferous, crustiform-banded quartz–adularia–hematite (syn-hematite–chlorite–sericite–K-feldspar–silica alteration
6	Hematite–chlorite–sericite–K-feldspar–silica alteration (pre- and syn-silica breccia)
5	Formation of auriferous, banded silica breccia
4	Emplacement of auriferous, crustiform-banded quartz-rich veins
Pre-precious-metal-mineralization	
3	Buff to light gray silica alteration
2	Hydrothermal brecciation and silica–pyrite–sericite alteration
1	Eruption of pyroclastic host rocks

the system is unknown, but it is unlikely that any of its component events are separated by an extensive hiatus. Early hydrothermal fluids responsible for the silica–pyrite–sericite alteration and related hydrothermal brecciation, as well as the buff to light-grey silica alteration, were chemically distinct and more reducing than all subsequent fluids, with high sulphur activity (greater than log -13), high oxygen activity (between log -40 and log -30), and a pH between 4.5 and 5.5 (Figure 6a,b). The relation of this stage of hydrothermal activity to later, and more typical, low-sulphidation style alteration is uncertain. Its link to pyrophyllite-rich advanced argillic alteration elsewhere in the eastern Avalon high-alumina belt remains unclear, and is the focus of the ongoing U–Pb zircon and ^{40}Ar–^{39}Ar geochronological studies.

Hydrothermal fluids responsible for the auriferous veins and brecccias were of near-neutral pH. The similarity in alteration mineralogy in these various veins and breccias (hematite–chlorite–sericite–adularia, lacking sulphides) implies that the fluids underwent little chemical variation over the life of the system. These fluids had a pH that varied between 5.5 and 6 (and higher, where sericite is absent), an oxygen activity of approximately log -34, and a sulphur activity between log -14 and log -11 (Figure 6a,b). The lack of sulphides and abundance of hematite suggest oxidiz-

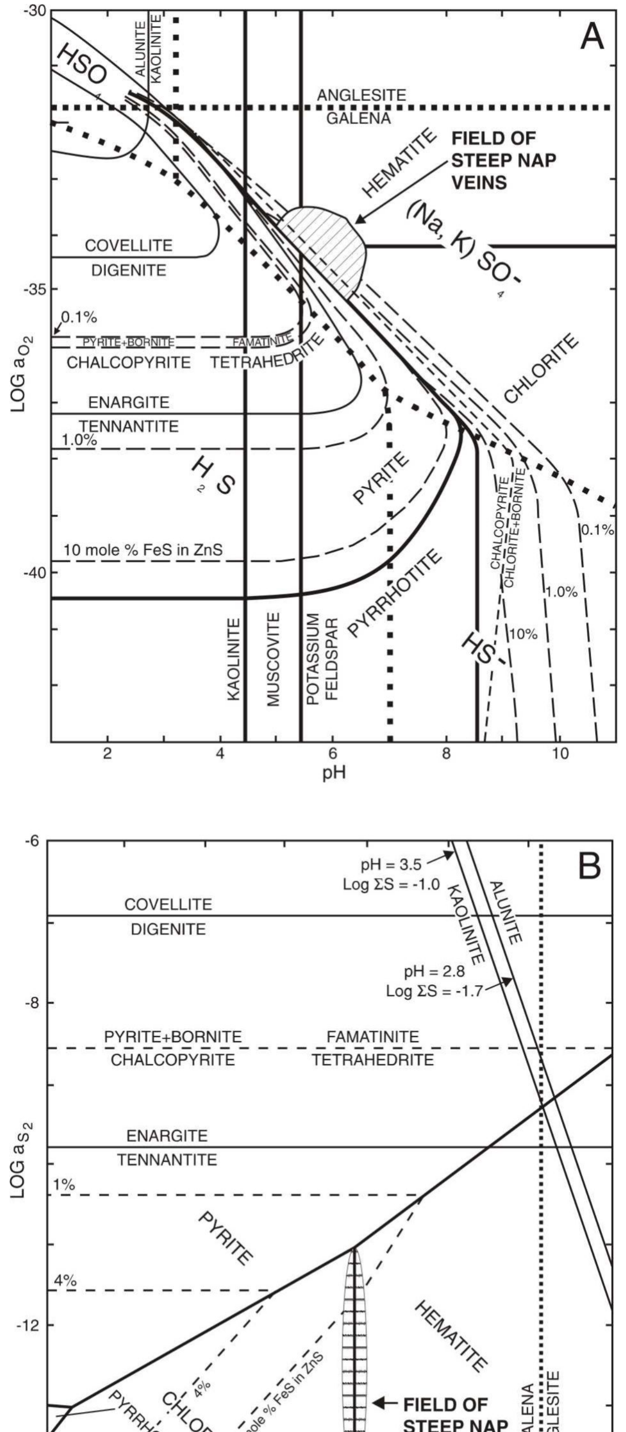

Figure 6. *A) Log a_{O_2} - pH diagram at 250°C, ∑S=molal (log ∑S= -1.7), and salinity = 1 molal with Na/K = 9. From Heald* et al., *1987; B) Log a_{S_2} - a_{O_2} diagram showing the mineral stability fields for the significant minerals in epithermal systems at 250°C. The magnetite field is pre-empted by the chlorite field; quartz is present throughout. From Heald* et al., *1987.*

ing conditions for the fluids and could be primarily a function of depth within the hydrothermal system (*see* Figure 1).

The lack of adularia in the early quartz-rich crustiform veins implies that hydrothermal fluids generated at this stage had a pH closer to 5.5, where hematite and chlorite are present together. Some boiling may have occurred to enrich the silica concentration to necessary levels to form a silica gel that deposited the mosaic-textured, creamy-white chalcedonic quartz. However, the predominance of crystalline quartz, together with the lack of replacement textures and the lack of adularia indicates that, at this stage, boiling was rare.

Later fluids, which formed the adularia-bearing crustiform-banded veins and related wall rock alteration, display a relative increase in pH, necessary to produce the assemblage hematite–chlorite–adularia–sericite (*see* Figure 6a,b). Evidence of boiling includes the presence of adularia, and the presence of textures formed by the replacement of carbonate, and those formed by the recrystallization of amorphous silica and chalcedony (*see below*). The deposition of adularia occurred at the onset of boiling, as a result of volatile-loss, and the resultant increase in pH of the fluid.

Fluids responsible for the generation of late hematite–comb-quartz veins and the associated chlorite–hematite vein/fracture halo alteration had a pH, and oxygen and sulphur activities, similar to earlier veins. The total dominance of crystalline comb-quartz and the lack of adularia and replacement and recrystallization textures, indicate that boiling did not occur in these veins. They were deposited under lower temperature conditions (<200°C) at or near the end of hydrothermal activity. The same type of veins seen elsewhere in the Avalon high-alumina belt may have formed slightly earlier but distal to the main site of low-sulphidation style hydrothermal activity, or may have formed at slightly deeper crustal levels.

The chlorite breccia represents the latest migration of similar fluids through the system and marks the last record of hydrothermal activity in the Steep Nap Prospect. The development of breccias rather than veins, in this instance, simply reflects the relative lack of sufficiently permeable pre-existing migration paths for fluids at that stage.

STYLE OF EMPLACEMENT

The presence of veins and vein swarms of similar orientation, coupled with the lack of extensive wall rock alteration, indicate that the primary geometrical control for the low-sulphidation mineralization at Steep Nap Road was structural in origin, rather than permeability-related. Orientation data demonstrate that all veins formed under a broadly similar stress field. The irregular shape and discontinuous nature of the late hematite–comb-quartz veins, coupled with their great abundance and widespread distribution, are seen as evidence for their emplacement along irregular fractures, rather than along planar faults. The textures and composition in the late veins demonstrate that at the time of this late fracturing, hydrothermal activity was minimal.

CORRELATION OF TEXTURE AND GOLD CONTENT

In the Steep Nap Prospect, the presence of 1) adularia, 2) textures reflecting the recrystallization of chalcedonic silica, and 3) chalcedony replacement textures, is directly related to the presence of gold mineralization (Figure 7a,b). Such a positive correlation between gold content and texture and mineralogy of the vein is typical in low-sulphidation systems (e.g., Morrison *et al.,* 1990; Dong *et al.,* 1995).

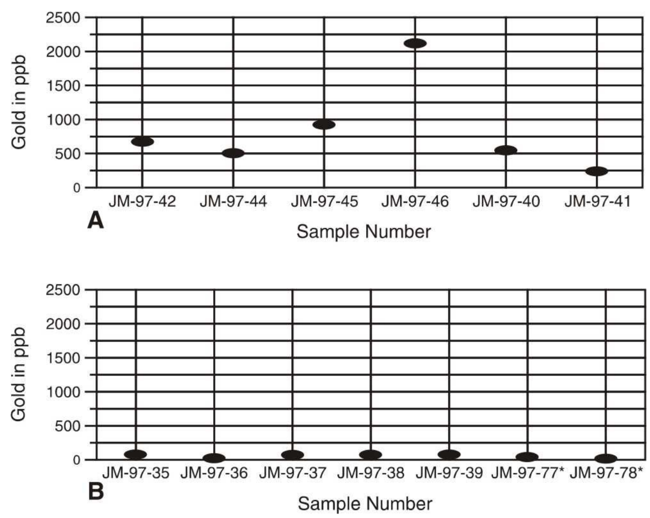

Figure 7. *Graphs showing the relationship between gold values and the presence (A) or absence (B) of replacement-recrystallization textures in hydrothermal veins in the Steep Nap Prospect.*

The deposition of adularia in veins and breccias at the Steep Nap Prospect is evidence that the exposed part of the hydrothermal system lies above the boiling level, and at a depth suitable for precious-metal deposition (Figure 1). The presence of crustiform- and colloform-banded mosaic-textured quartz is likewise consistent with vein formation within the precious-metal interval. In this zone, silica gels were deposited and gold precipitated as a result of boiling of near-neutral pH fluids (*see* Dong *et al.,* 1995). The deposition of silica gel in response to boiling is thought to provide a transportation mechanism for gold in low-sulphidation systems, whereby gold is transported as colloidal particles protected by colloidal silica in the silica gel (e.g., Dong *et al.,* 1995).

The presence of mosaic-textured quartz is a characteristic feature of the silica bands in crustiform veins that carry anomalous gold values at the Steep Nap Prospect. According to Lovering (1972), fine-grained quartz having this texture represents recrystallization of metastable amorphous silica or chalcedony. Vein quartz having this texture was originally deposited as a silica gel under relatively low-temperature conditions (200 to 300 °C, or lower).

HYDROTHERMAL HEMATITE

At least two generations of hydrothermal hematite can be identified in the prospect, each of which formed from different fluids at different times. Early formed hematite is associated with gold mineralization, and is found in the core of the main mineralized vein. The brecciation associated with this hematite is likely related to the boiling episode and/or to hydraulic fracturing due to the fluid overpressure. The brecciation is late relative to the most active stages of hydrothermal activity. A second generation of hematite occupies the core of the late comb-quartz-rimmed veins, and likely formed in the waning stages of hydrothermal activity. Some of this late hematite may have passively filled previously unsealed cores of earlier veins. Whereas the early hematite is associated with significantly elevated gold concentrations (up to 2.7 g/t), late hematite normally returns gold values less than 100 ppb.

SUMMARY

1) The Steep Nap Prospect is a low-sulphidation (adularia–sericite) gold-bearing epithermal system, hosted by a thick succession of late Neoproterozoic subaerial pyroclastic volcanic rocks (Harbour Main Group).

2) On a regional scale, the Steep Nap Prospect lies within a thick ash-flow tuff succession that is stratigraphically associated with coeval dome-facies rhyolite flows, plugs and *in-situ* breccias: a facies association consistent with a caldera setting (*see* O'Brien *et al.*, 1997, 1998a,b). The association of the mineralized rocks with (nearby) coarse-grained, granite-bearing pyroclastic breccias and porphyry may indicate that the low-sulphidation mineralization was sited proximal to synvolcanic intra-caldera structures.

3) The primary geometrical control for the low-sulphidation mineralization was structural in origin, rather than permeability-related. Orientation data demonstrate that all veins formed under a broadly similar stress field.

4) Gold and silver (having a high Ag/Au ratio) typically occurs in sulphide-poor banded crustiform- and colloform quartz–adularia–hematite veins and early, mineralogically similar hydrothermal breccias.

5) Mineralization is typically associated with the alteration assemblage sericite–adularia–quartz–chlorite–hematite.

6) The hydrothermal veins (and breccias) carry significantly anomalous gold where some combination of the following features are present: i) banded colloform–crustiform textures, ii) chalcedonic quartz, iii) adularia, and iv) recrystallization and replacement textures.

7) The best gold grade occurs where the banded colloform adularia-bearing veins have been disrupted by early hematitic-matrix breccia.

8) The potential for further mineralization at the property level is high. Mapping and prospecting have demonstrated that veins and breccias similar to those at Steep Nap Road occur elsewhere in the Manuels–Conception Bay South area. Similar style low-sulphidation precious-metal mineralization is an important exploration target farther south in the eastern Avalon high-alumina belt. As is the case in modern low-sulphidation systems, the texture and mineralogy of the veins and associated breccias at the Steep Nap Prospect, and elsewhere, are an important and fundamental tool in mineral exploration. These features may be used as an effective means to evaluate the geometry of the hydrothermal system and its level of erosion, allowing better testing of the vein system under investigation.

9) The presence of banded crustiform and colloform textures with chalcedonic silica and adularia, coupled with the absence of base metals, indicates that the exposed vein system is located within the precious-metal section of the host epithermal system, above the boiling level (*see* Figure 1).

10) A number of questions remain unanswered, and are the focus of ongoing work; these include i) the size and overall geometry of this low-sulphidation epithermal system; ii) the nature of the fundamental control(s) on its location and geometry (e.g., is faulting broadly coeval with the development of the host volcanic succession?), and iii) the relationship in time and space between the Steep Nap hydrothermal system and the large advanced argillic alteration zone present at the pyrophyllite mine, 3 km to the south.

11) The Steep Nap Prospect is the first late Proterozoic low-sulphidation epithermal system yet documented within the Appalachian Avalonian belt. It clearly highlights the potential for that style of mineralization in similar vol-

canic successions present elsewhere within the Avalonian belt in Newfoundland and elsewhere in the Appalachian Orogen. The most prospective areas are those where the caldera-facies subaerial felsic volcanic successions are thickest, and intersected by syn- to late-volcanic faults or caldera-related ring fractures.

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