ADVANCED ARGILLIC ALTERATION IN BONANZA VOLCANIC ROCKS, NORTHERN VANCOUVER ISLAND - LITHOLOGIC AND PERMEABILITY CONTROLS

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KEYWORDS: Economic geology, Bonanza volcanics, porphyry copper, copper-gold, epithermal, advanced argillic, acid sulphate, alunite, kaolinite, hydrothermal alteration, mineral deposits, mineralization.

INTRODUCTION

Hydrothermally altered rocks containing advanced argillic alteration are being studied in British Columbia (Panteleyev, 1992; Panteleyev and Koyanagi, 1993) as part of an investigation of acid sulphate type epithermal deposits and intrusion-related base and precious metal mineralization in settings transitional between porphyry copper and epithermal environments. The initiation of an integrated team project in northern Vancouver Island as part of the Ministry's 1993 *Mineral Strategy* enabled a revisit to the area and led to additional studies of the advanced argillic alteration and acid sulphate mineralization in Bonanza volcanic rocks to the west of the Island Copper mine in the Quatsino map area (NTS 92L/12; Figure 1). For a discussion of a related study of the generation of natural acid drainage in this mineralized environment, see Koyanagi and Panteleyev (1994, this volume). A summary of the integrated project (Panteleyev *et al.*, 1994, this volume) and more detailed descriptions of the other project components - surficial geology, bedrock geology and exploration geochemistry, are contained elsewhere in this volume (Bobrowsky and Meldrum, 1994; Nixon *et al.*, 1994; Sibbick, 1994).

HYDROTHERMAL ALTERATION

Large areas of clay-altered, and locally intensely acid leached siliceous rocks, are found in the belt of Bonanza volcanic rocks to the north of Holberg Inlet (Figure 2). The most intense hydrothermal alteration, including advanced argillic assemblages, is evident in the region from the Pemberton Hills westward to Mount McIntosh, a distance of 15 to 30 kilometres to the west-northwest of Island Copper mine. A second zone of similar alteration occurs even farther west along the regional trend of the Bonanza hostrocks at the Red Dog property and to the west of it, about 6 to 7 kilometres to the north of the village of Holberg. The alteration is most evident in the rhyolitic Bonanza map-units but also occurs in the
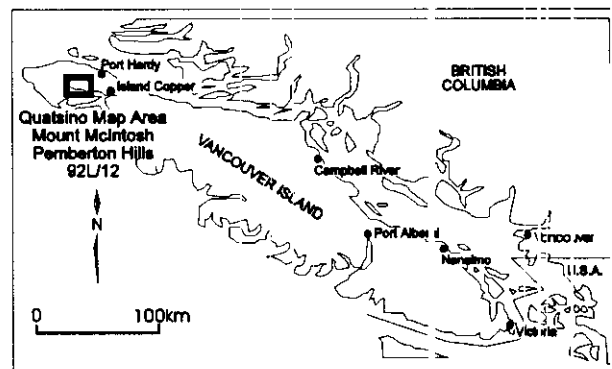

Figure 1. Location map; project area is north of Holberg Inlet in NTS 92L/12.

immediately underlying, feldspar-phyric, basic to intermediate volcanic rocks and, to a lesser extent, some of the adjoining intrusive bodies of the Island Plutonic Suite. The relationship between regional stratigraphic map units and the hydrothermally altered rocks is discussed in Nixon *et al.* (1994, this volume).

The advanced argillic alteration is characterized by the presence of kaolinite, dickite, alunite and pyrophyllite. Other associated minerals confirmed by X-ray diffraction analysis are abundant quartz, diaspore [AlO(OH)], zunyite [$Al_{13}Si_5O_{20}(OH,F)_{18}Cl$], various micas including sericite, muscovite and illite; lesser smectite, paragonite, gypsum, anhydrite, natroalunite, sulphur and rutile; and minor topaz, (? meta-halloysite. arsenian alunite (schlossmacherite) and tridymite.

The clay-rich hydrothermal alteration assemblages all contain some quartz. It is derived from both residual and, less commonly, added silica. Main alteration assemblages are: quartz + kaolinite; quartz + dickite ± pyrophyllite and/or kaolinite, all with or without alunite, diaspore, zunyite and minor mica; and quartz + alunite ± kaolinite. Peripheral rocks, both underlying and lateral to the clay-altered zones, contain pervasive zones with swelling-type, mixed-layer smectite clay species (montmorillonite) as well as extensive propylitic alteration characterized by albite, chlorite, epidote, carbonate, pyrite and zeolite. The propylitic rocks, in places, are crosscut by fracture-controlled sericitic and kaolinitic alteration.

Strongly altered rocks are bleached and chalky appearing. Where relict clay-altered plagioclase is present, the rocks can be determined to be derived from basaltic to andesitic protoliths. The more intense
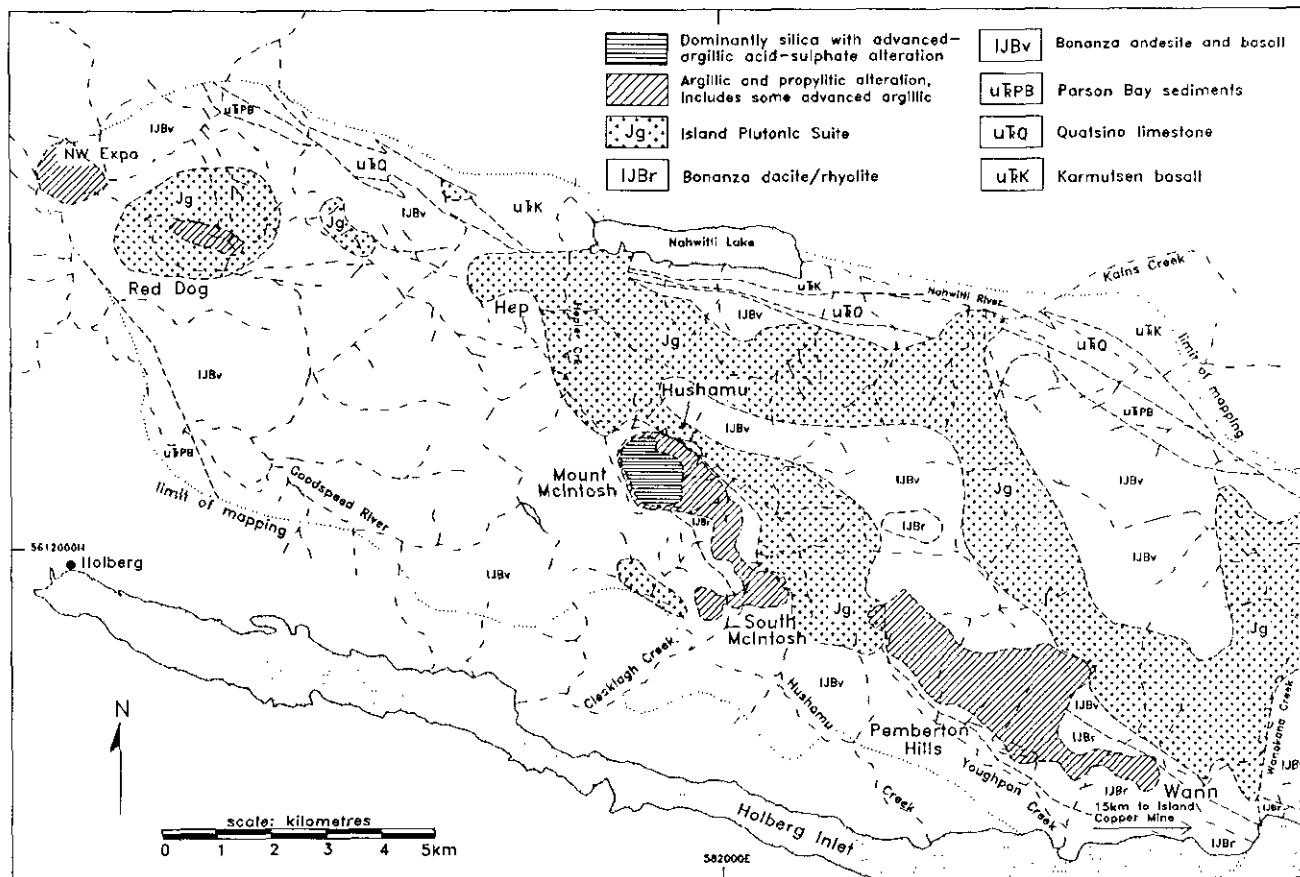
Figure 2. Generalized geological map units after Nixon *et al.* (1994), alteration zones and major mineral deposits north of Holberg Inlet in Quatsino map area 92L/12.

alteration in both feldspar-phyric and rhyolitic rocks creates a mottled rock with grey-buff-pink clay patches in grey, fine-grained to microcrystalline siliceous groundmass. The mottled anhedral, but generally equant, clay patches range in size from a few millimetres to a few centimetres in diameter. In thin section, they consist of aggregates of fine-grained clay minerals, mainly kaolinite. Streaks and irregular veins of kaolinite, quartz, diaspore or alunite and patches of zunyite crosscut the mottled rocks. In some outcrops, the rocks consist, in large part, of quartz stockworks, veins and patches of pervasive silica replacement. The most intensely leached rocks are made up of almost entirely quartz (>90%) and voids that give rise to a vuggy or "slaggy" texture or, less commonly, a friable, granular "sponge rock" appearance. This vuggy silica with attendant volume reduction of the altered hostrock is the characteristic siliceous residuum of intensely acid leached rocks in high sulphidation epithermal systems (White, 1991; Sillitoe, 1993). These highly porous rocks typically have 10 to 30% voids surrounded by fine, granular, interlocking, crystalline quartz grains. Other minerals present in various amounts are kaolinite/dickite, alunite and minor zunyite, rutile or other optically indeterminable iron-titanium minerals. The altered rocks commonly contain fine-grained pyrite; some silicified areas within the clay-altered zones contain 15% or more pyrite or, less commonly, specular hematite.

These residual, acid-leached textures are evident in the flow-banded rhyolite and other rhyolitic units, in feldspar-phyric basalt and basaltic andesite and, rarely, in some (quartz) diorite and monzonite stocks. Much, if not most, of the silica in these intensely altered rocks has been liberated from the breakdown of the hostrock silicate mineral grains. Remobilized and hydrothermally added silica is evident in places in the form of quartz veins and stockworks as well as crystalline and chalcedonic crusts and overgrowths in vugs and cavities.

Silica is also present as the main matrix component in many breccias and pervasively silicified or quartz-veined clasts in some crosscutting hydrothermal breccias, notably the youngest. The younger breccias tend to have rounded, strongly milled, hydrothermally altered polylithic clasts. In many breccias, fine-grained pyrite is a major matrix component.

PETROCHEMISTRY

Chemical compositions of typical Bonanza volcanic rocks and their altered equivalents in the map area were previously reported (Panteleyev and Koyanagi, 1993, Table 2-7-1, page 289) as major oxide data, including loss-on-ignition (LOI), CO_2, S and FeO. Additional analyses of the same sample suite, with the corresponding minor element data, are shown in Table 1.

TABLE 1: MINOR ELEMENT ANALYSES FOR TYPICAL HOST ROCKS; CORRESPONDING DATA FOR WHOLE ROCK ANALYSES PUBLISHED IN GEOLOGICAL FIELDWORK 1992, PAGE 289.

SAMPLE NUMBER	Map Unit*	Rock Type**	East	North	S %	Au ppb	Cu	Pb	Zn	Ni	Mo	Cr	As	Sb	Ba	Sr	Rb	Zr	Y	Nb	Ta	Th	U	Ce	Cs	Hf	Sc	V	La	Nd	Sm	Eu	Tb	Yb	Lu
Unaltered																																			
92AP01/1-1	1	1	578214	5612680	0.004	<2	37	6	100	6	<1	23	<0.5	0.1	706	622	<10	107	30	<5	<0.5	2.2	1.7	33	<1	3	20	142	17	16	4.3	1.3	0.7	2.9	0.47
92AP01/2-2	1	1	578159	5611115	0.001	<2	41	5	90	9	<1	28	<0.5	0.1	267	487	<10	106	29	<5	<0.5	2.2	2.0	34	<1	4	34	227	17	23	5.1	1.5	0.9	3.5	0.48
92AP11/5-53	1	1	578534	5612376	0.004	4	41	4	80	12	<1	26	1.9	0.1	469	589	<10	98	26	<5	<0.5	2.1	<0.5	38	2	3	26	183	16	13	4.4	1.5	0.7	3.1	0.51
92AP8/5-30	1	1	576128	5617652	0.010	5	13	3	110	149	<1	444	4.4	3.5	450	698	<10	59	21	<5	<0.5	0.5	<0.5	12	<1	2	45	258	4.3	12	2.7	1.2	<0.5	2.4	0.39
92AP5/8-18	1	1	581873	5616109	0.010	3	50	3	70	23	<1	42	<0.5	0.2	355	505	<10	81	23	<5	<0.5	1.8	<0.5	26	<1	<1	32	221	12	9	3.4	1.3	<0.5	3.0	0.50
92AP01/5-5	1	2	578644	5611570	0.001	<2	28	5	80	4	<1	21	<0.5	0.1	789	381	<10	114	28	<5	1.3	3.0	2.0	40	2	4	27	196	18	19	4.6	1.6	0.8	3.9	0.56
92AP13/10-68	1	2	582167	5611310	0.11	<2	83	8	65	3	<1	15	1.4	0.1	461	459	<10	158	32	5	<0.5	3.3	2.3	38	<1	5	18	155	16	13	4.3	1.3	1.0	3.5	0.55
92AP20/8-128	1	2	586784	5609612	0.040	<2	56	4	77	9	<1	24	<0.5	0.3	613	245	18	134	30	5	<0.5	3.1	1.6	30	<1	2	19	175	14	13	3.4	0.9	0.6	2.9	0.45
92AP21/7-132	1	2	589941	5608133	0.003	<2	58	4	70	55	<1	147	<0.5	0.1	657	464	11	139	28	5	<0.5	3.6	1.4	37	<1	4	26	191	16	13	3.8	1.2	0.6	2.9	0.49
92AP16/1-77	1	2	586791	5610934	0.014	<2	135	4	74	7	<1	24	11	0.2	631	598	<10	133	31	<5	<0.5	2.9	<0.5	34	<1	3	16	146	17	15	3.9	1.3	0.6	2.8	0.46
92VKO8-1	1	2	585921	5611889	0.10	<2	45	4	78	8	<1	34	5.8	1.0	467	653	20	120	29	<5	<0.5	5.2	1.2	42	<1	3	15	69	15	15	2.7	0.8	<0.5	2.9	0.44
92VKO8-4	1	3	585900	5612159	0.24	<2	16	4	29	3	<1	10	2.5	0.5	562	332	29	120	22	<5	1.4	5.2	2.1	39	<1	4	3.2	18	24	14	2.4	0.8	0.6	2.5	0.40
92AP167/83	1	3	585130	5612360	1.09	<2	8	3	37	4	<1	16	2.6	0.4	774	394	30	167	23	<5	1.6	4.3	1.8	35	<1	4	3.5	32	21	14	5.7	2.1	<0.5	2.1	0.33
92AP07/1-27	2	1	578376	5617526	0.007	<2	44	3	120	71	<1	125	1.4	0.3	41	371	<10	143	35	10	2.9	1.1	<0.5	35	<1	4	48	386	12	16	5.7	2.1	1.1	4.0	0.60
92AP22/1-140	2	2	579223	5618229	0.013	5	111	3	78	87	<1	241	<0.5	0.1	46	409	<10	98	25	8	0.8	0.7	1.0	15	<1	2	27	281	6.5	10	2.9	1.0	<0.5	1.9	0.26
Spillitized Matched Pair																																			
92AP19/2-119	1	1	586779	5608443	0.003	<2	51	3	78	33	<1	21	<0.5	0.1	542	588	<10	99	28	<5	1.3	1.8	0.8	32	<1	3	28	222	14	18	4.2	1.5	0.6	3.2	0.49
92AP19/2-120	1	4	586779	5608443	0.006	<2	53	6	77	4	<1	19	<0.5	0.3	329	478	<10	93	27	<5	<0.5	1.7	1.0	27	<1	1	27	196	13	16	4.1	1.5	<0.5	3.2	0.51
Hydrothermally Altered																																			
91AP41a	1	4	580931	5613075	0.050	10	20	8	14	1	20	24	3.0	<0.5	16	16	<10	125	<10	<5	<15	<15	<15	<15	<5		<5	83	<15						0.64
91AP20/6-95	1	4	580931	5613075	0.020	<5	5	<6	8	1	11	22	2.0	2.0	27	26	<10	249	12	15	<15	<15	<15	<15	<5		<5	<5	<15						0.55
92AP19/1-109	1	4	587379	5609236	8.16	10	150	17	14	15	<1	34	8.5	4.1	780	558	<10	196	24	6	<0.5	7.1	1.6	57	<1	7	33	189	26	23	7.5	1.9	1.2	3.7	0.64
92AP19/1-110	1	4	587379	5609236	0.19	8	25	23	6	2	3	29	11	19	375	315	<10	234	27	7	1	6.8	2.7	62	<1	8	18	195	28	29	9.0	2.4	1.3	3.4	0.55
92AP19/1-111	1	4	587379	5609236	0.10	16	67	4	10	2	14	26	16	2.7	108	157	<10	360	13	14	1.8	4.8	3.2	7	<1	13	9	113	2.1	18	1.5	0.4	<0.5	2.6	0.46
92AP19/1-112	1	4	587379	5609236	0.04	11	14	9	3	2	13	24	6.3	2.7	106	259	<10	512	21	18	4.2	7.4	4.3	10	<1	18	13	100	3.5	18	0.6	0.7	<0.5	4.5	0.76
92AP19/1-113	1	4	587379	5609236	5.78	<2	130	16	45	6	<1	14	24	1	1203	503	17	254	40	8	1.5	8.6	4.4	64	<1	8	16	114	30	20	6.8	1.7	1.1	5.2	0.81
92AP19/1-114	1	4	587379	5609236	6.87	<2	114	39	12	14	2	10	13	0.4	1862	41	20	220	33	<5	1.2	7.8	3.1	66	<1	8	13	95	31	21	6.1	1.8	0.9	4.9	0.79
92AP19/1-115	1	4	587379	5609236	6.99	4	167	30	70	24	5	21	17	0.5	40	147	<10	164	30	8	1.2	4.0	2.0	34	3	6	16	177	18	14	4.6	1.6	0.9	3.8	0.62
92AP19/1-116	1	4	587379	5609236	1.72	<2	35	3	42	9	4	31	4.4	0.1	103	300	11	197	42	7	1.3	6.8	2.1	66	2	4	27	185	30	26	7.4	1.7	1.4	4.3	0.15
92AP19/1-117	1	4	587379	5609236	0.57	<2	72	4	34	9	<1	28	6.3	0.5	630	266	30	191	35	8	1.5	5.8	2.9	37	2	6	21	170	20	19	5.4	1.4	<0.5	4.1	0.64
92AP19/1-118	1	4	587379	5609236	1.82	<2	136	4	18	5	<1	29	15	0.9	366		11	184	38	6	<0.5	6.4	2.6	51	4	5	23	176	24	23	5.7	1.7	0.9	4.2	0.69

* Map Unit: 1 = Bonanza volcanics; 2 = Karmutsen basalt;

** Rock Type Classification from TAS diagram: 1 = basalt; 2 = basalt/andesite; 3 = rhyolite/dacite; 4 = hydrothermally altered

All values in ppm except where noted

Analytical Methods: Sr, Rb, Zr, Y, Nb, Cr - XRF on fused disk (B.C. GSB laboratory)

As, Au, Sb, Ce, Cs, Sc, Ta, Th, U - thermal neutron activation (Activation Laboratories Limited)

Assay for Cu, Pb, Zn, Ni, Mo, Ag - by hydrofluoric - nitric - perchloric - hydrochloric digestion atomic absorption spectroscopy

Ba, V - XRF pressed pellet (Cominco Research Laboratories)

Elements not detected (below detection limit): Hg <1ppm, Ir <5ppb, Bi <5ppm, Se <3ppm except for samples 92AP19/1-109 @ 17ppm and 92AP19/1-115 @ 64ppm, all Ag <= 0.2ppm

91AP41a: F = 2800ppm, Hg <20 ppb, Te < 0.3 ppm; 91AP20/6-95: F = 660ppm, Hg = 60ppb, Te < 0.3ppm

Note for petrochemical studies and calculations of mass balance/flux, that titanium and possibly other immobile elements do not appear to be conserved, but rather are enhanced in the most strongly altered rocks. This observation is consistent with the modal abundance of rutile and other titanium species in the vuggy, siliceous rocks. Zirconium is probably not conserved either in the most silicified rocks, with up to 512 ppm zirconium in association with 2.8% TiO_2, but only 21 ppm yttrium.

MINERALIZATION

PORPHYRY COPPER DEPOSITS

Porphyry copper deposits are the dominant mineral deposit type in the belt of Jurassic Bonanza volcanics and Island intrusions in northern Vancouver Island. The 'volcanic-type' porphyry copper deposit (Sutherland Brown, 1976; McMillan and Panteleyev, 1988) at Island Copper mine is a superior copper-gold-molybdenum mine by British Columbia standards. Porphyry copper prospects with established mineral reserves are those at the Hushamu and Red Dog deposits, 26 and 37 kilometres respectively, to the west of Island Copper mine. Other prospects in the large EXPO claim block at which significant exploration has been done include the NW Expo, HEP and a number of other showings. Skarn deposits in the map area, mainly near Nahwitti Lake, are hosted by Parson Bay, Quatsino and basal Bonanza units; they have received attention in the past for their base metal potential, and recently for precious metals.

ISLAND COPPER

The Island Copper deposit has been described by Fleming (1992), drawing on the previous descriptions of Perello *et al.* (1989) and Cargill *et al.* (1976). The following description is extracted from these works. The mineralization is related to Early Jurassic (*circa* 180 Ma) rhyodacitic quartz feldspar porphyry dikes and related hydrothermal breccias. Initial ore reserves were estimated at 257 million tonnes at an average grade of 0.52% copper and 0.017% molybdenum. At the start of mining, in the near-surface and north end of the mine, gold grades in excess of 0.4 gram per tonne were common; they have diminished during the course of deeper mining. The average gold content (head-grade) for the mine will be about 0.18 gram per tonne (Fleming, 1992). The porphyry copper mineralization is characterized by stockworks, breccias, veinlets, disseminations and fractures with quartz, pyrite, chalcopyrite, molybdenite, magnetite, amphibole (tremolite/actinolite), biotite, chlorite, albite, sericite, epidote and calcite. Some breccias contain quartz, sericite, pyrophyllite, kaolinite and dumortierite, and there are extensive late stage veinlets with zeolite, calcite and hydrocarbon compounds.

Mineralization took place in both the central quartz feldspar porphyry dike and the andesitic hostrocks. The porphyries were emplaced at various stages. Early intrusions are quartz veined, strongly altered and mineralized; later intrusive rocks have fewer quartz veins and are less mineralized. The margins of the porphyritic intrusions are marked by well-mineralized breccias of various types. Intrusive breccias with rounded wallrock and porphyry fragments form hydrothermal pipes or dike-like bodies. Intrusion breccias with clasts contained in an igneous matrix are also present. The younger breccias with pyrophyllite, kaolinite, sericite and dumortierite occur in the uppermost and northern parts of the deposit. They contain quartz feldspar porphyry fragments and are interpreted to be phreatomagmatic hydrothermal bodies.

Hydrothermal alteration assemblages are centred on and zoned away from the central porphyry intrusions. The central, and early, alteration is a quartz-amphibole-magnetite assemblage with biotite, albite, apatite and much of the sulphide mineralization. This alteration grades outward into chlorite-pyrite ± magnetite, albite, calcite and further away, a propylitic assemblage characterized by abundant epidote. Mine staff regard this central, largely intrusion-hosted, chalcopyrite-rich mineralization to be a 'potassic' alteration due to the presence of abundant magnetite, biotite and hairline fractures filled with potassium feldspar (J. Fleming, personal communication, 1991). An intermediate stage alteration with quartz-sericite ± chlorite and kaolinite is associated with stockworking that grades locally into brecciation. It crosscuts, overlaps and locally flanks the central alteration zone. This intermediate stage has introduced some additional pyrite, molybdenite and chalcopyrite as fracture fillings. The late stage alteration is characterized by pyrophyllite, kaolinite and a distinctive, blue-coloured dumortierite-bearing, advanced argillic assemblage for which this deposit is renowned. It forms a carapace over much of the ore zone and is thought to be a very shallow, subvolcanic feature.

HUSHAMU

The Hushamu deposit consists of two partially overlapping components. The deeper part of the prospect, the Hushamu deposit *sensu stricto*, is a porphyry copper-gold-molybdenum deposit. Mineral reserves are stated to be 172.5 million tonnes with an average grade of 0.28% copper, 0.34 gram per tonne gold and 0.009% molybdenum (Dasler *et al.*, in preparation). The porphyry copper zone is exposed along the valley bottom near a small lake known locally as Hushamu Lake. The intermediate to uppermost part of the deposit, on Mount McIntosh, is transitional into an enargite-bearing, acid sulphate, high-sulphidation epithermal zone. A description of the deposit by Perello (1992) refers to multiple stage stockworks with quartz-magnetite-chalcopyrite-pyrite fracture fillings and disseminations hosted by feldspar and feldspar-quartz porphyries and andesitic volcanics. At least part, if not most, of the deposit to the north of Hushamu Lake is

hosted by diorite to quartz diorite of the Island Plutonic Suite. The most intense alteration in the diorite is seen as fractures and quartz stockworks carrying magnetite, amphibole, pyrite and chalcopyrite and surrounded by alteration envelopes containing albite, chlorite and epidote. Elsewhere, pervasive chlorite, albite and illitic clays are predominant. This alteration is locally overprinted by quartz-sericite ± kaolinite and rutile alteration with associated pyrite and minor chalcopyrite (Perello, 1992).

RED DOG

The Red Dog deposit has reported geological reserves of 31.2 million tonnes with an average grade of 0.313% copper, 0.446 gram per tonne, gold and 0.007% molybdenum (Crew Natural Resources Ltd., prospectus, 1992). The principal minerals of economic importance are chalcopyrite and molybdenite. In addition, fine-grained bornite and traces of (primary) covellite have been noted. The deposit is centred on Red Dog Hill, in an east-southeast-trending zone of silicification and quartz-eye, quartz feldspar and 'syenitic' dike intrusions within a larger feldspar-hornblende-phyric stock of medium-grained diorite to monzonite composition. Other investigators have described the altered rocks in the mineralized zone as 'andesite'. If this is the case, the strongly altered rocks are either andesitic dikes or pendants within the larger stock, 2 kilometres in diameter. Hydrothermal alteration in the mineralized zone has produced silicified breccias and stockworks of dominantly crystalline quartz and magnetite ± pyrite or quartz with either pyrite or hematite. Some of the hematite is strongly magnetic, suggesting an intermediate Fe_2O_3 phase is present - maghemite (γFe_2O_3). Hostrocks to the silica-rich altered zones are themselves silicified and have albitic plagioclase, sericite and variable chlorite, epidote and ankeritic carbonate. Crosscutting steeply dipping, east-trending fracture sets and altered bands contain quartz, pyrophyllite, sericite and kaolinite. These advanced argillic alteration sections appear to be, at most, a few metres wide. Late fractures and veins with pink laumontite selvages and calcite filling are abundant around the margins of the deposit.

HEP

In the area between the Red Dog and Hushamu deposits to the south and west of Nahwitti Lake, there is a belt about 7 kilometres long that contains propylitically altered Bonanza volcanic rocks. Within this belt are zones with pyritic stockworks, and locally, magnetite-amphibole ± hematite and widespread albitic alteration. The HEP prospect exemplifies this style of alteration. The MINFILE records (92L/078) describe the HEP occurrence as "(intruded) volcanics with propylitic, argillic and silicified units with widespread chlorite-epidote-zeolite". Pyrite, magnetite, chalcopyrite, molybdenite and lesser bornite are reported to be present, mainly as fracture fillings in sheared rocks. Some new logging roads to the north and northwest of the Hushamu

deposit and southwest of Nahwitti Lake expose notably widespread albitization in roadcuts and quarry pits. The albitization is recognized as a bone-white to buff, 'cherty-appearing', hard, vein-like to pervasive alteration that destroys original rock textures and fabrics in the andesitic, dioritic and thin-bedded sedimentary hostrocks. The albitic bleaching within larger zones of pervasive chlorite wallrock alteration is accompanied by fracture and vein-filling pyrite, epidote, calcite and minor white fine-grained micas. This is a more intense form of the regionally extensive propylitic alteration that is commonly peripheral to many of the other Island intrusions in the study area. In the lower intensity propylitic zones there is commonly widespread, but overall sparse development of hairline to thin quartz and quartz-calcite veinlets, some containing pyrite and minor chalcopyrite, galena and sphalerite. Widely spaced fractures and stockworks with calcite and the zeolite minerals laumontite or stilbite are common throughout the area.

HIGH-SULPHIDATION EPITHERMAL DEPOSITS

High sulphidation (Hedenquist, 1987) epithermal mineralization, also known as acid sulphate (Heald et al. 1987), Nansatsu-type and a number of other terms (White, 1991, and references therein), is present in some of the siliceous, advanced argillic alteration zones studied. The most notable are those at Mount McIntosh and in the Pemberton Hills area (Panteleyev and Koyanagi, 1993; Perello, 1992, and other unpublished company reports). Mineralization consists predominantly of pyrite as veins, disseminations, breccia matrix, crystalline open-space filling and massive to semi-massive rock replacements. Marcasite is present locally, generally as banded veinlets and fine-grained overgrowths on pyrite grains and rims on rock fragments in breccias. Pyrite commonly forms 5 to 10 volume per cent of the rock; there can be as much as 30% and locally, more. Typical high-sulphidation assemblages, those derived from strongly oxidized hydrothermal fluids with high sulphur to metal ratios, have deposited small amounts of enargite, chalcocite, covellite and bornite. Iron oxide minerals are locally abundant as both magnetite and hematite. The abundance of iron oxides is generally inverse to the amount of pyrite present. 'Limonitic' minerals, including goethite, lepidocrocite, other amorphous hydrous ferric oxides, earthy hematite and jarosite (Blanchard, 1966) are abundant. The minerals are thought to be mainly supergene although a hypogene origin for some of the crystalline limonite might be argued. The presence of limonite at depths of 200 metres or more, demonstrates the great extent to which groundwaters have been able to penetrate and leach the mineralized zones. Minor alteration minerals present are rutile, other opaque and semi-opaque iron-titanium (?) oxides, iron sulphates (melanterite and rozenite) and native sulphur.

MOUNT MCINTOSH

The landscape and geology at Mount McIntosh are an expression of the upper part of the Hushamu porphyry copper system - a high temperature, advanced argillic alteration zone. The peak of the mountain is the uppermost part of the system, complete with hydrothermal and phreatomagmatic breccias. The strongly silicified, vuggy, acid-leached rocks there with underlying weakly developed high-sulphidation mineralization appear to be the epithermal part of the porphyry-related system. To the southeast about a kilometre, at the South McIntosh zone, there is an east-trending, steeply dipping silica-kaolinite-alunite 'ledge' 1300 metres long. This zone, 20 to 100 metres wide, is discordant with the trend of the host volcanic units. It defines a rhyolitic dike intrusion or swarm of intrusions and their coincident autobrecciated, magmatic-hydrothermal to magmatophreatic equivalents. Alteration in the core of the zone produced vuggy, mainly residual, silica rock with fine-grained crystalline to patchy alunite and kaolinite. The silicified rocks are surrounded by clay-altered rocks. They grade outward over a few metres from zones of dominantly kaolinite into zones with illite-chlorite, chlorite and finally, the widespread propylitic alteration with epidote, calcite and late laumontite veins that is prevalent in the area. Fine-grained pyrite, which locally constitutes up to 15% of the clay-altered rocks, is apparently the only sulphide present.

PEMBERTON HILLS

In the Pemberton Hills area there is exploration interest in, from east to west, the Wann property and the Pemberton East and West Pemberton zones of the EXPO claims. Hydrothermal alteration in the area is dominated by pervasive kaolinite, and locally, alunite as bedding replacement, fracture and breccia-matrix fillings. Locally there is considerable, although not pervasive, acid leaching with residual vuggy silica textures. In places the porous rocks contain native sulphur; locally it constitutes up to 5% of the rock. Perello (1992) reports the occurrence of diaspore, anhydrite and widespread illite and (peripheral) chlorite.

Two types of pyritic mineralization are associated with the advanced argillic alteration (Figure 3). In one type, siliceous breccias and pyritic stockworks crosscut the rhyolitic and underlying interlayered intermediate to mafic rocks and dioritic to monzonitic intrusions that make up the Pemberton Hills. In one locality immediately west of Youghpan Creek, one of the pyritic stockworks contains native gold together with arsenian alunite (schlossmacherite) (Panteleyev and Koyanagi, 1993). In the creek bed 250 metres to the northeast, there is also much stockworking and breccia-matrix replacement by pyrite, marcasite and the iron sulphate minerals melanterite and rozenite. The second style of mineralization is stratabound pyritic replacement of fragmental beds within the basal part of the rhyolite unit

and its underlying tuffaceous succession. The tuffaceous rocks comprise laminated to thin and thickly bedded tuffaceous sandstone, wackes, carbonaceous mudstones and minor conglomerates. The most visually impressive mineralization is present as massive to semi massive pyritic replacements. These have an evident lithologically determined, bedding-porosity permeability control. Permeable horizons at a regional or district scale are mainly along the contact zone of the lapilli tuff and breccia units of the basaltic to intermediate Bonanaza volcanics and the overlying rhyolite map units (see Nixon et al., 1994, this volume). In more detail, as evident in diamond-drill cores, the rhyolitic units are replaced along permeable, coarse airfall pyroclastic members and the brecciated flow units that are capped by less permeable, welded ash-flows. Clasts of massive sulphide (pyrite) occur in some of the lapilli tuff and breccia basal members of the rhyolite unit. Some of the sulphide clasts have rims of fine-grained marcasite. This is the best evidence observed that mineralization took place repeatedly in a near-surface, subaerial environment as a synvolcanic process early in the history of rhyolite unit deposition. The subaerial setting negates the possibility, despite the similarity in appearance, that the pyritic replacements in the fragmental rhyolitic rocks and underlying tuffaceous beds are 'Kuroko-type' massive sulphide mineralization. Generally, base and precious metal values in these pyritic, siliceous, clay-altered rocks are uninspiring. Small amounts of chalcocite and covellite have been noted in a few diamond-drill cores. The copper minerals are probably primary rather than supergene as they are associated with minor amounts of enargite.

STRUCTURAL CONTROLS

The distinctive advanced argillic hydrothermal alteration occurs in permeable rocks above high-level magma chambers that have given rise to extrusive rhyolite, coeval quartz feldspar and feldspar porphyry dikes and possibly the underlying (altered) dioritic stocks. There are abundant rhyolitic units in the Bonanza stratigraphic section throughout northern Vancouver Island but in Quatsino map area the rocks are only locally clay-altered and, even less commonly, have undergone advanced argillic alteration. The larger scale control on alteration in the study area might well be faults that control the distribution of the bedded, tuffaceous sedimentary map unit that underlies rhyolites of the Pemberton Hills. The existence of a maar diatreme complex in this area has been suggested by Perello (1992). However, project regional mapping (Nixon et al., 1994, this volume) shows that the tuffaceous sediment unit occupies a linear map trend and the rocks are neither equant nor circular in their distribution as would be the case in a maar setting. The bedded rocks are more likely deposited in a graben, or similar fault-bounded basin, possibly a caldera or series of nested calderas, along the trend of the andesitic volcanic arc. The rhyolite assemblage that overlaps the structurally

bounded tuff-inundated basin forms the thick flow-dome complexes with flanking welded and coarse pyroclastic deposits that define the Pemberton Hills. Within this structural setting, the most important control on movement of hydrothermal fluids and on alteration is the inherently high permeability of coarse subaerial pyroclastic, and possibly lacustrine, volcaniclastic rocks as well as the structurally imposed permeability.

Additional permeability has been created by the congruency of high and low-angle faults, late dike emplacements and the extensive systems of fractures and hydrothermally brecciated and leached rocks that acted as effective fluid conduits. Explosive hydrothermal fluid conduits, presumably above intrusive bodies, are marked by clusters of small, individual breccia bodies or breccia complexes. Those on Mount McIntosh are considered by Perello (1992) to be of various ages and are, in part, intramineral in age. The breccias contain mineralized fragments of various lithologies and are cut by moderately mineralized, quartz-veined porphyry dikes, younger breccias and pebble breccias. Most commonly observed in the intensely altered, silicified rocks are late, crosscutting, strongly milled pebble breccias in which there are abundant pervasively silicified clasts. A number of the most strongly leached, vuggy silica zones, commonly containing breccias, trend westerly and crosscut the regional east-southeasterly trending lithologic and alteration patterns. Within these zones, individual subvertical quartz veins and open space fractures and dilations commonly form at 070°.

Other sites of mineralization with some degree of structurally focused fluid flow are lithologic contacts, commonly those between intrusive stocks and their volcanic hostrocks; unconformities, notably those inferred between the andesitic and rhyolitic or bedded tuffaceous successions; and permeable inerstratal beds, especially those in contact with impermeable units that act as aquitards.

GENETIC INTERPRETATIONS

A current hypothesis is that the extensive clay alteration and related high-sulphidation copper-gold-silver epithermal mineralization in the study area are derived from fluids generated by intrusions of the Island Plutonic Suite. The intrusions are considered to be coeval and cogenetic with the rhyolitic, upper units of the Bonanza volcanic assemblage. The implicit genetic relationship between the subvolcanic high-sulphidation

epithermal and porphyry copper mineralization is being tested. Age relationships are being determined by radiometric dating of intrusive hostrocks and hydrothermal alteration minerals using K-Ar and ^{40}Ar-^{39}Ar techniques. Preliminary age determinations from a few of the samples submitted for age determinations are shown below (Table 2). The results to date suggest that either the porphyry copper mineralization is considerably younger than any Early Jurassic Bonanza subvolcanic events, or the radiometric ages are reset by thermal overprinting.

Sources of hydrothermal fluids and the genesis of the mineral deposits can be interpreted from light stable isotopic studies. Preliminary results from a 20-sample suite submitted for analysis indicate that there is much variation in 'clay' minerals. The range in values from 4.6 to 12.7 per mil $\delta^{18}O$ is possibly due to combining both hypogene and supergene clays in the sample suite. The values of δD show a very narrow range from -49 to -77 per mil, possibly indicative of origin in warm latitudes. Work on additional clay, quartz, sericite, hornblende and alunite mineral separates is ongoing and genetic interpretations await the completion of he analyses.

DISCUSSION

Much of the advanced argillic alteration observed in the study area, and the associated (weakly developed) high-sulphidation mineralization, appears to be magmatic-hydrothermal in origin, is related to intrusions and took place during late porphyry copper mineralization and hydrothermal brecciation. Examples are the Mount McIntosh and Red Dog deposits. This type of mineralization in the upper parts of porphyry copper-gold deposits is commonplace in western Pacific island arcs (Sillitoe, 1989), Chile (Sillitoe and Camus, 1991), and elsewhere (Mitchell, 1992). In the Pemberton Hills area, strongly pyritized, siliceous rocks containing crystalline, pink alunite in veins, stockworks and as breccia matrix appear to be a similar alteration. This, too, is likely to be magmatic-hydrothermal in origin, at least in part. But elsewhere in the Pemberton Hills, where native sulphur is abundant, sulphate minerals are present, and much of the kaolinite and alunite occurs as fine-grained to massive, white, bedding-plane replacements, there is a strong likelihood that the alteration and attendant acid leaching are derived from vapour-dominated groundwater systems. There is little potential for ore deposition in this 'geothermal' setting,

Island Plutonic Suite - Hushamu stock:	sericite (alteration)	~171 Ma ^{40}Ar-^{39}Ar plateau age
Island Plutonic Suite - Hushamu stock: (or plagioclase-hornblende porphyry dike)	hornblende	~172 Ma ^{40}Ar-^{39}Ar plateau age
Island Intrusive Suite - Mead Creek stock: hornblende		168 ±4 Ma K/Ar conventional dating

K/Ar age by J. Harakal, the University of British Columbia; Argon plateau dates from P. Reynolds, Dalhousie University

but ample barren pyrite can be deposited. Sillitoe (1993) outlines how to recognize the various alunites present in the different geological environments and describes other shallow features of epithermal deposits. The origins of alunite and acid sulphate alteration, and the implications on ore potential of their genetic differences in advanced argillic zones, are reviewed by Rye *et al.* (1992) and Thompson (1992).

Enlightening examples that emphasize the large size of the advanced argillic alteration and related high-sulphidation mineralization that is possible are contained in the discussions of the Negros-Masbate arc (Mitchell and Leach, 1991) and Mankayan district, Lepanto deposit (Garcia, 1991), the Philippines. Note that the lateral extent of acid leaching and mineralization commonly far exceed their vertical dimensions. In the Negros-Masbate region, silicified, acid-leached rocks, mostly unmineralized except for pyrite, marcasite, sulphur and some sulphate minerals, form prominent topographic features over a distance of about 300 kilometres along the trend of the andesitic arc (Mitchell, 1992). At Lepanto, a silicified ledge containing enargite-gold mineralization within a zone of advanced argillic alteration occurs over a distance of 6 kilometres (Garcia, 1991). The size and origins of other, similar zones of recent alteration and mineralization in the Philippines are summarized in studies of active geothermal wells and fields by Reyes (1990). Her discussions are especially revealing about the detailed mineralogy, alteration zoning, structural controls and both the lateral and vertical extents of acid leaching in recent and active, acidic hydrothermal systems. In comparison, the size and geometry of the advanced argillic alteration systems in our study area very closely resemble many of the features in the Tongonan, Palinpinon and other wells she describes. Figure 3 incorporates some of Reyes' observations into a model for the geometric and fluid-flow relationships of typical northern Vancouver Island advanced argillic zones.
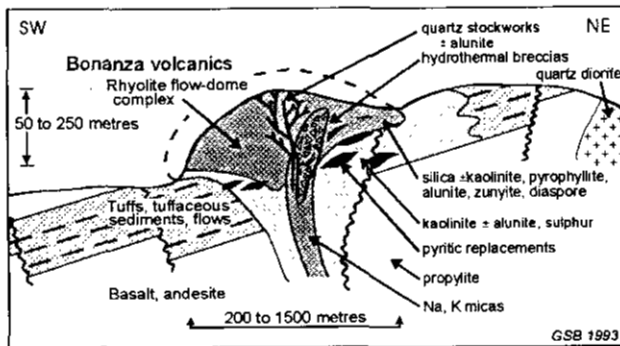

Figure 3. Schematic relationships between permeable lithologies, volcanic structures, hydrothermal conduits and mineralization in the Pemberton Hills; adapted, in part, from Reyes (1990).

Mitchell (1992) illustrates the spatial relationships between mineralized magmatic-hydrothermal systems and barren vapour-dominated, acid leaching environments in 'perched aquifers'. The relationships of mineralized and barren alteration zones with respect to the (hydrothermal) groundwater table, as described by Mitchell, are illustrated on Figure 4. In this model, the intrusion of epizonal stocks or dike complexes initiates magmatic fluid flow and produces a central porphyry-type mineralized zone with peripheral, meteoric fluid-dominated propylitic alteration. Magmatic acidic gases at depth and in the higher level fluid conduits, as well as gas condensates near surface, form acid sulphate alteration with accompanying acid leaching of the hostrocks. The resulting, commonly stacked, zones of advanced argillic alteration can be later mineralized below the water table by magmatic hydrothermal fluids but are barren nearer the surface in the zone of 'boiling' vapour-dominated fluids and groundwater dilution.

Other recent investigations concerning the origins of advanced argillic and acid sulphate alteration, with instructive discussions about exploration for epithermal deposits in this setting, are those by White and Hedenquist (1990), Matsuhisa *et al.* (1991) and Giggenbach (1992).
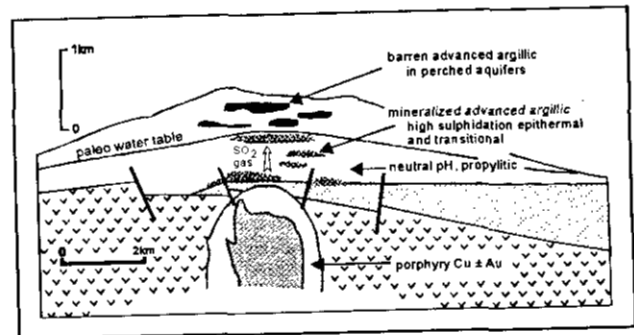

Figure 4. Generalized model for advanced argillic lithocaps showing the relationships between intrusions, porphyry copper deposits, alteration zones and the (hydrothermal) water table; after Mitchell (1992).

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