Copper-gold mineralization in the Willa breccia pipe, southeastern British Columbia

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ABSTRACT

The Willa intrusive breccia-hosted gold-copper-silver deposit occurs within a pendant of Lower Jurassic Rossland Group volcanic rocks enclosed within granitic rocks of the Middle Jurassic Nelson Batholith. The breccia is a pipe-like body and occurs at the centre of a hypabyssal complex of quartz and feldspar porphyritic intrusions considered to be coeval with the volcanic rocks of the pendant.

Three main phases of intrusion and two distinct systems of sulphide mineralization are recognized within the pendant on the Willa property. The earliest phase of intrusion consists of quartz latite porphyry as ring and radial dikes cutting andesitic volcanic rocks and is genetically-related to a weak system of quartz-molybdenite mineralization and associated weakly to moderately developed phyllic alteration. This system is cut by a small, plug-like body of feldspar porphyry marked locally by moderately to intensely developed pervasive potassic alteration and incipient brecciation. Intrusive into and incorporating fragments of all these rocks, including examples of quartz-molybdenite mineralization, is a body of hydrothermal intrusive breccia. Auriferous and argentiferous chalcopyrite, pyrite, and magnetite mineralization comprise three zones within and peripheral to the breccia pipe. All zones are associated with a pervasive calc-silicate alteration, consisting of actinolite, diopside, epidote, and andradite garnet or anhydrite, which has over-printed the earlier phyllic and potassic events.

The two phases of mineralization, though evolving from a single intrusive complex of calc-alkalic affinity, are separated by a period of intrusion of feldspar porphyry, a change from K- to Ca-metasomatism and volatile brecciation.

Introduction

The Willa gold-copper-silver deposit is in mountainous terrain and centred near the headwaters of Aylwin Creek, which flows westerly into Slocan Lake, approximately 12 km south of the town of New Denver in southeastern British Columbia (NTS: 82F/14W; 49°53′N, 117°22′W). Access is via Highway 6, which passes through the western portion of the property (Fig. 1). Occurrences of copper on the rusty cliffs along Aylwin Creek were first discovered and staked by prospectors in 1893. By 1898, tunnels had been driven on the Willa, Rustler and Rockland Crown Grants and appreciable gold values associated with chalcopyrite reported. Granby Consolidated examined the showings in 1901 and 1912 but turned the prospect down because of low grades. The property remained dormant until 1955 when Egil Lorntzen re-opened and sampled two of the three tunnels. Again, only low gold values were obtained and no further work was done. From 1964 to 1970, Cominco, Amax Exploration Inc., Riocanex, and Western Canadian Mining Company, in turn, examined the prospects or conducted surface exploration, including limited shallow diamond drilling, and, although surface chip sampling returned up to 5.83 g/t Au and 0.37% Cu over 30.5 m, the property was returned to the various owners each time. During the late 1970s, the key claims of the present property were assembled by local prospectors, P. Leontowicz and W.C. Wingert. In early 1979, on the recommendation of J.R. Woodcock, a consultant to Riocanex (now Rio Algom Exploration Inc.), the central Crown Grants were optioned by Riocanex as a deep porphyry molybdenum target. BP Minerals Ltd. staked surrounding ground at the same time, also believing in the porphyry molybdenum potential of the area. The interlocking land holdings were combined under a joint venture agreement in late 1979. Initial diamond drilling by the joint venture in 1980, comprising two deep holes to test for buried molybdenum mineralization, intersected 2.5 g/t Au, 0.67% Cu, and 10.0 g/t Ag over a 54 m drill interval at a shallow depth. This was hosted within a heterogeneous intrusive breccia, which was also seen to contain clasts of quartz latite porphyry with molybdenite in a quartz stockwork. From 1980 to 1984, the joint venture completed 14 300 m of surface diamond drilling in 47 holes to further delineate the breccia body and its associated Cu-Au mineralization (Spence, 1982; Wong 1983, 1984). In early 1985, Northair Mines Limited became a third joint venture partner and embarked on a program of underground exploration. From 1985 to 1987, approximately 1550 m of tunnelling and 15 000 m of underground diamond drilling were completed and a drill-indicated reserve of 470 400 tonnes grading 5.86 g/t Au and 0.86% Cu was calculated for the West zone, the most significant of three zones of mineralization hosted within or adjacent to the breccia. In 1990, the property was sold by the joint venture to Treminco Mining Ltd. which has continued to hold the property but without further work.

Regional Geology

The Willa deposit is situated within a roof pendant of basic volcanic and felsic hypabyssal rocks (Fig. 1). The preponderance of volcanic and volcaniclastic rocks, especially augite porphyritic varieties, suggests a closer affiliation with the Lower Jurassic Rossland Group volcanic rocks prevalent further to the south, than with the sediment-dominated Triassic Slocan Group which occurs to the north. The pendant is wholly-enclosed and intruded by coarse-grained granodiorite to quartz monzonite of the Nelson Batholith. Rossland Group volcanic rocks form the southern portion of a Mesozoic arc that extends the length of the Quesnellia terrane.

Structurally, the area is dominated by a major, north-trending fault, the Slocan Lake Fault. As defined by Parrish (1984), this fault is a 35° to 40° east-dipping detachment zone of Eocene age. Rocks of the Permian Kaslo, Upper Triassic Slocan and Lower Jurassic Rossland groups intruded by batholithic and plutonic bodies of the Middle Jurassic Nelson Batholith make up the upper plate of this fault. Granitic rocks exposed along the highway on the east shore of Slocan Lake and west of the fault have been dated by

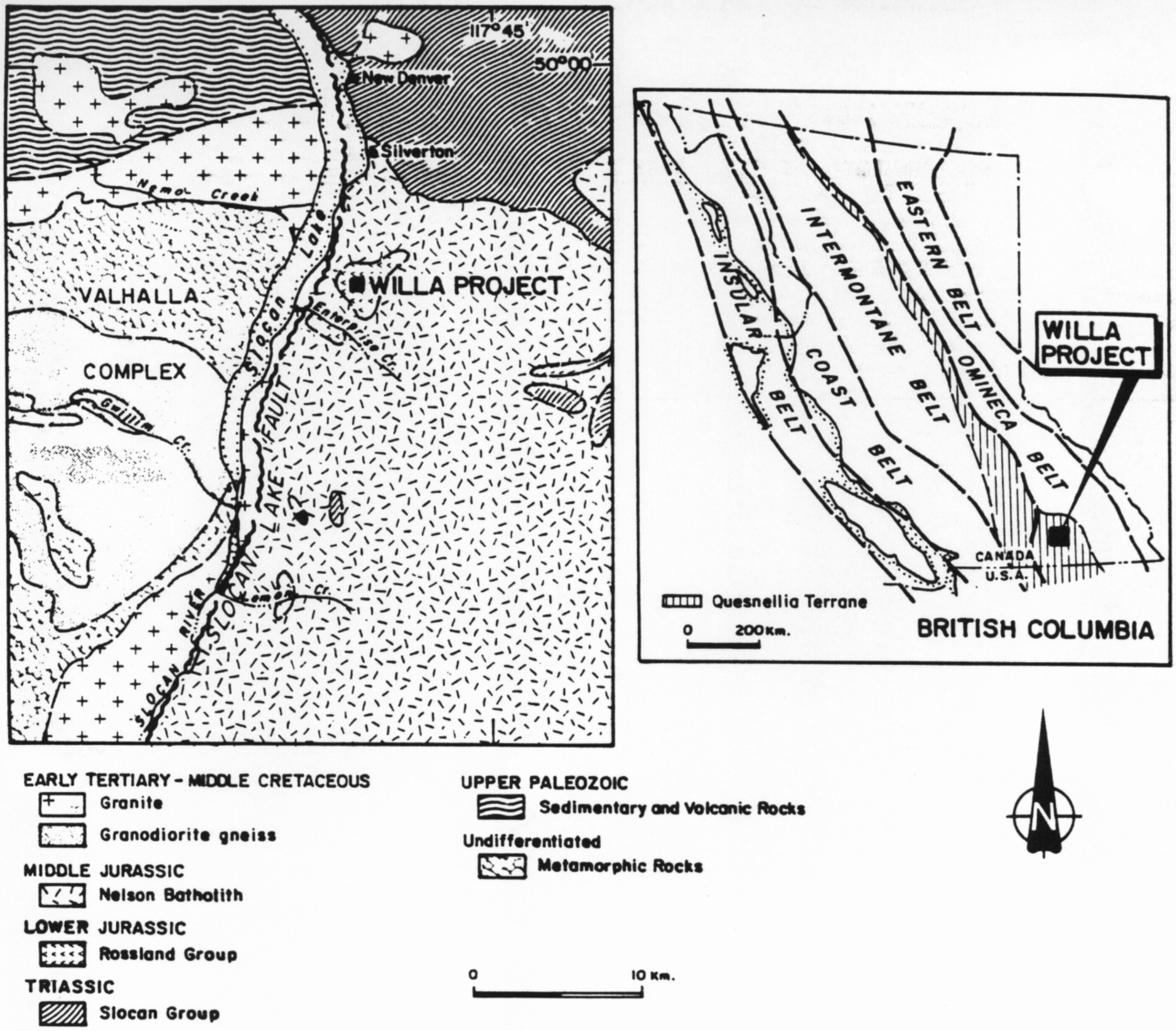

FIGURE 1. Location and regional geology.

U-Pb zircon methods to be as young as 63.5 ± 1 Ma (Parrish, 1984), and together with highly metamorphosed rocks of the Valhalla Complex, form the lower plate. Mafic dikes of probable Tertiary age commonly occur along normal faults developed in the hanging wall of the detachment zone.

Property Geology

The Willa copper-gold-silver mineralization and earlier weakly developed stockwork molybdenite mineralization is associated with a porphyritic felsic intrusive complex preserved within the pendant. The complex, possibly coeval with the Rossland Group, consists of a ring dike and two radial dikes of quartz latite porphyry and, centrally located within these, a plug of feldspar porphyry around which is developed an intrusive breccia (Fig. 2). The breccia crosscuts and contains clasts of both porphyries, including some of quartz latite porphyry mineralized with molybdenite in a quartz stockwork, and the volcanic rocks. Copper-gold mineralization is found in three zones within or at the margins of the breccia (Fig. 3).

Rossland Group

Volcanic rocks that are interpreted to belong to the Rossland Group comprise approximately 75% of the pendant and vary in lithology from flows and coarse breccias and tuffs to volcanic siltstones. Augite porphyry is predominant within the Willa mineralized zone and much of it may be hypabyssal in origin.

Fragmental rocks consist of medium grey to green pyroclastic breccias and conglomerates with monolithic clasts to 50 cm in diameter in an ash matrix, and finely-bedded augite-plagioclase crystal and/or lithic tuffs. Light, grey-green, volcanic siltstones usually comprise thin-bedded units intercalated with either the pyroclastic or augite porphyry lithologies. Graded bedding is occasionally discernible within the siltstones.

Augite porphyry is dark green in colour and consists of 10% to 20%, euhedral to subhedral augite phenocrysts 0.5 mm to 4.0 mm in diameter. Plagioclase phenocrysts are evident locally. The matrix is made up of a fine-grained mixture of augite, feldspar, and magnetite. Augite porphyry comprises irregular discordant bodies, some sill-like bodies, and possible flow units. The presence of hypabyssal augite porphyry central to the felsic intrusive complex may indicate proximity to a volcanic centre.

Chemical analyses of the Willa volcanic rocks by Heather (1985) and reinterpreted by A. Spence (pers. commun., 1985) show them to belong to a mildly alkaline or shoshonitic suite of probable arc affinity.

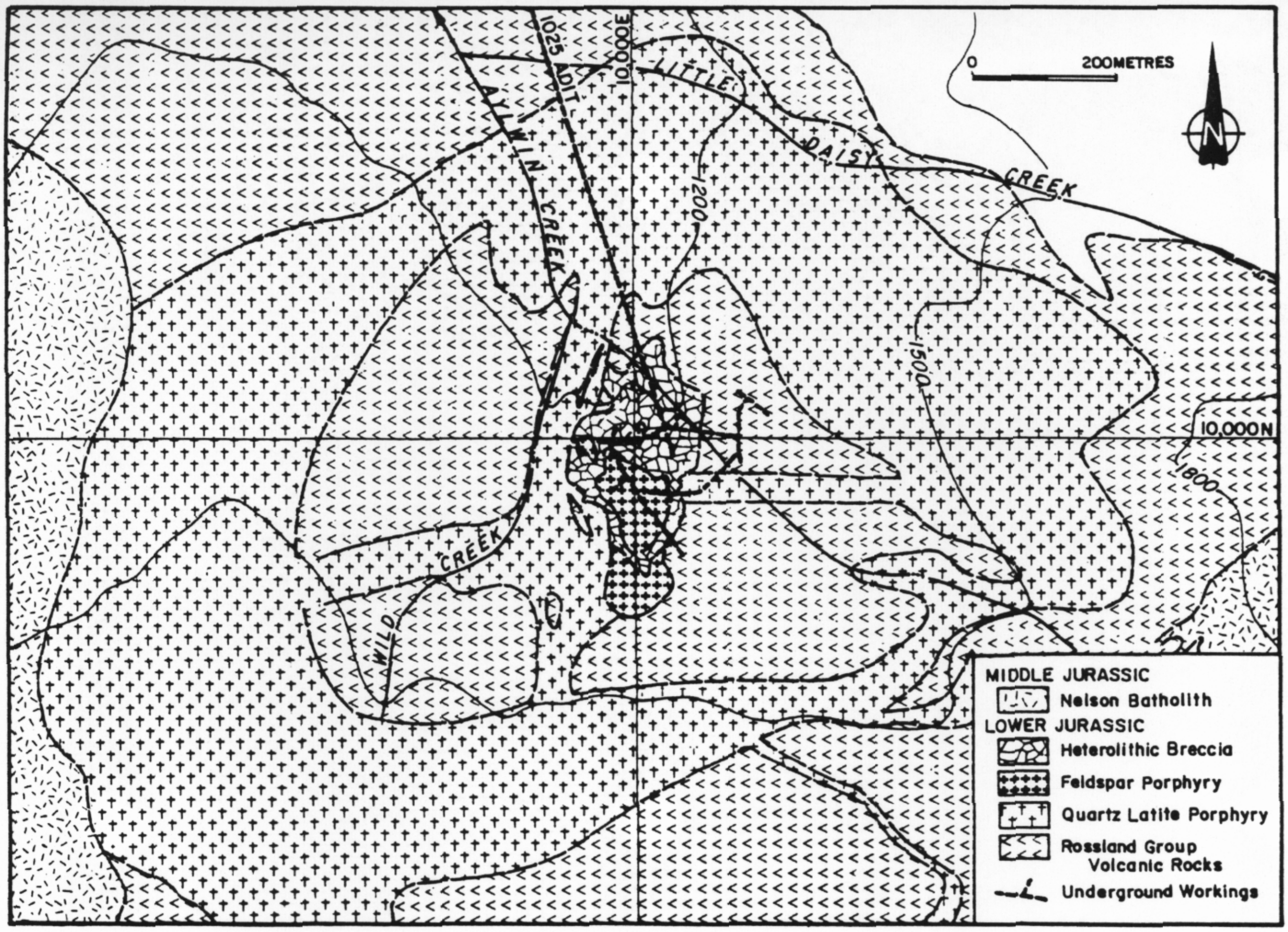

FIGURE 2. Geology of pendant.

Quartz Latite Porphyry

Quartz latite porphyry forms a complex of a ring and radial dikes. The ring dike comprises a continuous sub-circular body approximately 1200 m in diameter (Fig. 2). In plan, the dike ranges in thickness from 75 m in the southeast, to 400 m in the west and northeast. Near the centre of the ring are two intersecting east-west- and north-south-trending radial dikes, each approximately 50 m to 100 m wide. The north-south-trending dike is vertical and appears continuous, while the east-west-trending dike appears to dip to the north at approximately 55° but it has, in part, been disrupted by and assimilated into the later breccia pipe.

Quartz latite porphyry is a generally leucocratic rock distinguished by the presence of rounded quartz phenocrysts from 2 mm to 8 mm in diameter, which make up 5% to 20% of the rock. Plagioclase phenocrysts (An_{32}), 1 mm to 3 mm in length, commonly comprise up to 50% of the rock, and mafic minerals, predominantly hornblende, generally less than 15%. The aphanitic groundmass is made up of K-feldspar, quartz, untwinned plagioclase, and minor sphene and apatite. Textural variations, including variable phenocryst to matrix ratio, variable phenocryst size, and variable proportion of quartz to plagioclase phenocrysts, are evident and are thought to reflect multiple pulses of intrusion.

Feldspar Porphyry

Feldspar porphyry occurs as remnants of a plug-like body with an upward-flaring southern margin and is partially to completely enclosed by the breccia pipe (Figs. 3, 4 and 5). In surface plan, the feldspar porphyry appears as a north-trending, elongate mass approximately 100 m by 225 m divided into two portions by a narrow band of the breccia. Diamond drilling has revealed that the southern portion represents the gently north-dipping flared rim, while the northern portion is relatively deep-seated, extending at least 300 m below surface with nearly vertical contacts.

Distinction between feldspar porphyry and quartz latite porphyry is often difficult. Both rock types may contain hornblende but are generally leucocratic. Feldspar porphyry may contain up to 7% quartz phenocrysts, although these are generally finer-grained (1 mm to 2 mm in diameter) and therefore not as conspicuous as those in the quartz latite porphyry. Plagioclase phenocrysts, averaging 1 mm to 2 mm in length, comprise approximately 25% of the feldspar porphyry, and the groundmass is made up of fine-grained to aphanitic K-feldspar, quartz, plagioclase, with minor apatite and sphene. As with the quartz latite porphyry, slight textural variations are evident.

Where feldspar porphyry and quartz latite porphyry occur in contact with one another, or where hydrothermal alteration has masked original texture and mineralogy, the distinction between these two lithologies is vague. As molybdenum mineralization is clearly associated with quartz latite porphyry and feldspar porphyry clearly post-dates both, the presence or absence of either quartz-molybdenite veining or elevated geochemical levels of molybdenum was often used as a criteria for distinction.

Margins of feldspar porphyry and adjacent quartz latite porphyry or volcanic rock locally display development of monolithic biotitic breccia. This is thought to have resulted from crackle-type fracturing caused by magmatic hydrothermal brecciation and is associated with pervasive biotitic alteration of the matrix. Clasts are subangular to angular, show little rotation, and average 1.5 cm in diameter. This incipient brecciation may be a precursor to the devel-

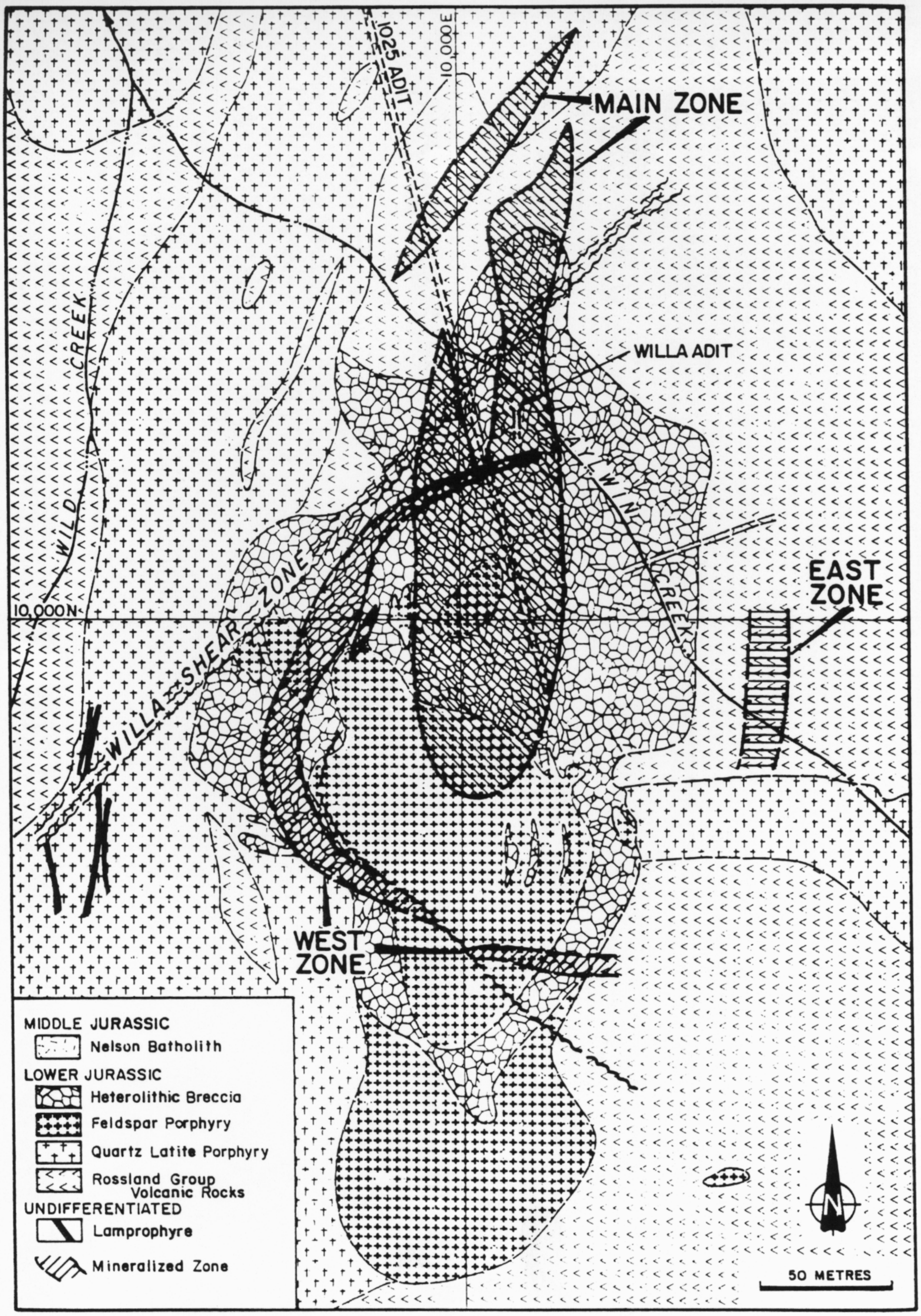

FIGURE 3. Surface geology of Willa area showing generalized projection to surface of mineralized zones.

opment of the heterolithic breccia event which followed emplacement of the feldspar porphyry.

Heterolithic Breccia

Heterolithic breccia occurs in a pipe-like body, located centrally within the ring dike and near the intersection of the two radial dikes. It plunges to the north at about 70° and has a surficial area of about 25 000 m². It has been found by drilling to continue to at least 700 m below surface.

The breccia is well-exposed in Aylwin Creek and in the nearby Willa adit but because of the superposition of a deformation fabric related to what is referred to as the Willa shear zone, early workers assumed the fragmental nature of this rock to be due to tectonic brecciation. Work completed since 1980 has clearly shown the breccia to be magmatic hydrothermal in origin (Durgin, 1981) displaying most of the distinguishing features cited by Sillitoe (1985).

Wallrocks adjacent to the breccia are commonly marked by zones of crackle breccia ranging from one to tens of metres in width. Within these zones, proximity to the breccia is evidenced by increasing fracture density and, nearer the contact, some rotation of clasts. The first presence of other types of clasts was used to denote the limits of the breccia.

Clasts of all of the above described rock types, as well as relatively common clasts of quartz-molybdenite mineralized quartz latite porphyry and rare clasts of a fine-bedded, calcareous sedimentary rock containing disseminated galena and a tan coloured sphalerite along beds are seen in the breccia. This sedimentary rock, which has been seen only in the breccia, may have been derived from a unit at depth. No clasts of Nelson plutonic rocks have been seen in the breccia.

Breccia clasts range in size from large blocks several tens of metres in length to pebble size (Fig. 6a). The largest, relatively intact blocks which could be mapped, were principally of feldspar porphyry and quartz latite porphyry. The margins of these large blocks, particularly their undersides, are commonly crackle-brecciated. Within the pipe, the upper portion of the east-west radial quartz latite porphyry dike is largely incorporated as breccia clasts, though, at depth it is recognized as an intact, north-dipping slab.

The degree of rounding of the clasts varies widely, as does the proportion of matrix to clasts. Matrix typically comprises from 20% to 50% of the rock. It is predominantly pale to dark green, altered rock flour which, in thin-section, is seen to consist of salite-ferrosalite pyroxene or actinolite with lesser plagioclase, quartz, and K-feldspar. At upper levels within the breccia, the matrix commonly has a vuggy nature due to incomplete filling of the inter-clast spaces. Many clasts, especially those more rounded, show a bleaching of their rims. No pattern of either clast rounding or matrix proportion could be mapped. While clasts of the adjacent rocks predominate near the contacts of either the pipe or of large blocks within it, the breccia is generally unsorted. Clast rotation, rounding and mixing suggest considerable movement within the breccia and formation under fluidized conditions. The textural heterogeneity displayed by the breccia is thought to be due mainly to the presence of several large blocks which have served to divert the path and movement of the fluidized breccia into several localized channels.

Nelson Plutonic Rocks

Nelson plutonic rocks crop out on the outer parts of the property and are not seen in outcrop within the Willa mineralized zone. The main phase consists of light to dark grey, K-feldspar megacrystic granodiorite. This rock is made up of 5% perthitic K-feldspar phenocrysts from 1 cm to 3 cm in length within a medium-grained groundmass consisting of 45% to 60% plagioclase (An_{26}-An_{32}), 10% to 25% K-feldspar, 10% to 20% quartz, and 5% to 15% subhedral hornblende and/or biotite. Locally, mafic minerals comprise 20% to 40% of the rock adjacent to the contact with the pendant. Unaltered dikes of a rock type similar to the Nelson granodiorite are observed locally in drill holes to cut the heterolithic breccia.

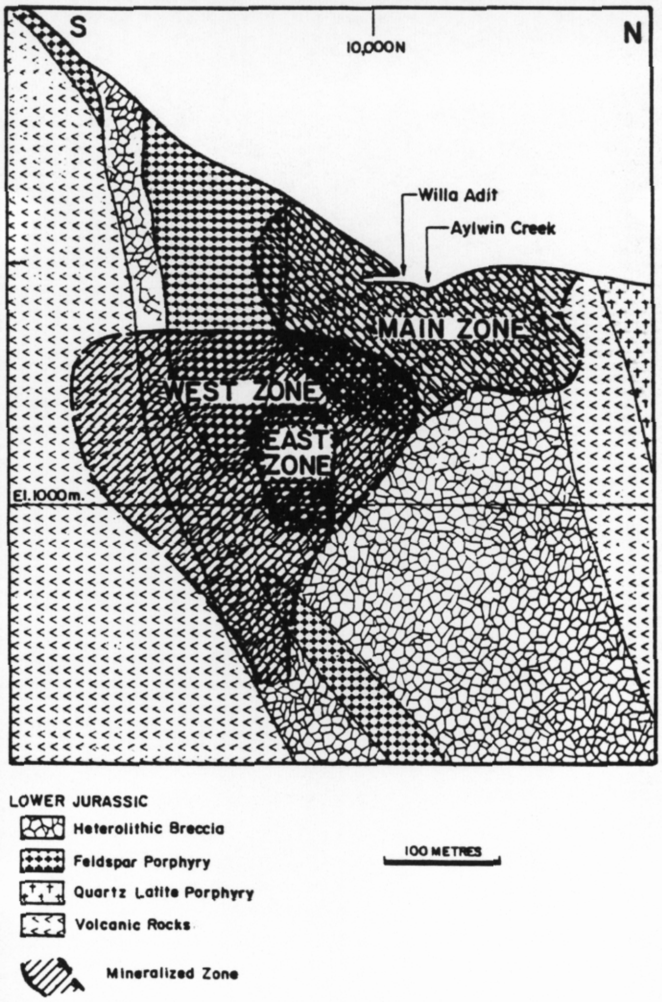

FIGURE 4. Generalized north-south section on 10 000E with projected outlines of mineralized zones.

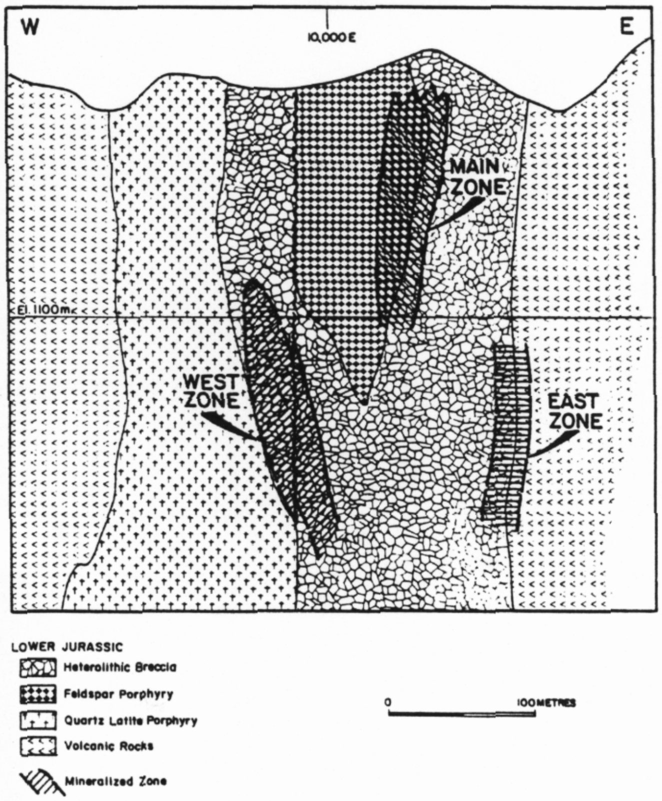

FIGURE 5. East-west section on 9950N.

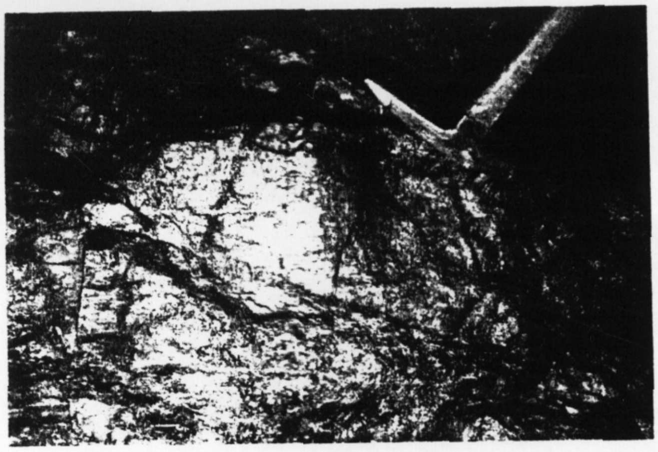

FIGURE 6a. Underground exposure in north end of west zone. Pyrite and chalcopyrite occur in and as matrix in breccia and as fracture fillings *in feldspar porphyry fragments.*

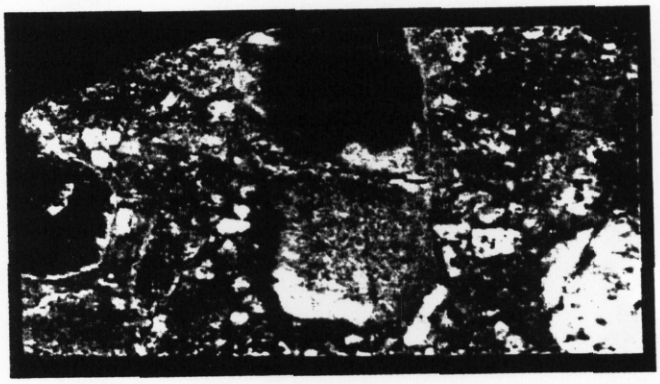

FIGURE 6b. Heterolithic breccia with sub-rounded clasts of metavolcanic rocks and quartz latite porphyry. Note bleached alteration on clast rims. Matrix consists of altered rock flour with pyrite and chalcopyrite. Specimen of NQ drill core approximately 8 cm in length.

Late intrusive phases associated with the Nelson intrusions consist of aplitic and pegmatitic dikes and are found both peripheral to and within the Willa mineralized zone. Dikes ranging in thickness from 5 cm to 20 cm are seen to cut all lithologies except the mafic dikes.

Mafic Dikes

Mafic dikes, commonly referred to as lamprophyre dikes by Cairnes (1935) and others, are ubiquitous throughout the Slocan area. Many such dikes were intersected by drilling and in the underground workings within the Willa mineralized zone, and are clearly the youngest rock present. Dikes range from 10 cm to generally less than 2 m in width, commonly exhibit chilled contacts, and display a predominant north-south, near-vertical orientation. They appear, for the most part, to have been emplaced along young, postmineral faults. Sheared contacts of some dikes are considered to indicate later structural adjustment.

Age

The age of the Rossland Group, as determined by fossil evidence, spans the Lower Jurassic from the Early Sinemurian to the Early Toarcian (204 Ma to 190 Ma) (Tipper, 1984). The Nelson Batholith has been dated by U-Pb and K-Ar dating techniques at 160 Ma to 172 Ma (Armstrong, 1988).

Initial K-Ar and Rb-Sr dating of Willa intrusive rocks at The University of British Columbia (Armstrong, 1981) yielded ages clustered about 153 Ma implying a period of emplacement slightly later than the Nelson Batholith. U/Pb analyses of five zircon fractions from the Aylwin Creek porphyry by Murphy et al. (in press, 1994) plot as a non-linear discordant array. Based on the best-fit lower intercept to a line through the array, Murphy et al. (op. cit.) consider ca 183 Ma as a reasonable minimum age for the Aylwin Creek porphyry. This latter age supports field evidence showing that the Willa intrusive system pre-dates the Nelson plutonic rocks and indicates that the system was coeval with the Rossland Group volcanism. The initial mid-Jurassic age, determined by K-Ar and Rb-Sr techniques, probably represents a resetting of dates by Nelson plutonism and other events possibly related to the Slocan Fault (Woodsworth et al., 1991).

Structure

On a property scale, perhaps the most significant structural feature of the Willa deposit is the ring and radial quartz latite porphyry dike system and the apparent influence it exerted on emplacement of the feldspar porphyry plug and the breccia pipe. The northerly dip and plunge displayed by both the east-west radial dike and the breccia pipe, suggest that the entire system may have been tilted. Bedding determinations from volcaniclastic strata within the area enclosed by the ring dike are rare but steep.

Post-breccia pipe structures are numerous and include mineralized ring and radial(?) fracture zones, and postmineral deformation, fault, and shear zones. Mineralized structures will be discussed in the following section on mineralization.

Postmineral deformation zones, displaying highly variable orientations and widths, are characterized by a moderate to strong biotitic foliation. These zones are best recognized in the volcanic rocks, where fine- to medium-grained, black biotite may locally exceed 30%, and in heterolithic breccia where clasts commonly display a moderate degree of flattening. Drilling has indicated a general increase in the intensity of this deformation with depth and metamorphism, related to the Nelson Batholith, is envisaged as the cause.

High-angle, predominantly north-striking, normal faults, commonly occupied by mafic dikes, are seen to offset the mineralized zones in a number of places. Displacements across these structures are generally in the order of 10 m to 50 m with the western side down-dropped. Extension producing Eocene detachment faulting is considered the probable cause of these structures.

The most prominent postmineral structure is the Willa Shear zone, a near-vertical, northeast-striking zone of intensely fractured rock averaging 10 m to 20 m in width and traceable for at least 350 m. This feature cuts all rock types within the mineralized zone, including foliated rocks and mafic dikes, and is, therefore, the youngest recognized structural event on the property.

Mineralization

Three distinct ages of mineralization are recognized in the Willa area. Molybdenum mineralization and gold-copper-silver mineralization are genetically related to the Lower Jurassic intrusion of the quartz latite porphyry and of the heterolithic breccia, respectively. Argentiferous, lead-zinc, vein-type mineralization, representative of the Slocan Silver Camp, post-dates emplacement of the Nelson Batholith.

Molybdenum

Quartz-molybdenite mineralization occurs scattered throughout the quartz latite porphyry but is perhaps best developed within the north-south radial quartz latite porphyry dike and within hornfelsed volcanic rocks adjacent to the dike. Quartz-molybdenite veins, comprising stockwork or sheeted zones, generally contain minor pyrite and range from 1 mm to 20 mm in width. They are characterized by fine-grained, white to grey quartz with thin selvages and disseminations of fine-grained molybdenite. Sericite, pyrite and clay commonly occur as narrow alteration envelopes to the veins. Two ages of quartz-molybdenite veining are evident. Massive silicaflooded zones occur where stockwork veining is locally intense. An extensive pyritic halo, with pyrite present in amounts up to 10%, partially overlaps quartz-molybdenite zones.

The highest grade of molybdenum intersected during the initial deep drilling was 0.008% Mo. The low grades of molybdenum reflect the weakly developed nature of the molybdenum system. Consequent to the two initial deep drill holes to test for a deep molybdenum deposit, the focus of exploration was shifted to the gold-copper-silver mineralization found within the heterolithic breccia. As a result, detailed information on the molybdenum mineralization is lacking.

Gold-Copper-Silver

The Aylwin Creek pendant hosts two significant gold occurrences. In the northeast portion of the pendant, 2.5 km from the Willa, the LH prospect consists of northeast-striking shears containing gold-arsenopyrite mineralization within volcanic rocks. The Willa gold-copper-silver deposit is notably lacking in arsenic. Between the two is a widespread coincident gold-copper and arsenic in-soils anomaly. The overall distribution of metals suggests a zonation from gold-copper to gold-arsenic within the pendant.

At the Willa, gold-copper-silver mineralization occurs in three distinct zones; the West zone which is a deep, arcuate zone on the western margin of the breccia pipe, the Main zone which is a shallow lens-like zone centred on the breccia axis, and the East zone which is a deep, sheeted-fracture zone within volcanics immediately outside the eastern contact of the breccia (Fig. 7).

West Zone

The West zone contains the highest grade of gold-copper-silver mineralization (overall approximately 1.8 million tonnes averaging 2.93 g/t Au, 0.66% Cu, 9.30 g/t Ag) and is hosted by a steeply inward-dipping, ring-like fracture zone in the breccia and adjacent volcanic rocks, which roughly parallels the western contact of the feldspar porphyry plug. The top of the zone occurs at approximately 1100 m elevation, some 130 m to 200 m below surface.

The West zone averages 150 m in height and has been delineated over a strike length of 250 m. It varies in width at the 1025 m elevation from a maximum of 40 m at its southern end to a minimum of 8 m at its northern end. At its southern end, the zone is truncated by a north-northeast striking fault; while in the north, the zone pinches out along strike but extends upward to form a keel to the overlying Main zone. Due to higher Au:Cu ratios in this northern part, it has been interpreted to be a feeder to the lower grade Main zone mineralization. Overall, the West zone is effectively outlined by a gold grade cut-off of 1 g/t. Lateral contacts are generally sharp with mineralization falling off rapidly within two metres of the zone. Several drill intersections of high-grade gold were encountered at depth near the centre of this arcuate structure suggesting the presence of a feeder conduit for the West zone mineralization.

Within the mineralized zone, sulphides, occurring mainly as matrix replacement, comprise 10% of the rock on average (Fig. 6). Locally however, sulphides may constitute 50% of the rock over lengths of 1 m to 2 m. Pyrite and chalco-pyrite are the principal sulphides present and occur in varying proportions. Pyrrhotite and minor sphalerite generally comprise less than 1%. Traces of a Pb-Bi-bearing Sb-sulphosalt have been identified during examination of polished sections. Magnetite is ubiquitous throughout the heterolithic breccia, averaging 1% to 3%. Intergrowths of magnetite with sulphides indicate that they were deposited contemporaneously.

Gold occurs in native form as inclusions and microveinlets in pyrite, and as grains along contacts between pyrite and either chalcopyrite or silicates. Average gold grain size is 10 microns. Silver values are associated with sphalerite, which commonly occurs as inclusions in chalcopyrite and pyrite.

As a result of their underground exploration, Northair Mines Limited calculated a diluted, weighted, drill-proven mineable reserve of 464 035 tonnes grading an average of 5.93 g/t Au and 0.91% Cu at a cut-off grade of 3.43 g/t Au for West zone (Northair Mines Ltd. News Release, October 20, 1988).

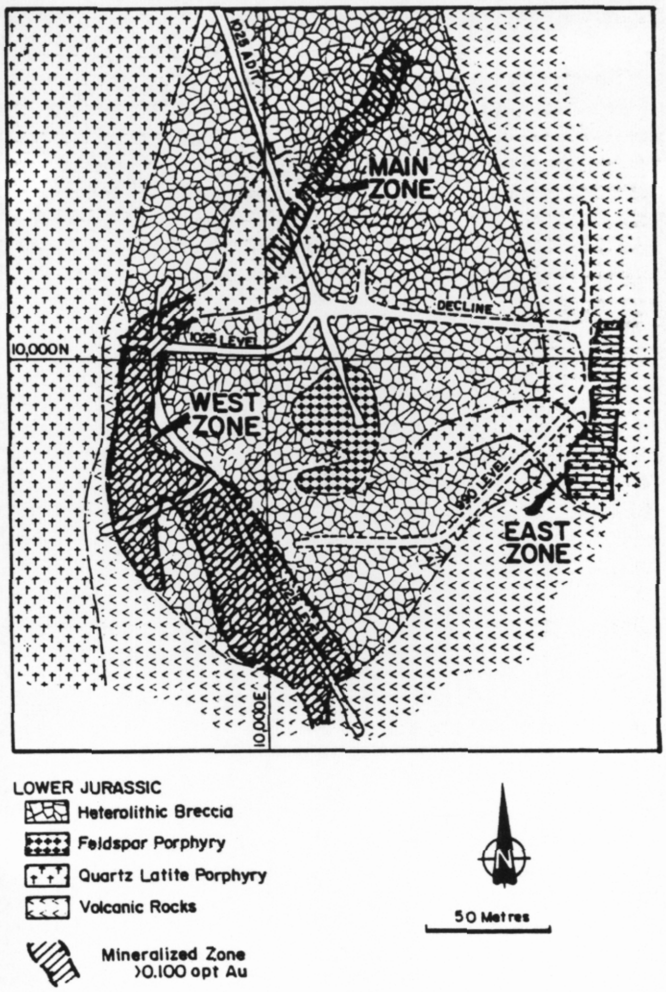

FIGURE 7. Plan of 1025 level showing mineralization.

Main Zone

The Main zone consists of a low-grade (approximately 3.4 million tonnes averaging 1.34 g/t Au, 0.32% Cu, 4.8 g/t Ag), north-trending lens of mineralization aligned along the axis of the breccia pipe. It is exposed at surface in the canyon of Aylwin Creek and in the nearby Willa adits. The zone is 250 m long and ranges from 20 m to 50 m in width. Mineralization occurs within heterolithic breccia except at its southern end where crackle-fractured feldspar porphyry is the host.

The style of mineralization in the Main zone differs from that in the West zone in a number of ways. Pyrrhotite is much more significant, generally occurring in equal proportion to both pyrite and chalcopyrite, and overall sulphide content of the zone is lower, averaging a relatively uniform 5%. Heterolithic breccia in this area is commonly vuggy. The sulphides ± magnetite occur predominantly as inter-clast fillings. Sphalerite is less abundant but tungsten is geochemically significant, suggesting the presence of a tungsten-bearing mineral. Lateral limits to the zone are less well-defined and are gradational over 3 m to 6 m. Gold and silver occur mineralogically in the same manner as in the West zone.

In general, the Main zone appears to represent a uniformly dispersed, disseminated type of mineralization hosted within vuggy, porous breccia. Though calculated as twice the tonnage of the West zone, with half the grade, it contains about the same amount of metals.

East Zone

The East zone was discovered during underground drilling late in the delineation program and only limited data are available. It represents structurally controlled mineralization hosted by propylitically-altered volcanic rocks adjacent to the eastern margin of the breccia pipe. Morphologically, the zone appears to comprise at least six east-west striking, moderately north-dipping, parallel fracture zones each ranging from 2 m to 6 m in true width and separated by 10 m to 12 m of unmineralized rock. Drill intersections through individual fracture zones have yielded values of up to 12.82 g/t Au and 1.76% Cu over 7.5 m.

Silver-Lead-Zinc (Gold)

Argentiferous, lead-zinc vein-type mineralization is prolific on the east side of Slocan Lake and is referred to collectively as the Slocan silver camp. Most of these veins strike northeasterly and dip southeasterly and are hosted by argillaceous sediments of the Slocan Group, by Nelson batholithic rocks, and by volcanic rocks in the Willa pendant. Significant values in gold occur in some veins hosted by Nelson granitic rocks.

Alteration

Hydrothermal alteration evident in the area of the Willa deposit is a consequence of three discrete, but successive intrusive events and two major episodes of mineralization. Overlap and over-printing of the various alteration assemblages has resulted in a complex zonation. The two earliest alteration assemblages, associated with molybdenum mineralization, consist of biotite-pyrite and quartz-pyrite-molybdenite. These are spatially-associated with quartz latite porphyry. Following this and associated with intrusion of feldspar porphyry is a potassic assemblage of K-feldspar-biotite accompanied by up to 5% disseminated pyrite. Emplacement of heterolithic breccia was closely followed by pervasive calcium metasomatism resulting in a prograde calc-silicate alteration assemblage. It is believed that most, if not all, of the gold-copper-silver mineralization accompanied this alteration. Retrograde alteration of this calc-silicate assemblage resulted in the formation of and over-printing by minerals such as epidote, actinolite, gypsum, quartz, calcite, and zeolites. Emplacement of the Nelson Batholith produced only minor propylitic effects in the Willa area.

Biotite-Pyrite Assemblage

Fine- to medium-grained black biotite accompanied by 2% to 5% disseminated and fracture-filling pyrite is locally preserved within mafic volcanic rocks adjacent to quartz latite porphyry. While more probably a product of contact metasomatism related to intrusion rather than a true hydrothermal alteration, it remains a recognizable assemblage where it is not over-printed by later hydrothermal events. The biotite also occurs as felted masses predominantly pseudomorphic after augite and may comprise up to 50% of the rock. Ubiquitous pyrite associated with this assemblage contributes to the large pyritic halo which encloses the overall intrusive complex.

Quartz-Pyrite-Molybdenite Assemblage

Quartz-pyrite-molybdenite stockwork veins, sheeted veins, and pervasive flooded zones occur mainly in quartz latite porphyry but are also found within volcanic rocks adjacent to the quartz latite porphyry contact. Alteration around individual veins is best developed in the quartz latite porphyry where quartz-sericite-pyrite envelopes pass outward into zones of albitized plagioclase. Where the veins cut biotite-pyrite altered volcanic rocks, wallrock alteration is minimal, probably due to the dense, impermeable nature of these rocks.

K-feldspar-Biotite Assemblage

A K-feldspar-biotite assemblage is spatially associated with the feldspar porphyry plug and locally is superimposed upon the first two alteration assemblages. Heather (1985) recognized a horizontal zonation within this assemblage with K-feldspar dominant in the centre of the plug and biotite more prominent on the periphery. K-feldspar-dominant alteration is marked by partial to total replacement of groundmass and plagioclase phenocrysts to yield a hard, whitish-coloured rock with original textures obscured.

Biotite-dominant alteration is marked by the development of disseminated, fine-grained, purple biotite laths which impart a distinct pinkish colouration to the rock. Biotite development is most intense near the margins of the feldspar porphyry in zones of monolithic breccia. In these zones, fine-grained biotite, albitized plagioclase, and pyrite form the matrix of the brecciated rock.

Prograde Calc-Silicate Assemblage

Following development of the heterolithic breccia pipe, prograde calc-silicate alteration resulting from calcium metasomatism associated with the gold-copper-silver mineralizing event resulted in replacement of the breccia matrix, and formation of veins and fracture-fillings in crackle-fractured clasts and peripheral crackle zones. The alteration assemblage consists of various combinations of the following minerals listed in order of decreasing abundance: pyroxene, amphibole, epidote, garnet, plagioclase, K-feldspar, quartz, anhydrite, sphene, and calcite.

Retrograde Alteration Assemblage

Retrograde alteration of earlier calc-silicate alteration minerals is widespread as crosscutting veinlets and replacements. Epidote is particularly prominent as an alteration product within the garnet-anhydrite and pyroxene zones. Veinlets of amphibole, pyroxene, calcite, and quartz are seen to cut all of the prograde assemblages. Fibrous clusters of zeolite locally replacing garnet and sparry gypsum replacing anhydrite are also considered to represent retrograde alteration as the hydrothermal system collapsed.

Late-stage Veinlets

Veinlets consisting of varying proportions of calcite, chlorite, quartz, and gypsum are seen to cross-cut all rock types, including Nelson plutonic rocks. They are especially common adjacent to late shear zones and may contain minor pyrite, hematite, or magnetite.

Weathering

The entire mineralized area has undergone shallow surface leaching and oxidation resulting in the development of limonitic coatings up to several tens of centimetres thick on most outcrops. Rusty zones are especially prominent along Aylwin Creek and the western slope of Red Mountain. Limonite staining on fractures extends to several tens of metres below surface.

Synthesis

The Lower Jurassic sequence of volcanism, hypabyssal intrusion and related mineralization at Willa displays aspects of Cordilleran calc-alkalic porphyry molybdenum deposits, alkalic porphyry copper-gold deposits and possibly auriferous skarn deposits. This complex nature is also evident in the Rossland mining camp, located approximately 100 km to the south and hosted by volcanic and intrusive rocks similar in age and composition to those hosting the Willa deposit.

At Willa, a number of features point to the existence of a Lower Jurassic volcanic vent. Although much of the pendant comprises pyroclastic rocks, coarse sub-volcanic augite porphyry is predominant. In the Willa area, intrusion of quartz latite porphyry as ring and radial dikes, followed successively by emplacement of feldspar porphyry and heterolithic breccia near the centre of this complex, suggest a focus of igneous activity. Also, preservation of the Aylwin Creek pendant is anomalous in its isolation and may indicate that this inlier possessed deep-seated roots as might be expected beneath a volcano.

The following chronological sequence is postulated for the development of the Willa deposit.

1. Extrusion of andesitic flows and tuffs from the Willa volcanic centre, one of a number of discrete vents within the Lower Jurassic Rossland arc. Volcanism was followed by continued differentiation due to episodic tapping of the underlying magma chamber.
2. Intrusion of ring and radial dikes of quartz latite porphyry in a near-surface environment along extensional structures related to incipient collapse of the vent. Hydrothermal fluids exsolved during final solidification of the quartz latite porphyry magma yielded a poorly focused system of quartz-molybdenite veining and weakly developed phyllic alteration. Development of biotite and pyritization associated with emplacement of the porphyry preceded this hydrothermal activity.
3. Intrusion of the feldspar porphyry plug, perhaps localized along the main volcanic conduit. This episode was relatively forceful, judging by the brecciated nature of feldspar porphyry contacts. Some tilting of the adjacent volcanic strata may have occurred at this time. Feldspar porphyry crystallization and associated fluids formed pervasive potassium metasomatism that resulted in replacement by K-feldspar at the core of the plug and biotization on the margins, but did not precipitate metals.
4. Magmatic hydrothermal brecciation of intrusive and volcanic rocks localized along the same structure that controlled emplacement of the feldspar porphyry. This brecciation is thought to have been caused by explosive vapour release from a deep-seated, volatile-enriched, and as yet undetected intrusion.
5. Fluidization of the pipe-like zone of fragmented rock to produce the body of heterolithic breccia and, by abrasion, the rock flour.
6. Following brecciation and fluidization in the pipe, structural relaxation resulted in the development of an inward-dipping ring fracture around the remnant inlier of feldspar porphyry.
7. Hydrothermal fluids evolved from the postulated solidifying intrusion ascend along the ring fracture and are dispersed throughout the permeable body of the breccia pipe and less intensely into adjacent rocks. Calcium metasomatism associated with these solutions results in calc-silicate alteration of the breccia matrix and deposition of auriferous and argentiferous chalcopyrite, pyrite, pyrrhotite and magnetite mineralization.
8. Overprinting by a lower temperature retrograde calc-silicate assemblage as the hydrothermal system cools and collapses upon itself.
9. Emplacement of the Nelson Batholith in the Middle Jurassic results in restricted thermal and dynamothermal metamorphism and development of calcite, chlorite, quartz and gypsum veining.
10. Tertiary extension and detachment faulting results in north-striking normal faults which locally offset mineralized zones and may have localized the emplacement of young mafic dikes.
11. Erosion to the present day level with surface leaching and oxidation contributing to the formation of a limonitic coating up to several tens of centimetres thick.

The Willa porphyry system is particularly noteworthy in that it contains both an early phase of molybdenum mineralization with associated K-metasomatism (phyllic) and a younger phase of copper-gold mineralization with associated Ca-metasomatism. Superposition of these two distinct types of mineralization and alteration, previously considered by many to represent end-members in the spectrum of porphyry deposits, indicates that it is possible for both types of deposit to have evolved from a single intrusive complex of calc-alkalic affinity.

The close spatial relationship and succession of feldspar porphyry, a second event of K-metasomatism, volatile brecciation and Ca-metasomatism with Cu-Au mineralization implies that these events are related. The feldspar porphyry might be the crystallized carapace of the unseen intrusion that subsequently underwent volatile saturation and brecciation. From the evidence described, this was apparently accompanied by a change from K- to Ca-metasomatism which bracketed in time the development of the breccia. The Cu-Au mineralization is, therefore, seemingly associated with but subsequent to the feldspar porphyry.

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REFERENCES

ARMSTRONG, R.L., 1981. Unpublished company report, Riocanex Ltd.

ARMSTRONG, R.L., 1988. Mesozoic and Early Cenozoic magmatic evolution of the Canadian Cordillera. *In* Processes in Continental Lithospheric Deformation. *Edited by* S.P. Clark, Jr., B.C. Burchfield and J. Suppe. Geological Society of America, Special Paper 218, p 55-91.

CAIRNES, C.E., 1935. Description of properties, Slocan Mining Camp, British Columbia. Geological Survey of Canada, Memoir 184, 237 p.

DURGIN, D.C., 1981. Aylwin Creek Project. Unpublished company report, Riocanex Inc., 110 p.

HEATHER, K.B., 1985. The Aylwin Creek gold-copper-silver deposit, southeastern British Columbia. Unpublished M.Sc. thesis, Queen's University, Kingston, Ontario, 273 p.

MURPHY, C.M., GERASIMOFF, M., VAN DER HEYDEN, P., PARRISH, R.R., KLEPACKI, D.W., McMILLAN, W.J., STRUIK, L.C. and GABITES, J., 1994. New geochronological constraints on Jurassic deformation of the western edge of North America, southern Canadian Cordillera. *In* Jurassic magmatism and tectonics of the North American Cordillera. *Edited by* D.M. Miller and R.G. Anderson. Geological Society of America, Memoir, in press.

PARRISH, R., 1984. Slocan Lake Fault: A low angle fault zone bounding the Valhalla gneiss complex, Nelson map area, southeastern British Columbia. *In* Current Research, Part A. Geological Survey of Canada, Paper 84-1A, p. 323-330.

SILLITOE, R.H., 1985. Ore-related breccias in volcanoplutonic arcs. Economic Geology, 80, p. 1467-1514.

SPENCE, C.D., 1982. Aylwin Creek project, Slocan district, British Columbia. Unpublished company report, Riocanex Inc., Vancouver, 150 p.

SPENCE, C.D., 1985. Shoshonites and associated rocks of central British Columbia. *In* Geological Fieldwork 1984. British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1985-1, p. 426-442.

TIPPER, H.W., 1984. The age of the Jurassic Rossland Group of southeastern British Columbia. *In* Current Research, Part A. Geological Survey of Canada, Paper 84-1A, p. 631-632.

WONG, R.H., 1983. Aylwin Creek project, Slocan district, British Columbia. Final report on 1983 Diamond Drilling Program. Unpublished company report, BP Minerals-Riocanex Joint venture.

WONG, R.H., 1984. Aylwin Creek project, Slocan district, British Columbia. Final report on 1984 Field Program. Unpublished company report, BP Minerals-Riocanex Joint Venture.

WOODSWORTH, G.J., ANDERSON, R.G. and ARMSTRONG, R.L., 1991. Plutonic Regimes Chapter 15. *In* Geology of the Cordilleran Orogen in Canada. *Edited by* H. Gabrielse and C.J. Yorath. Geological Survey of Canada, Geology of Canada, No. 4, p. 491-531 (also Geological Society of America, The Geology of North America, Volume G-2).