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The Galore Creek porphyry copper-gold deposits, northwestern British Columbia

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ABSTRACT

Situated about 200 km southeast of Juneau, Alaska, within the lower Stikine River region of northwestern British Columbia, the Galore Creek porphyry Cu-Au deposits are hosted by Upper Triassic to Lower Jurassic alkaline volcanic rocks and comagmatic syenite intrusions. Early and late breccias are also locally important host rocks for mineralization. Of the twelve identified Cu-Au deposits, the most important are the Central zone, Southwest zone and the Junction deposits with a combined resource of 284 million tonnes at 0.67 % Cu.

The composition of the intrusive rocks is predominantly silica-undersaturated, alkaline, and metaluminous. Four intrusive suites are identified from field, petrographic and petrochemical data. Variation within suites or lineages can be explained by alkali feldspar fractionation. An oscillation between porphyritic and equigranular intrusions is suggested by the sequence of different intrusive lineages. The youngest intrusive phase is silica-saturated.

A complex succession of intrusive and hydrothermal events is demonstrated at Galore Creek, with the most intense alteration and mineralization developing early in its history. In the Central zone, early Ca-K-silicate alteration, dominated by garnet, biotite, K-feldspar, and anhydrite grades outward into K-silicate alteration. Both are locally overprinted by retrograde sericite ± anhydrite ± carbonate (SAC) alteration. The most intense Ca-K-silicate alteration, a magmatic-hydrothermal breccia, and an early syenite intrusion are all coincident with copper mineralization in the core region of the Central zone. However, higher grade mineralization in the zone, exceeding 1% Cu with more than 0.5 g/t Au, is typically associated with intense biotite-rich, K-silicate alteration primarily hosted by altered volcanic rocks. The highest gold grades, commonly exceeding 1 g/t, are associated with bornite-rich mineralization situated in the northern and southern parts of the Central zone.

Mineralization in the Southwest zone occurs as disseminated chalcopyrite within a late, diatreme breccia and adjacent K-feldspar porphyry. In the other satellite deposits, disseminated chalcopyrite and bornite occur in volcanic rocks with alteration that is similar to the Central zone.

Introduction

Galore Creek is located in northwestern British Columbia, 950 km from Vancouver. The property is centred at latitude 57°07′30″N and longitude 131°27′00″W within the Liard Mining Division in NTS map sheets 104G/3 and 104G/4. The two nearest service communities on tidewater are Stewart, 200 km to the south, and Wrangell, Alaska 96 km southwest. Access to the property is by helicopter or by fixed wing aircraft to a 500 m gravel airstrip on the property.

Copper mineralization was discovered in 1955 by two prospectors working for Hudson Bay Exploration and Development Company Limited in the upper West Fork of the Galore Creek valley. In 1959, Kennco (Western) Limited conducted a helicopter-supported reconnaissance stream geochemistry survey in northwestern British Columbia. They defined a spectacular copper anomaly in the Galore Creek watershed and in 1960, Kennco staked 110 mineral claims surrounding Hudson Bay's original 16 claims and the four claims optioned by prospectors to Cominco (Barr, 1983). The Stikine Copper Company was incorporated in 1963 to explore and develop the claims. In 1993, ownership of Stikine Copper Limited was 55% Kennecott Canada Inc. and 45% Hudson Bay Mining and Smelting Co. Ltd.

Early exploration from 1960 to 1976 utilized mainly stream sediment surveys, prospecting and geological mapping. All currently known deposits on the property cause elevated copper in stream sediments (Barr, 1966). Soil surveys were of limited use because thick glacial till masks a number of the mineralized zones but I.P./resistivity surveys were effectively used over a number of prospects. Diamond drilling during 1961 to 1967 and 1972 to 1973 outlined most of the known mineralization on the property, and is described by Allen et al. (1976). Renewed exploration on the property in 1989 and 1990 focused on the gold potential. In 1991, a major program was carried out to re-evaluate the economic potential of Galore Creek. It included an airborne geophysical survey, I.P./resistivity surveys, geological mapping, re-logging the core of more than 300 diamond drill holes, and drilling 48 new diamond drill holes to test extensions of known mineralization and new targets. More than 18 000 coarse reject samples were re-assayed for gold. Exploration work carried out on the property in the period 1960 to 1991 is summarized in Table 1.

The re-interpretation of the geology and mineralization at Galore Creek is based on re-logging of drill core from the Central and Southwest zones, detailed geological mapping, and information from the 1991 diamond drilling program. These exploration data have been augmented by petrographic and geochemical studies conducted at the Mineral Deposit Research Unit at The University of British Columbia.

Regional Geology

The Galore Creek deposits are located in Stikine terrane at the western margin of the Intermontane Belt. Tectonostratigraphic elements include:

LANG, J.R., STANLEY, C.R. and THOMPSON, J.F.H., 1992. Quartz-alkalic and nepheline-alkalic: Two distinct subtypes of porphyry deposits related to alkalic igneous rocks. Geological Society of America, Programs with Abstracts, 24, p. A143.

LANG, J.R., STANLEY, C.R. and THOMPSON, J.F.H., 1995. Porphyry copper-gold deposits related to alkalic igneous rocks in the Triassic-Jurassic arc terranes of British Columbia. *In* Bootprints Along the Cordillera: Porphyry deposits from Alaska to the Andes. *Edited by* F.W. Pierce and J.G. Bolm. Arizona Geological Society, Digest 20.

LEITCH, C.H.B., 1992. Petrographic report of 45 specimens from the Lorraine porphyry Cu-Au property, British Columbia. Unpublished company report, Kennecott Canada Inc., Vancouver, British Columbia, 50 p.

LUECK, B.A. and RUSSELL, J.K., 1994. Silica-undersaturated, zoned, alkaline intrusions within the British Columbia Cordillera. *In* Geological Fieldwork 1993. *Edited by* B. Grant and J. Newell. British Columbia Ministry of Energy Mines and Petroleum Resources, Paper 1994-1, p. 285-289.

SOUTHER J.G., 199[illegible] Volcanic regimes. *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. 457-490.

STANLEY, C.R., 1993. Thermodynamic geochemical model for the co-precipitation of gold and chalcopyrite in alkalic porphyry copper-gold deposits. *In* Copper-gold porphyry systems of British Columbia, Annual Technical Report-Year 2, July 1992-July 1993. Mineral Deposit Research Unit, Vancouver, British Columbia.

WILKINSON, W.J. STEVENSON, R.W. and GARNETT, J.A., 1976. Lorraine. *In* Porphyry deposits of the Canadian Cordillera. *Edited by* A. Sutherland Brown. Canadian Institute of Mining and Metallurgy, Special Volume 15, p. 397-401.

WOODSWORTH, G.J., ANDERSON, R.G., ARMSTRONG, R.L., STRUIK, L.C. and VAN DER HEYDEN, P., 1992. Plutonic regimes. *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.

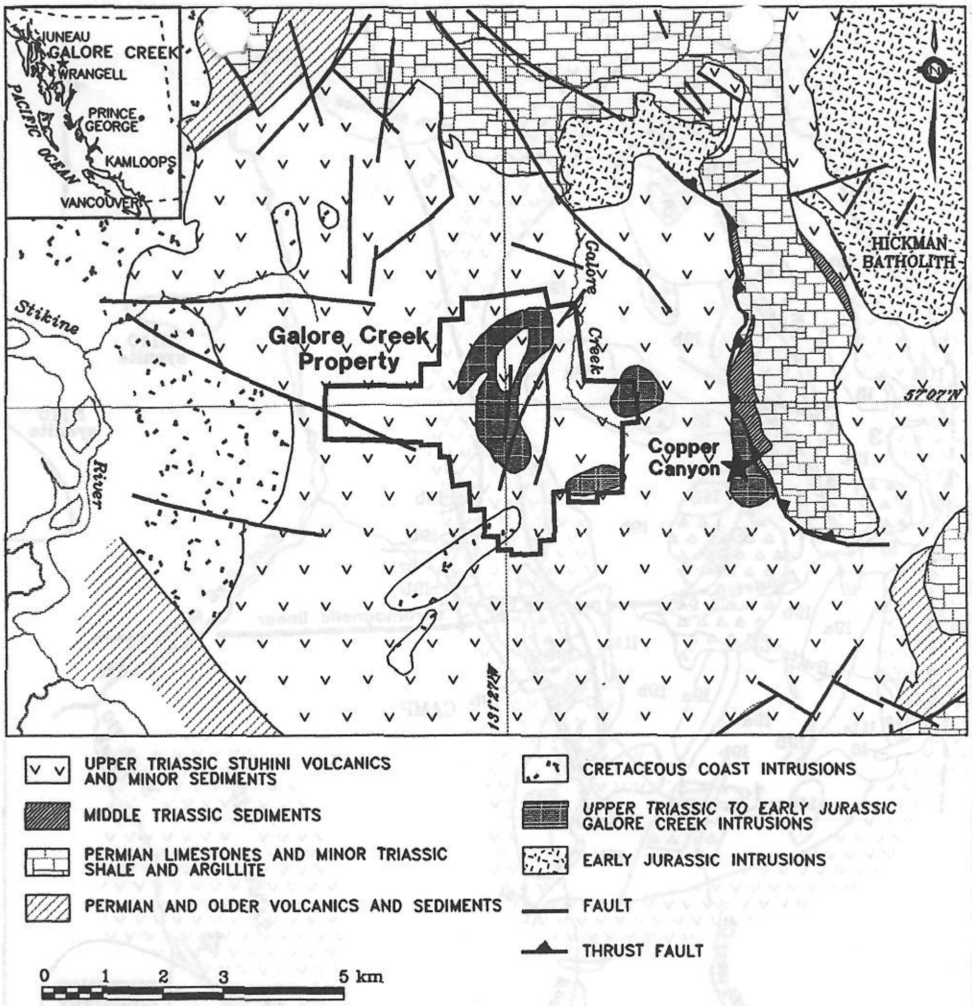

FIGURE 1. Regional geology of the Galore Creek area (adapted from Logan et al., 1989).

1. Late Paleozoic to Middle Jurassic island arc volcanic and sedimentary rocks of the Stikine assemblage, the Stuhini Group and Hazelton Group;
2. *Middle Jurassic to early Late Cretaceous basinal sediments of* the Bowser Lake Group;
3. Late Cretaceous to Tertiary continental arc volcanic assemblages of the Sloko Group; and
4. Late Tertiary to Recent post-orogenic plateau basalt of the Edziza and Spectrum Ranges.

The Stikine assemblage forms the basement to Stikine terrane. It consists of a sequence of Devonian to Permian mafic and intermediate flow and volcaniclastic units, interbedded carbonate and *minor shale, and beds of chert (Monger, 1977). Extensive units of* Mississippian and Permian carbonate are exposed northeast of Galore Creek. Figure 1 shows the regional geology in the immediate area of Galore Creek.

Rocks of the Upper Triassic Stuhini Group include a variety of green and maroon flows, tuffs, volcanic breccias and sedimen-

TABLE 1. Work history

	1960-63	1964-65	1966-67	1972-73	1974-76	1989	1990	1991	Total
Geophysical surveys (*line* km)									
Airborne Magnetic	270.0							459.0	729.0
Ground Magnetic	55.2						18.4	85.0	158.6
Ground VLF						11.4	10.9	70.0	92.3
IP/Resistivity	114.8							90.2	205.0
Geochemical survey (samples)									
Stream Sediment	92					157			249
Soil	950					729	37	600	2316
Diamond drilling									
Surface (m)	15 761	31 290	5992	24 729	5318		1925	13 829	98 844
(holes)	97	145	18	112	24		18	48	462
Underground (m)			163						163
(holes)			7						7
Construction									
Road (km)		47.2	0.8						48.0
Airstrip		1	1						2

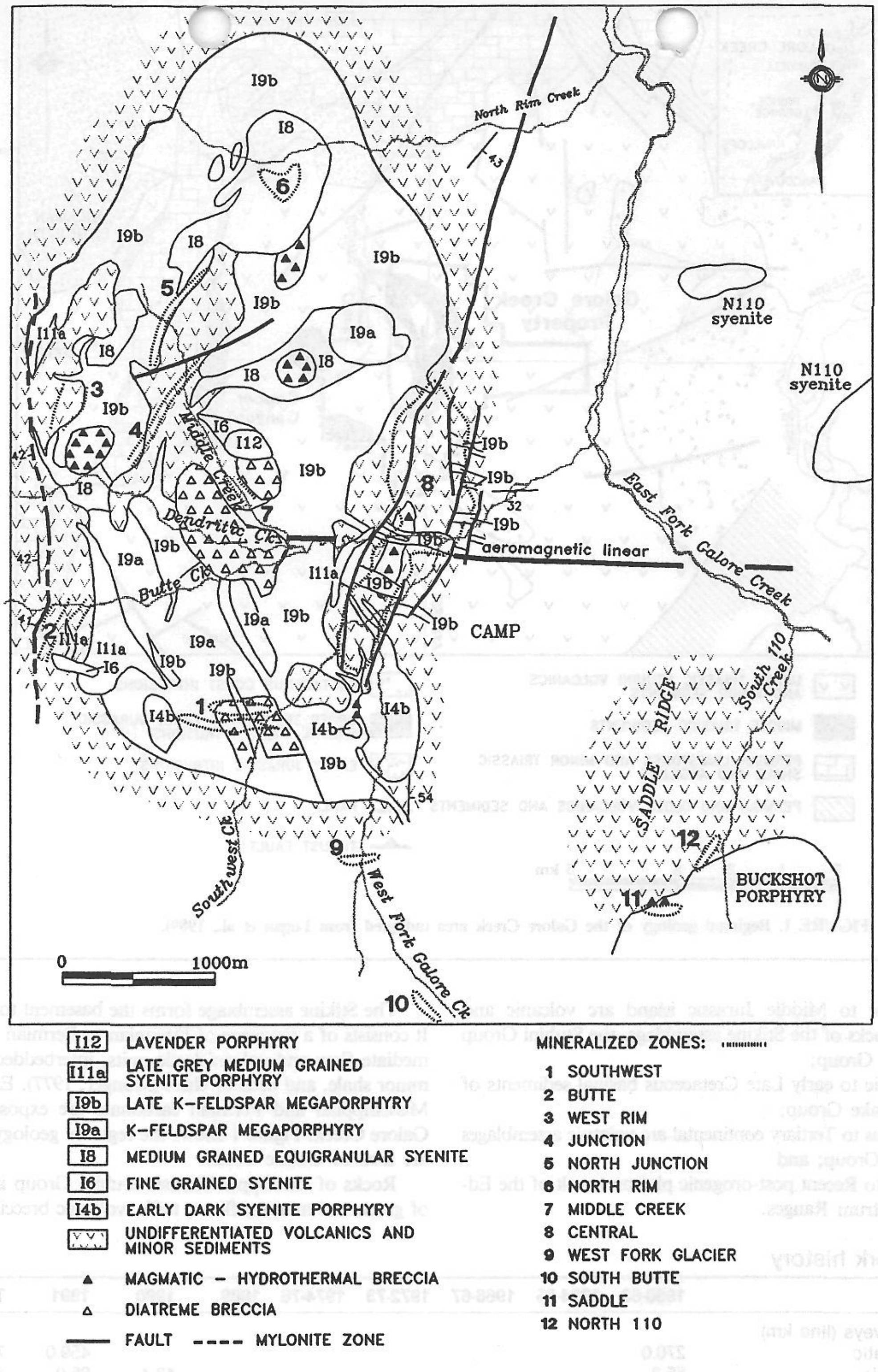

FIGURE 2. Geology of the Galore Creek camp.

tary rocks that unconformably overlie the Stikine assemblage (Kerr, 1948). The Stuhini Group in the Galore Creek area may define a volcanic centre flanked by distal volcaniclastic and sedimentary turbidites (Monger, 1977). Panteleyev (1976) subdivided the volcanic rocks at Galore Creek into a lower unit of submarine basaltic to andesitic flows and breccias typical of the Stuhini Group, and an upper unit of partially subaerial, compositionally distinct alkali-enriched flows and pyroclastic rocks. Radiometric dates by Anderson (1984) and fossil ages by Souther (1972), indicate ages for the Stuhini Group that range from early Carnian to late Norian. Rocks equivalent to the Lower Jurassic Hazelton Group have been recognized to the north of Galore Creek (Logan et al., 1989).

Three major periods of intrusive activity have been recognized in the region:

1. Upper Triassic to earliest Jurassic intrusions that include the calc-alkaline Hickman pluton and the alkaline intrusions at Galore Creek, Copper Canyon and other similar bodies to the north and south. These intrusions appear to be coeval and comagmatic with parts of the Stuhini volcanic rocks (Logan and Koyanagi, 1989).

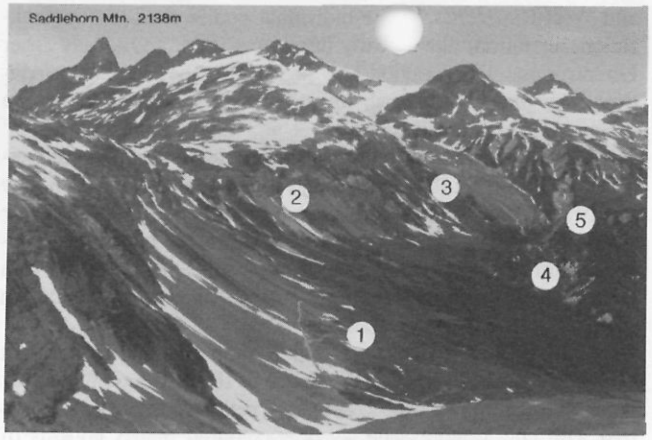

FIGURE 3a. View to northwest overlooking (1) Southwest, (2) Butte, (3) West Rim, (4) Junction and (5) North Junction zones.

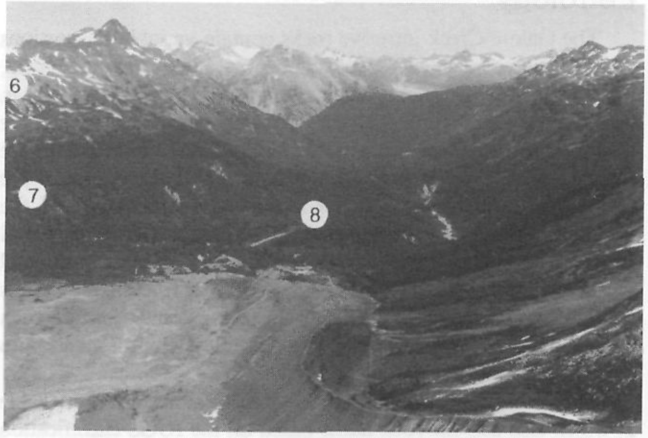

FIGURE 3b. View to north down the West Fork Glacier overlooking (6) North Rim, (7) Middle Creek, and (8) Central zones. Camp and airstrip are shown in the centre of photograph.

FIGURE 4a. Photograph of pseudoleucite-bearing volcanic flow from Southwest Zone area. Core is 47 mm across.

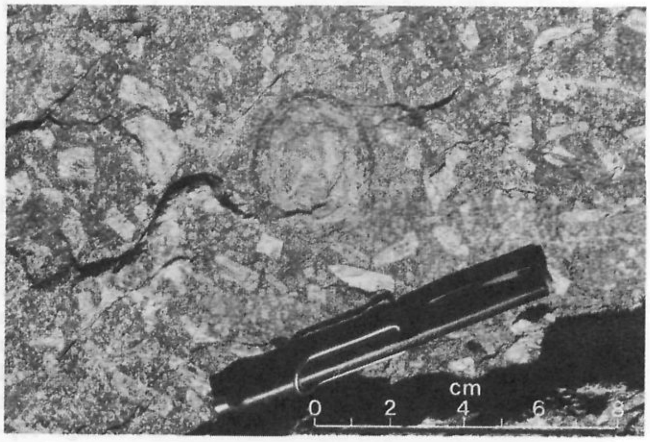

FIGURE 4b. Photograph of concentric banded pseudoleucite in dark I4b syenite porphyry from south of the Central zone. Magnet is 950 mm in length.

2. The Late Cretaceous to Paleocene Coast plutonic complex that occurs as several distinct granitoid phases west of Galore Creek.
3. Eocene quartz monzonite and diorite stocks, and mafic to felsic dikes within west- and north-striking extensional structures.

At least three phases of deformation have been recognized in the area (Logan and Koyanagi, 1989). The first phase is marked by penetrative planar fabrics and associated isoclinal folding in older Paleozoic formations. The second phase consists of large upright, tight to open folds, with east-striking axes. Upright north striking box folds with chevron cores characterize the final phase of deformation. The second and third phases occur in both Paleozoic and Mesozoic rocks. Fault sets strike north, northwest, west and northeast and divide the region into a mosaic of fault-bounded blocks. Faults striking north are most common.

Geology of Galore Creek

The Galore Creek intrusive-volcanic complex is composed of multiple intrusions emplaced into volcanic rocks of similar composition. It is centred in the West Fork of Galore Creek and is 5 km in length and 2 km in width (Fig. 2). At least twelve Cu-Au mineralized zones are known at Galore Creek (Figs. 3a and 3b). Most zones, including the Central, North Junction, Junction, Middle Creek, West Rim, Butte and South 110, occur in highly altered volcanic rocks, and to a lesser degree in syenite intrusions. The Southwest and Saddle zones are hosted by breccias and the North Rim zone occurs within a syenite intrusion.

Country rocks to the syenite intrusions are volcanic flows and volcaniclastic sediments, with subordinate greywacke, siltstone and local conglomerate. The volcanic rocks include augite-phyric, orthoclase-phyric, and locally pseudoleucite-bearing flows (Fig. 4a), tuffaceous and coarser fragmental units, and related volcanic sediments. The pseudoleucite-bearing and orthoclase-rich units, which are prominent in the south and southwest parts of the complex, are interpreted to overlie augite-phyric flows and tuffaceous rocks that are more abundant in the topographically lower, northern part of the complex.

Multiple igneous intrusive phases occur in the complex and are divided into early and late intrusive suites on the basis of field relations. Early intrusions have been most intensely altered and mineralized and are of probable pre- to syn-mineralization age. The present intrusive nomenclature differs from that used previously (Allen et al., 1976; Barr, 1966). It generally portrays a temporal sequence with I1 to I4 being oldest and I9 to I12 the youngest intrusions (Table 2). This classification is based on cross-cutting relationships together with the degree of alteration and mineralization (Sillitoe, 1991a), as well as essential phenocryst mineralogy, texture and grain size of least altered samples.

Previous K-Ar age determinations on hydrothermal biotite by White et al. (1968) in the Central zone gave ages from 177 Ma to 192 Ma (Early Jurassic). Logan et al. (1989) report an Ar-Ar plateau age of 212 Ma that was obtained from a volcanic rock at Copper Canyon. More recently, Mortensen et al. (this volume) have obtained dates from three intrusions at Galore Creek using U-Pb and Pb-

Pb isochron methods on zircon and titanite, respectively. Probable crystallization ages range from 210 ± [illegible] Ma for a syn-mineral intrusion (I4) immediately south of the Central zone, to 205.1 ± 2.3 and 205.0 ± 1.8 for post-mineral intrusions (I9b) in the central part of camp. These results are consistent with the timing relationships of these intrusions relative to mineralization and alteration, and suggest that magmatic activity continued for a minimum of 1.6 m.y. with mineralization occurring early in this period.

Intrusive Suites

The early intrusive suite is premineral to intermineral and includes thin pseudoleucite porphyry dikes (I1 and I2), syenite porphyry (I3), dark syenite porphyries (I4a, I4b) and dikes of fine-grained orthoclase syenite megaporphyry (I5). These phases are generally the most intensely altered and mineralized of all the intrusions in the area. The early suite occurs mainly in the south part of the complex and is volumetrically subordinate to the late intrusive suite.

An I3 syenite is exposed in lower Dendritic Creek, and was recognized in drill core from the same area. It is closely associated with the most intense hydrothermal alteration and may represent the causative intrusion for the main stage Cu-Au mineralization. This intrusive phase is characterized by a hiatal texture with approximately 5% subhedral and equant K-feldspar crystals (4 mm to 10 mm and 10 mm to 20 mm in size). Locally, altered mafic minerals and relict pseudoleucite crystals are recognizable.

An early dark syenite porphyry (I4b) occurs as remnant, small bodies exposed in the south part of the complex. This unit is characterized by a uniform dark grey colour due to 15% to 20% disseminated, fine-grained hydrothermal biotite. It also contains 5% to 15% stubby white orthoclase phenocrysts, 5 mm to 25 mm in length, and concentrically-zoned pseudoleucite crystals up to 5 cm in diameter (Fig. 4b). Unit I4a is less abundant and was distinguished from I4b on the basis of orthoclase and pseudoleucite phenocryst size and content, more intense biotite alteration and stronger copper mineralization. One intrusive contact, I4b cutting I4a, was noted in drill core. Both I4 syenites are less mineralized and altered than the I3 phase, and therefore, may be slightly younger.

The most abundant syenite intrusions mapped within the complex are considerably less altered. They locally cut intense mineralization and alteration, and are interpreted to be largely postmineral. Most common phases in this suite are grey, equigranular to porphyritic, medium-grained syenite (I8), megaporphyry (I9a) and(I9b), grey medium-grained syenite porphyry (I11a) and lavender porphyry (I12). Minor phases include dikes and small stocks of fine-grained syenite (I6), fine-grained syenite porphyry (I7), plagioclase syenite porphyry (I10) and medium-grained syenite porphyry (I11). Most of these late minor phases were defined from drill core in the Central zone. Minor mineralization associated locally with these dikes, suggests that they are either synmineral, or minor late mineralization was introduced with them.

Irregular bodies of the I8 intrusive phase are abundant in the north and western parts of the complex. This phase is characterized by 5% biotite, 5% to 10% chloritized hornblende and clinopyroxene, and rare K-feldspar phenocrysts in a generally equigranular grey syenitic matrix. The I9a phase occurs only in the southern part of the complex and has a similar appearance in hand sample as I9b. It is more altered than I8 and is characterized by 15% to 25% tabular K-feldspar phenocrysts that are 1 cm to 3 cm in length within an intensely altered matrix. Megaporphyry (I9b) forms the greatest volume of the syenite intrusions and is equivalent to the epidote syenite megaporphyry of Allen et al. (1976) and the epidotized syenite porphyry of Barr (1966). It is characterized by 10% to 20% cream-coloured, orthoclase phenocrysts up to 19 cm in length in a medium- to coarse-grained matrix. Variable amounts of epidote and garnet occur as irregular patches. Locally, near contacts, large K-feldspar phenocrysts show strong crystal alignment. The I9b phase intrudes the Central, North Junction, Butte and West Rim zones, where individual bodies cross-cut mineralization, alteration, altered early intrusive phases, and locally other I9b intrusions. Field relationships suggest that the I9b phase is relatively late and postmineral, an interpretation supported by the geochronolgical data (Mortensen et al., this volume).

I11a is a widespread, minor, unaltered and essentially unmineralized phase within the complex and it cuts I9b. It is medium grey and of equigranular to porphyritic texture with about 7% K-feldspar phenocrysts 5 mm to 25 mm in length, up to 3% biotite and similar amounts of hornblende. This phase consistently contains vugs (1 mm to 5 mm across) that are partially filled with pale brown garnet and epidote crystals.

The Lavender porphyry (I12) is a quartz-bearing syenite that occurs as a small body near the centre of the complex. It intrudes a late-mineral breccia exposed in Dry Creek and is locally mineralized with chalcopyrite. The lavender-coloured matrix consists of more than 50% orthoclase phenocrysts (5 mm to 20 mm in length) that commonly display a trachytic texture.

Petrology

The Galore Creek intrusive rocks contain variable proportions of orthoclase, plagioclase (oligoclase or albite), pseudoleucite, melanite, clinopyroxene, biotite and hornblende phenocrysts set in a matrix of pilotaxitic K-feldspar, disseminated magnetite, apatite and titanite. Petrologic differences among these intrusive rocks are due largely to differences in the mode, size and abundance of the phenocryst assemblage, and the texture and mineralogy of the groundmass. Some of these intrusions are interpreted to be derived from common parental melts. The observed differences in mineral mode are interpreted to reflect: (1) the different fractionation paths which each unit followed; (2) the extent of fractionation which each unit underwent; and (3) the physicochemical environments into which each unit was emplaced.

The petrography of the intrusive units is summarized in Table 2, which also lists the rock name based on the IUGS classification (Philpotts, 1990; Morse, 1980). A petrographic and geochemical study was conducted on a suite of least-altered samples, based on the presence of fresh or relict phenocrysts and minimal recrystallization of the groundmass. Compositions of primary minerals were determined using a Cameca SX-50 electron microprobe. Ferric iron compositions were determined using crystal chemical and charge balance constraints.

Definition of intrusive phases, although largely based on field observations, was modified by petrography and geochemistry. Unit I3 was subdivided into two phases (I3 and I3′) based on significant petrologic and trace element differences. Conversely the I4a and I4b intrusive units, which display cross-cutting relationships as well as differences in hydrothermal alteration, do not exhibit significant petrologic or geochemical differences. Similarly, no petrologic or geochemical difference distinguish I9a from most I9b intrusions. Their petrologic similarity indicates that, despite an apparent temporal distinction, these units may be comagmatic. The I4b and I9b phases, however, consist of petrologically distinct phases (I4b/I4b' and I9b/I9b') that display significantly different textures, mafic phenocryst mineral assemblage and geochemical signatures.

Unaltered hornblende from the I9b intrusion displays no significant compositional variation or zoning. It was classified as magnesian hastingsite, or ferric iron-bearing hornblende (Leake, 1978). Clinopyroxene in most Galore Creek igneous rocks are ferrian aluminian diopside and reflect the undersaturated nature of the Galore Creek intrusive suite. The clinopyroxene has pastel colours, strong pleochroism similar to aegirine-augite, compositional variation, but no identifiable zoning.

Igneous garnet identified in some of the Galore Creek intrusive rocks is an isotropic, Ti-bearing andradite (melanite), with euhedral form, growth zoning and clinopyroxene inclusions. Electron microprobe traverses across these garnets reveal minor compositional variation with consistently lower TiO_2 concentrations on the

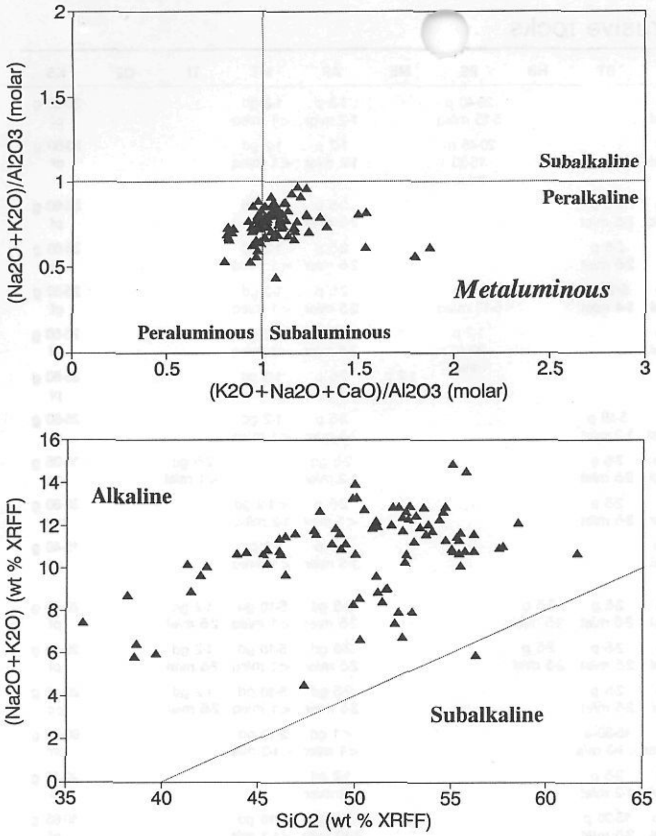

FIGURE 5. Alkali-alumina (A) and alkali-silica (B) plots for least altered samples of intrusive rocks from Galore Creek.

melts (Philpotts 1990; Morse 1980).

3. **In situ growth of phenocrysts**: Several of the porphyritic, as well as some equigranular dikes, have significantly fewer and smaller K-feldspar phenocrysts in their chilled margins than in their centres. In some cases, small dikes are filled with large K-feldspar megacrysts with less than 20% interstitial material. Both observations suggest that part of the growth of the larger phenocrysts may have occurred in situ under conditions of high volatile concentration.
4. **Magma types**: The modal change in the primary mineral assemblage of Galore Creek intrusions, from syenite and alkali syenite intrusions in (I1 through I5), to monzonite and monzodiorite intrusions (I6 through I8), to syenite intrusions in (I9b through I11) and, finally, to quartz syenite intrusions (I12) suggests differences in the compositions of the parent melts. Changes from chemically more-evolved to less-evolved magma compositions associated with the intrusion of the I6 phase may signal an introduction of new, less-evolved magma into the sub-volcanic environment (lineage C).

Breccias

Six large and numerous smaller breccia bodies were outlined (Fig. 2) and broadly divided into two types: clast-supported and matrix-supported. Clast-supported breccias are characterized by predominantly monolithic fragments with a wide range in clast size often showing little evidence of clast rotation. The clasts are subangular to angular with breccia margins typically transitional into stockwork vein zones. The matrix and vugs in the breccias contain magnetite, diopside, K-feldspar, epidote, garnet and apatite in varying proportions. Matrix-supported breccias consist of highly comminuted, heterolithic, rounded to subrounded clasts, with a highly variable clast size, and a high matrix to clast ratio. In places, these breccias contain mineralized and altered clasts. The clast-supported and matrix-supported breccias are interpreted to be magmatic-hydrothermal and phreatomagmatic respectively, using the classification and criteria of Sillitoe (1985). The phreatomagmatic breccias occur in discrete, vertically extensive zones, which combined with their textural characteristics, suggest formation in diatremes. Hereafter, these are referred to as diatreme breccias.

TABLE 3. Average conserved element ratios from Galore Creek intrusive rocks

Ratio	Lineage A	Lineage B	Lineage C	Lineage D
TiO_2/Zr	65	30	100	30
TiO_2/Hf	2200	1100	4000	1600
TiO_2/Nb	180	90	500	130
TiO_2/Th	800	375	2500	725

One of the most prominent breccias at Galore Creek is exposed in lower Dendritic Creek on the west side of the Central zone (Fig. 7). This large breccia is clast-supported with sub-angular to sub-rounded clasts of pseudoleucite-bearing grey syenite (I3) and pseudoleucite-phyric volcanic rock. The matrix consists of brown garnet, K-feldspar, diopside, anhydrite, biotite and chalcopyrite. The breccia grades into the highly altered I3 intrusion and adjacent pseudoleucite-phyric volcanic rock. Intense pervasive alteration and copper mineralization in this breccia and its close spatial association with the early I3 intrusion suggest that this breccia formed early during the main stage of mineralization. It is interpreted as a magmatic-hydrothermal breccia

Other magmatic-hydrothermal breccias include the mineralized Saddle zone breccia and the West Fork breccia. Both consist of a framework of subangular clasts in a matrix of mainly magnetite with garnet, diopside, epidote, orthoclase, and apatite. The West Fork breccia contains clasts of unaltered intrusive phases, including the late I11 phase, suggesting that it formed late in the sequence of events.

The most significant diatreme breccia at Galore Creek hosts the Southwest zone. The breccia is composed of unsorted, heterolithic clasts supported by a fine-grained rock-flour matrix. Most clasts are subrounded and include I9a megaporphyry phases, whole or broken K-feldspar crystals, as well as altered mineralized fragments. This diatreme breccia is cut by I9b megaporphyry dikes, confirming the temporal distinction between the phases of I9 intrusions.

Two other large diatreme breccias occur in upper Dendritic Creek and Dry Creek (Fig. 2). Both bodies are poorly sorted and heterolithic, with subrounded to subangular matrix-supported clasts in a dark grey, highly comminuted rock-flour matrix. The relatively late timing of these breccias is indicated by the presence of I9b clasts, highly altered clasts with truncated magnetite and K-feldspar veins, and chalcopyrite-mineralized clasts. Whereas the Dry Creek breccia contains secondary biotite and K-feldspar, particularly near its southern contact, the larger upper Dendritic Creek body is altered only in places by K-feldspar flooding and local zones of magnetite and diopside veining. Both breccias contain minor copper mineralization.

Structure

The most important structures at Galore Creek are faults. They were recognized in mapping and core logging as well as from the interpretation of topographic and aeromagnetic linear features. The main elements are listed below in approximate chronological order:

1. A mylonite zone, at least 100 m thick, striking north and dipping 42° to the west, is exposed in volcanic rocks along the west margin of the complex (Fig. 2). Mineralization and alteration cut across the mylonite fabric in upper Butte Creek indicating a pre-mineralization age for the mylonite.
2. A first order regional structure indicated by a prominent, east-trending, aeromagnetic linear lies parallel to lower Dendritic Creek (Fig. 2). Part of this linear feature is now occupied by a late-mineral I9b megaporphyry dike at section 6773N, where

TABLE 2. Petrographic sur ary of Galore Creek intrusive rocks

Unit	IUGS Name	Texture	OR	PL	CP	BT	HB	PS	ME	AP	MT	TI	QZ	KS
I1	Pseudoleucite Porphyry Alkali Syenite	porphyritic	2-5 p 2-5 m/sq		5-10 p 1-4 m/sl			20-40 p 5-15 m/aq		1-2 p 1-2 m/qr	1-2 gd <1 m/eq			30-50 g pf
I2	Pseudoleucite Megaporphyry Alkali Syenite	megaporphyritic	2-5 p 2-5 m/sq		5-10 p 1-4 m/sl			20-45 m 15-30 m/aq		1-2 p 1-2 m/qr	1-2 gd <1 m/eq			30-50 g pf
I3	Gray Orthoclase Porphyry Syenite	porphyritic	5-10 p 5-15 m/sq	2-5 p 2-5 m/sl	5-10 p 2-5 m/eq	2-5 p 2-5 m/et				2-5 p 2-5 m/er	1-2 gd <1 m/eq			35-60 g pf
I3′	Gray Orthoclase Porphyry Alkali Syenite	porphyritic	5-10 p 5-10 m/sq			2-5 p 2-5 m/et				2-5 p 2-5 m/er	1-2 gd <1 m/eq			35-65 g pi
I4a	Dark Orthoclase Porphyry Syenite	porphyritic	5-10 p 5-15 m/st	2-5 p 2-5 m/sl	5-10 p 1-2 m/el	5-10 p 1-4 m/et		1-2 p 5-10 m/aq		2-5 p 2-5 m/er	1-2 gd <1 m/eq			25-50 g pf
I4b	Dark Orthoclase Porphyry Alkali Syenite	porphyritic	10-15 p 5-15 m/st		5-10 p 1-4 m/el			1-2 p 20-40 m/sq		2-5 p 2-5 m/er	1-2 gd <1 m/eq			25-50 g pf
I4b′	Melanite Porphyry Alkali Syenite	porphyritic	5-10 p 5-15 m/st						1-2 p 1-4 m/eq	2-5 p 2-5 m/er	1-2 gd <1 m/eq			35-60 g pi
I5	Biotite-Bearing Orthoclase Porphyry Syenite	porphyritic	10-20 p 4-10 m/sly	2-5 p 2-5 m/el	2-5 p 2-10 m/sl	5-15 p 1-2 m/et				2-5 p 2-5 m/er	1-2 gd <1 m/eq			25-50 g pi
I6	Monzonite	equigranular/ seriate	10-25 e 2-10 m/sl	10-25 e 2-10 m/sl	20-30 e 2-5 m/sl	2-5 e 2-5 m/st				2-5 gd 1-2 m/er		2-5 gd <1 m/el		15-35 g pc
I7	Orthoclase Porphyry Alkali Syenite	porphyry	5-10 p 4-10 m/sl		2-5 p 1-3 m/sr	2-5 p 2-5 m/et				2-5 p <1 m/er	<1-2 gd 1-2 m/eq			35-60 g pm
I8	Monzodiorite	equigranular/ seriate/ porphyritic	2-10 e/p 5-10 m/st	1-2 e 2-5 m/sl	10-20 e 2-5 m/el					2-5 p 1-5 m/er	1-2 gd <1 m/eq			15-40 g pf
I9a	Hornblende-Bearing Orthoclase Megaporphyry Syenite	megaporphyritic/ hiatal	10-20 p 1-10 c/ely	5-10 p 2-5 m/sl	5-10 p 2-5 m/sl	2-5 p 2-5 m/et	2-5 p 2-5 m/el			2-5 gd 2-5 m/er	5-10 gd <1 m/eq	1-2 gd 2-5 m/el		20-40 g pf
I9b	Hornblende-Bearing Orthoclase Megaporphyry Syenite	megaporphyritic/ hiatal	10-20 p 1-20 c/ely	5-10 p 2-5 m/sl	5-10 p 2-5 m/sl	2-5 p 2-5 m/et	2-5 p 2-5 m/el			2-5 gd 2-5 m/er	5-10 gd <1 m/eq	1-2 gd 2-5 m/el		20-40 g pi
I9b′	Orthoclase Megaporphyry Syenite	megaporphyritic	10-20 p 1-20 c/ely	5-10 p 2-5 m/sl	5-10 p 2-5 m/sl	2-5 p 2-5 m/et				2-5 gd 2-5 m/er	5-10 gd <1 m/eq	1-2 gd 2-5 m/el		20-45 g pc
I10	Biotite-Bearing Orthoclase Porphyry Alkali Syenite	equigranular/ hiatal	1-5 p 5-10 m/el		2-5 e <1-3 m/sr	15-30 e <1-3 m/a				<1 gd <1 m/er	2-10 gd <1-3 m/a			60-80 g pm
I11	Orthoclase Porphyry Syenite	porphyritic	10-15 p 2-5 m/sly	2-5 p 1-2 m/sl	5-10 p 1-2 m/el	2-5 p 1-2 m/et				1-2 gd 1-2 m/er				40-75 g pi
I11a	Clinopyroxene-Biotite Porphyry Syenite	porphyritic	<1-15 p 5-10 m/el	2-5 p 1-2 m/sl	15-20 p 2-5 m/el	15-20 p 2-5 m/et				2-5 gd 2-10 m/er	2-10 gd <1-3 m/a			40-65 g pf
I12	Lavender Quartz Syenite	equigranular/ seriate	25-50 e/p 5-10 m/el	10-20 e/p 2-5 m/sly	2-10 e 1-3 m/el	1-2 e 1-3 m/et							2-10 e 1-2 m/sq	30-60 g pv

Abbreviations:

Top Line: p = phenocryst
e = equigranule
g = groundmass
d = disseminated

Bottom Line: m = millimetres
c = centimetres
e = euhedral
s = subhedral
a = anhedral

l = elongate
t = tabular
r = prismatic
q = equant
p = pilotaxitic (felted)
y = trachytic
f = fine grained
i = medium grained
c = coarse grained
v = very coarse grained

Minerals: OR = Orthoclase
PL = Plagioclase
CP = Clinopyroxene
BT = Biotite
HB = Hornblende
PS = Pseudoleucite
ME = Melanite
AP = Apatite
MT = Magnetite
TI = Titanite

QZ = Quartz
KS = Alkali Feldspar (groundmass)

margins of the grains. Concentrations of TiO_2 in these garnets are generally between 3 wt% and 4 wt% and V_2O_5 concentrations are approximately 1 wt%.

Igneous biotite in several intrusions commonly displays kink-banding which may be evidence of a deformational event at elevated temperatures. The igneous biotite displays anomalous brown colours and strong pleochroism similar to hornblende and clinopyroxene which is indicative of a high ferric iron-concentration.

Major oxide geochemistry of least altered samples from the major intrusions at Galore Creek indicates metaluminous and alkaline compositions (Fig. 5). Petrologic relationships between the intrusive phases were investigated by examining conserved element ratios with Pearce element ratio analysis (Pearce, 1968; Russell and Nicholls, 1988; Stanley and Russell, 1989; Russell and Stanley 1990). Igneous phases show constant and distinctive TiO_2/Zr ratios (Fig. 6), which together with various conserved element ratios define four igneous suites or lineages (Table 3). Intrusive phases that have been analyzed and have a common set of conserved element ratios include:

1. I1, I3, I4a/b, I9a/b and I11a intrusions (lineage A),
2. I3′, I5 and I9b′ intrusions (lineage B),
3. I6 and I8 intrusions (lineage C), and
4. I12 intrusion (lineage D).

Lineages A and B are both coarsely K-feldspar and/or pseudoleucite porphyritic whereas lineage C is predominantly equigranular. Magmas in lineages A and B are more chemically evolved syenite and alkali syenite but magmas from lineage C are less evolved monzonite and monzodiorite. Lineage D is silica-saturated whereas the other three lineages are silica-undersaturated. Most of the variation in the lineages can be explained by the fractionation of alkali feldspar based on a Pearce element ratio analysis. Leucite fractionation may have been involved in the evolution of lineage A and plagioclase fractionation may have been important in lineage C. Lineages A and B are syn- to post main-stage mineralization, but lineages C and D are exclusively post main-stage copper mineralization.

The identified intrusive phases at Galore Creek show four distinctive features:

1. **Silica saturation and undersaturation**: Intrusive rocks associated with the four different magmatic lineages as well as the volcanic host rocks in the Galore Creek area are predominantly silica-undersaturated with a few samples showing weak silica-saturated compositions. Apparent variation in the degree of silica saturation may reflect fractionation across the critical plane of silica undersaturation (possibly due to changes in volatile fugacity), sub-solidus re-equilibration, or subsequent hydrothermal alteration and metasomatism.
2. **Intrusive textures**: Early intrusive units (I1 through I5) consist of K-feldspar and pseudoleucite porphyritic dikes and sills. These are succeeded by relatively equigranular intrusions (I6 and I8), K-feldspar porphyritic and megaporphyritic units (I9b through I11), and a relatively equigranular intrusion (I12). Although inconsistent cross-cutting relationships hinder the determination of relative timing among all phases, the general intrusive sequence appears to oscillate between porphyritic and equigranular textures. This may reflect variations in the volatile fugacities of the

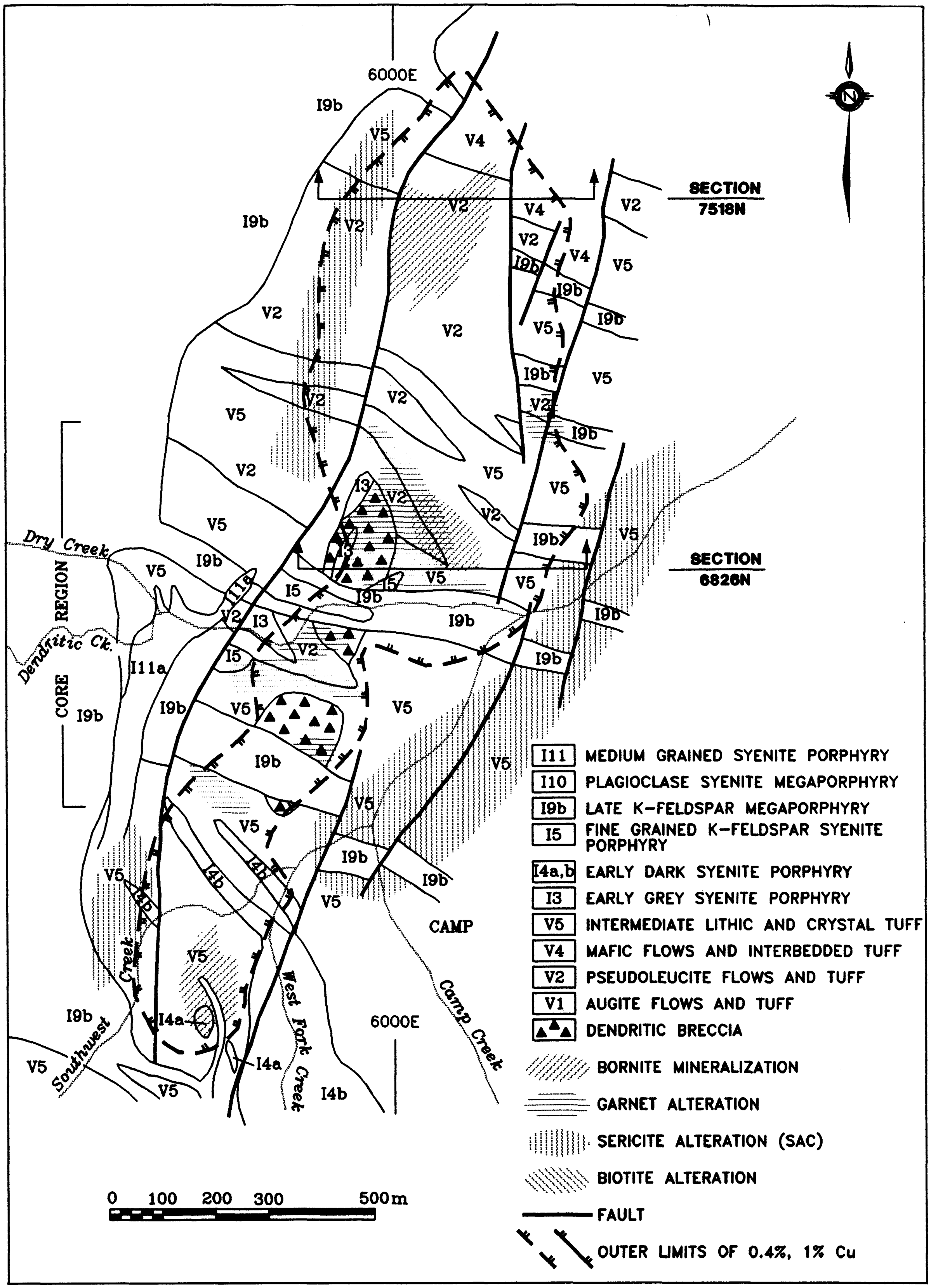

FIGURE 7. Generalized geology of the Central zone. The locations of the sections shown in Figure 8 are indicated.

gently north-dipping, unaltered megaporphyry (I9b) dikes that dilute higher grade mineralization (Fig. 8). A magmatic-hydrothermal breccia known as Dendritic breccia, near the west side of the Central zone, has a maximum width of 150 m and has been traced over a distance of 600 m in a northeast direction. It is variably brecciated, mineralized and highly altered. Remnants of early I3 syenite were traced from section 6139N to section 7303N with the greatest thickness of the I3 intrusion observed on section 6879N in the core of the Central zone. The spatial association of the I3 intrusion with the most intense alteration and mineralization in the core of the Central zone suggests that this intrusion is a significant mineralizing phase.

the Central zone abruptly changes in width. The linear feature extends eastward from the Central zone and bisects the North 110 syenite and the intrusions underlying Saddle Ridge. To the west this structure follows the course of upper Dendritic Creek. It is interpreted to be an early fault.

3. A northeast-striking fault system, identified within the Central zone and elsewhere, forms part of a regional-scale feature that can be traced from east of the Southwest zone, northward beyond the boundary of the claims. The long axes of both early porphyry (I3) and Dendritic breccia in lower Dendritic Creek are aligned parallel to this fault indicating a common regional structural control. Both the I3 intrusion and the magmatic hydrothermal breccia are approximately centred near section 6773N at the intersection of this northeast fault system with the east-trending linear described above. Smaller scale, northeast-striking faults with moderate to steep west dips mark the outer limits of mineralization within the Central zone where up to 200 m of normal postmineralization movement is evident.
4. Several large megaporphyry I9b dikes cut mineralization in the Central zone. The dikes strike west to northwest, have a shallow north dip and truncate relict bedding (Barr, 1966). Some of these dikes may occupy faults.
5. Young, east-trending structures are also evident. In plan view, the Southwest zone shows an east-trending linearity. Elsewhere on the property, east-trending structures are marked by postmineralization, subvertical mafic dikes and felsic dike swarms of probable Tertiary age.

Geophysical Interpretation

A number of important features that relate to lithologies, alteration and structure are recognized from the airborne geophysical data. Generally, patterns of magnetic highs correspond with syenite intrusions while volcanic rocks have relatively low magnetic susceptibilities. Numerous magnetic lineaments parallel to the 010° regional structural trend and a subsidiary east-west trend are apparent in the airborne magnetic data. Some of these lineaments coincide with geologic contacts while others appear to coincide with structurally controlled zones of hydrothermal alteration. The Central zone occurs at the intersection of two regional magnetic lineaments, within a magnetic low, adjacent to a magnetic high. The location of the Southwest zone correlates with a magnetic high caused by an increased magnetite content.

Airborne EM data reveal clusters of negative in-phase responses with a small out-of-phase component that correlate directly with mineralization at the Southwest zone and in the southern half of the Central zone. Similar responses are lateral to mineralization at the Junction zones, the North Rim zone, and the northern half of the Central zone.

Several I.P./resistivity ground surveys have been completed at Galore Creek. Reprocessing of original data showed that high percent frequency effect correlates directly with mineralization in the Central zone. Data from surveys in 1991, in the areas of the Central, Southwest and North Junction zones, showed that moderate to strong I.P. chargeabilities define linear anomalies related in part to chalcopyrite and bornite mineralization. The chargeability anomaly over the Southwest zone is nearly 500 m in diameter and is a response to the large volume of disseminated pyrite that extends beyond the copper mineralization.

Mineralized Zones

Central Zone

Situated near the eastern margin of the Galore Creek intrusive-volcanic complex, the Central zone is the largest known Cu-Au deposit with mineralization exceeding 1700 m in length along a strike of 015°. The zone is up to 500 m wide and dips steeply to the west to a depth of at least 450 m. Mineralization is exposed in the southern part of the Central zone, but elsewhere it is covered by up to 75 m of glacial overburden. More than 80% of the copper-gold mineralization is hosted by volcanic rocks. The grade of mineralization commonly exceeds 1.0% Cu decreasing rapidly at the margin of the zone. Figure 7 shows the generalized geology of the complex Central zone with the north unexposed half projected to the 600 m level. Two generalized cross-sections through the core region and the north part of the zone are shown in Figure 8.

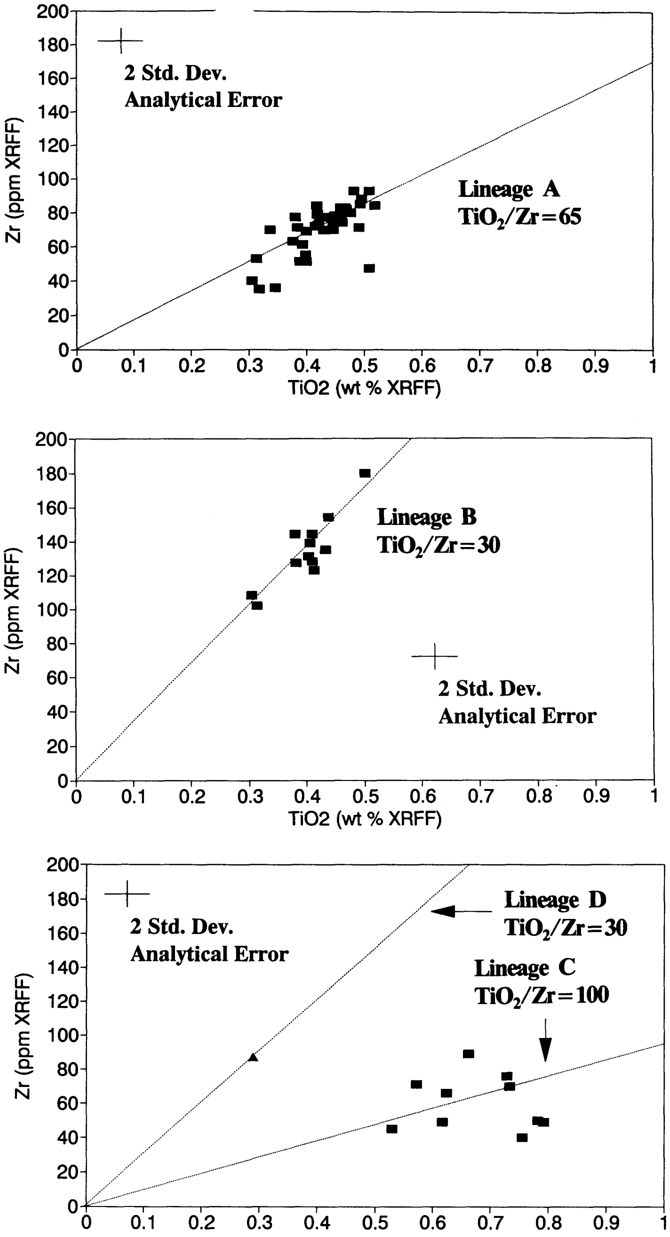

FIGURE 6. TiO_2/Zr plots for least altered samples of Galore Creek intrusive rocks showing different ratios for lineages A, B, and C. Lineage D (I12 phase) is silica-saturated but has a similar ratio to lineage A.

The Central zone shows internal variations in mineralization and alteration. In the northern part of the Central zone, mineralization is hosted by pseudoleucite-bearing volcanic rocks interbedded with augite-bearing and intermediate flows, and minor mafic volcanic rocks. In the southern part, mineralization occurs in a thick succession of K-feldspar crystal lithic tuff cut by early I4a and I4b syenite intrusions. The complicated core region of the Central zone (Fig. 7) consists of a highly altered succession of interbedded pseudoleucite-bearing and minor augite-bearing volcanic rocks, as well as brecciated and unbrecciated I3 syenite. The volcanic sequence dips moderately to the southwest and is cut by two, east-striking, calcic and potassic assemblage (Ca-K-silicate) that includes garnet, biotite, K-feldspar, anhydrite and apatite. The concentrations of garnet and biotite are commonly antipathetic. Where they occur together, garnet appears to be the earlier of the two alteration minerals although, in places, coarse biotite and garnet appear to have intergrown in equilibrium. Hydrothermal garnet occurs as massive replacements, veins and vein envelopes. Biotite forms coarse flakes in veins, locally intergrown with garnet, and finely disseminated grains. Hydrothermal K-feldspar forms a pervasive replacement of igneous feldspars that is difficult to place in a paragenetic sequence. Anhydrite partially replaces garnet and occurs interstitially to, or intergrown with coarse-grained garnet, and locally, biotite. Anhydrite also forms extensive cross-cutting veins. Apatite is enclosed by coarse-grained garnets, forms discrete garnet-apatite veins and is disseminated within secondary K-feldspar and biotite. Other minor minerals include diopside, albite, carbonate, analcite, sodalite and fluorite. Albite and carbonate form discrete veins that appear to post-date the garnet-biotite alteration. Minor analcite, sodalite and fluorite occupy a similar paragenetic position to anhydrite; they are interstitial to garnets and replace early K-feldspar, but their precise timing is uncertain. The dominant early alteration is locally overprinted by patchy development of sericite-anhydrite-carbonate-pyrite ± hematite alteration (referred to as SAC), particularly on the outer parts of the zone (Fig. 7).

Hydrothermal garnets vary from isotropic to anisotropic in thin section. The coarse-grained garnets commonly show complex zoning with dark brown cores surrounded by multiple bands of pale and dark garnet. The majority of the hydrothermal garnets are andraditic (Ad 75-90) with individual bands representing variations in the grossular content (down to Ad 10) (J. Lang, pers. comm., 1993). Some of the hydrothermal garnets have elevated TiO_2 (up to 4 wt%) concentrated in the core and adjacent dark bands. These garnets may be classified as melanite with compositions similar to the igneous melanite garnets that occur in some of the intrusive phases.

Coarse-grained biotite is commonly zoned from brown pleochroic cores to green margins. Fine-grained biotite is disseminated and forms aggregates after probable mafic phenocrysts and fragments. Primary apatite phenocrysts in altered rocks are cloudy due to the presence of fluid inclusions. Hydrothermal apatite occurs as individual discrete prismatic grains within garnet, biotite and K-feldspar, and also forms veins, aggregates and disseminated needles. Both types of apatite are relatively uniform in composition and are classified as fluorapatite.

South part: South of section 6773N, in the southern part of the Central zone, the hydrothermal alteration is intense and pervasive, yet porphyritic textures in the I4 intrusions and fragmental textures in the volcanic protolith are well preserved. Alteration throughout these host rocks is dominated by hydrothermal K-feldspar, biotite, magnetite and hematite (K-silicate). K-feldspar replaces primary phenocrysts and the groundmass in the I4 intrusions. Hydrothermal biotite occurs after mafic phenocrysts and lithic fragments. Locally, biotite constitutes more than 20% of the matrix. Disseminated magnetite (up to 5%) is commonly intergrown with specular hematite. Widely disseminated, to concentrated patches of hydrothermal apatite and minor rutile are associated with biotite. In this region, anhydrite is less abundant than in the core region of the Central zone and occurs mainly as cross-cutting veins. Minor albite-epidote veins appear to represent a secondary alteration that preceded a locally extensive SAC overprint. SAC alteration is prevalent along the southeast flank of the Central zone (Fig. 7). Late hematite is associated with carbonate and anhydrite in SAC alteration where it replaces the margins and cracks in magnetite grains.

North part: In the northern part of the Central zone (north of section 7091N) alteration is also complex and often texture-destructive. The dominant alteration consists of coarse-grained hydrothermal biotite (up to 40% of the rock), with K-feldspar, anhydrite, magnetite (up to 10%) and minor hematite. Magnetite and bladed specular hematite are commonly intergrown and are closely associated with bornite-chalcopyrite mineralization.

Hydrothermal apatite and minor rutile are present in amounts similar to that found in the southern part of the Central zone. The SAC alteration extensively overprints the earlier K-silicate alteration in the northwest part of the Central zone (Fig. 7). With increasing intensity, SAC alteration varies from interconnected fractures and irregular patches to coalescing patches, and finally, to complete replacement of the rock. The SAC overprint is marked by increasing pyrite ± hematite and decreasing bornite-chalcopyrite suggesting that copper was remobilized during SAC alteration.

In the northeast part of the Central zone, some individual augite-bearing volcaniclastic units are altered to calc-silicate mineral assemblages over widths up to a few metres. This alteration is characterized by an early assemblage of diopside and garnet partially replaced by biotite, epidote and carbonate. The lithological control on this alteration, suggested by the concentration of calc-silicate minerals in the matrix of fragmental protoliths, and textural evidence that indicates calc-silicate minerals preceded K-silicate alteration and mineralization, differentiate this localized skarn alteration (*sensu stricto*) from the extensive garnet-rich alteration in the core region of the Central zone. These small zones may reflect the development of early hornfels and skarn alteration in calcareous units that occur mainly in the northern part of the Central zone.

Controls: Alteration in the Central zone shows two main controls. The first is a spatial zonation around the core of the zone, and the second is a temporal variation that is present throughout the zone, but is particularly important in the northern part. Hydrothermal alteration changes from Ca-K-silicate in the core region to a more conventional porphyry-style intense K-silicate alteration toward both the south and north parts of the Central zone. The alteration in the core is complex and includes minerals such as garnet, diopside, analcite, sodalite and fluorite that are not widely documented from calc-alkaline porphyry systems. Although part of the alteration mineral assemblage in the core region (calc-silicate minerals in intrusions and volcanic wall rocks) suggests skarn affinities, the zonation from the Ca-K-silicate core outward to the relatively normal K-silicate assemblage is the reverse of that found in typical porphyry-skarn systems. This zonation does not appear to reflect the influence of specific types or compositions of wall rocks. The decreasing Ca-component in the alteration (decreasing garnet and less anhydrite) from the core region to the north and south regions of the Central zone is accompanied by generally increasing magnetite and early hematite.

The relative timing of Ca-K-silicate and K-silicate alteration in the Central zone is difficult to determine. Complex zoning in garnets and their relationship to a variety of interstitial minerals (biotite, K-feldspar, anhydrite, analcite, sodalite, fluorite and apatite) suggest variations in fluid composition with time, although the magnitude of the variation and the full influence of wall rocks and other factors are unknown. Variations in the spatial and temporal oxidation states of the fluids are also suggested by changes in the iron oxide mineralogy. Given these limitations, the general paragenetic scheme illustrated in Figure 9 approximates the precise timing of different styles and mineralogies of alteration.

Copper mineralization is associated with both early Ca-K-silicate and K-silicate alteration. Disseminated and minor fracture-controlled chalcopyrite occurs throughout the Central zone, and is accompanied by significant disseminated bornite in the northern and southern parts of the zone. Pyrite increases in abundance to the east of the Central zone where up to 5% is present locally. Supergene copper mineralization, as malachite, azurite and chrysocolla is relatively unimportant and occurs primarily on fractures within 60 m of the present erosional surface.

The most important host rocks for mineralization in the north part of the Central zone are pseudoleucite-bearing volcanic rocks. Augite-bearing volcanic rocks appear to have been less receptive. This results in copper mineralization that appears to broadly conform to volcanic stratigraphy with a moderately steep dip to the west in sections 7197N to 7727N (Fig. 7). In the southern part of

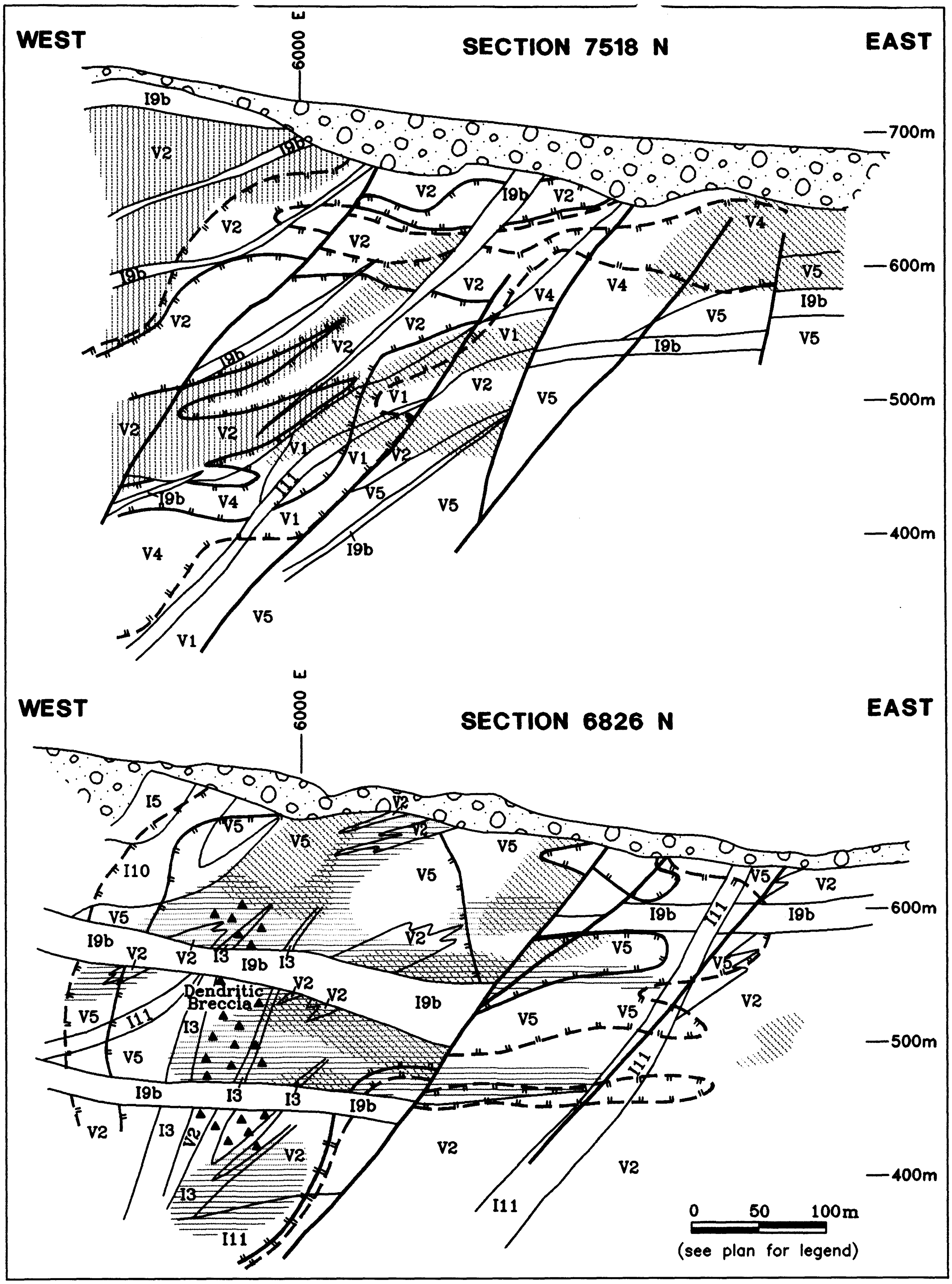

FIGURE 8. Sections 6826N and 7518N through the Central zone.

Core Region part: Much of the core region of the Central zone is intensely altered and protoliths are often unrecognizable. In drill core, discontinuous intervals of altered but recognizable I3 syenite are separated by intervals of pervasively altered rock lacking primary textures. In place, the presence of volcanic rocks is suggested by pseudomorphs of phenocrysts and relict fragmental textures. The shape of the altered phenocrysts suggests original pseudoleucite with textures similar to weakly altered volcanic units found on the ridge to the west of Galore Creek. The contact relations between the I3 intrusion and the probable volcanic country rocks were not observed in drill core.

In the core region, hydrothermal alteration is dominated by a

TABLE 4. Galore Creek resourc

Deposit	Tonnes	Cu %	Au g/t	Ag g/t	Cut-off
Central Zone	233 900 000	0.67	0.35	7 (estimate)	0.27% Cu equivalent
Southwest Zone	42 400 000	0.55	1.03	7 (estimate)	0.27% Cu equivalent
North Junction	7 700 000	1.50			0.40% Cu
Total	284 000 000	0.67			

late megaporphyry I9b intrusions, the lavender porphyry (I12), and the large diatreme breccia in upper Dendritic Creek.

At the Saddle zone, mineralization occurs in a breccia dominated by a matrix of magnetite. Drilling in 1990 intersected two 12 m zones of mineralization grading 0.55% Cu and 2.19 g/t Au, and 2.49% Cu and 3.98 g/t Au, respectively. Except for the mineralization, this breccia is nearly identical to the West Fork breccia east of the Southwest zone.

Discussion

Igneous History

The Galore Creek intrusive suite is dominated by syenites, that are both alkaline and metaluminous. The compositions of igneous hornblendes and clinopyroxenes in intrusions are generally Si-deficient and Al-rich, features consistent with the overall, silica-undersaturated chemistry of the magmas. These, and other primary igneous minerals (melanite and biotite) in the intrusive suite, contain significant ferric iron, which combined with the abundance of magnetite and sphene, attest to the relatively high oxidation state of the Galore Creek magmas.

The intrusions are divided into four different magmatic suites or lineages on the basis of petrography and geochemistry. Lineages A, B and C contain silica-undersaturated intrusions, whereas lineage D is silica-saturated. Two of the lineages are dominated by strongly porphyritic intrusions, while textures in intrusions from the other two are mainly equigranular. The porphyritic intrusions in lineages A and B consist of I1, I3, I4a/b, I9a/b and I11a, and I3', I5 and I9b', respectively. The equigranular phases in lineages C and D are less-evolved and consist of I6 and I8, and I12, respectively.

The textural variability of the intrusive rocks, and the presence of both silica-saturated and silica-undersaturated magmas, suggest that large variations in the fugacities of volatiles occurred in the magmas during fractionation. Evidence for the periodic release of magmatic-hydrothermal fluid includes the abundance of magmatic-hydrothermal breccias, and the extensive hydrothermal alteration and mineralization spatially associated with individual intrusions. In addition, many of the I9b intrusions, previously called garnet- or epidote-syenite megaporphyries (Allen et al., 1976), contain aggregates of garnet and epidote that either replace mafic phenocrysts or occur in miarolitic cavities. The proportions of garnet and epidote vary, and these minerals are often accompanied by sulphides. Garnet aggregates and miarolitic cavity fillings also occur in I5 and I11 phases. Secondary garnet, epidote and sulphides in these intrusions are interpreted to reflect deuteric alteration, internal to individual intrusions, that documents the exsolution of a calcium-rich magmatic fluid phase from the intrusions at Galore Creek.

Alteration

Hydrothermal alteration at Galore Creek differs significantly from that described in other alkaline porphyry Cu-Au deposits of British Columbia (Fox and Cameron, 1991; Lang et al., 1994). The core of the Central zone is dominated by intense Ca-K-silicate alteration (garnet, biotite, K-feldspar, anhydrite), while to the north and south, typical "porphyry style" K-silicate alteration (biotite, K-feldspar) becomes dominant. Both Ca-K-silicate and K-silicate alteration types are associated with the main stage of copper mineralization but the highest cop -gold grades occur in K-silicate altered host rocks. Propylitic alt on, although not well documented, is present in volcanic rocks to the east and north of the Central zone. SAC alteration (sericite, anhydrite, carbonate) overprints Ca-K-silicate and K-silicate alteration, particularly on the periphery of the Central zone. The SAC alteration correlates well with lower copper and gold grades suggesting that these metals may have been leached during overprinting alteration. This style of alteration is not developed in other alkaline porphyry deposits in British Columbia.

Alteration at the Southwest zone is dominated by intense K-silicate alteration that is similar to the north and south parts of the Central zone. The alteration in the other deposits at Galore Creek is also similar to the Central zone although Ca-K-silicate alteration is less abundant.

At least three types of garnet are recognized at Galore Creek:

1. Melanitic garnet occurs as a phenocryst in some intrusive phases, such as I4b.
2. Garnet, locally containing TiO_2 at levels equivalent to the igneous garnets, is the dominant alteration mineral in the core of the Central zone.
3. Garnet also occurs as a deuteric phase in late intrusions, particularly I9 and I11a, and is present in the matrix of late magnetite breccias (West Fork and Saddle zone).

All three types of hydrothermal garnet appear to be related to high temperature magmatic-hydrothermal processes, probably involving silica-undersaturated, calcic magmatic fluids that were generated from silica-undersaturated magmas. Garnet is clearly important in both magmatic and magmatic-hydrothermal events at Galore Creek, and its presence in alteration zones does not appear to be strongly influenced by the composition of wall rocks.

Mineralization

The mineralization consists predominantly of disseminated and minor fracture-controlled hypogene copper sulphides that occur in linear zones suggesting structural control. Chalcopyrite dominates, but significant disseminated bornite is also important in the Central, North Junction, Junction, Middle Creek, West Rim, and Butte zones. The bornite mineralization is closely associated with high levels of gold in the Central, North Junction and Junction zones. Pyrite is not abundant within mineralized zones, except at the Southwest zone, where it is commonly associated with the higher gold grades. In the Central zone, a pattern of higher bornite, magnetite and hematite contents, together with increased gold grades, coincides with a change from Ca-K-silicate alteration in the core to K-silicate alteration to the north and south.

The tabular geometry of the Southwest zone suggests structural control for the localization of mineralization within and outside a diatreme pipe. Presence of altered and copper-mineralized breccia clasts indicate emplacement of the diatreme after other mineralizing events.

Minor mineralization in most intrusive phases, including the youngest syenite intrusions (I12), and a variety of magmatic-hydrothermal and phreatomagmatic (diatreme) breccias of different relative ages indicates a protracted history of copper-gold mineralization at Galore Creek.

Economics and Engineering Studies

The Galore Creek mineral resource (Table 4) is contained in three separate deposits, known as the Central, Southwest and North Junction zones. New estimates of tonnage for the Central and Southwest zones were derived in 1992 by using geostatistical analysis with computer-based models for open pit design. Parameters used in the estimates include pit slopes of 40° and 45° and a bench height of 12 m. The mine waste-to-ore stripping ratio was calculated as 2.2:1. A resource for the North Junction zone was derived using a conventional, cross-sectional polygonal estimate. The copper equivalent grade listed as cutoff grade (Table 4) is the net of all concentrate, smelting and refining recoveries, and reflects paythe Central zone, higher grade mineralization generally occurs as irregular pods in dark K-feldspar-rich volcaniclastic units. These features suggest a primary permeability control for mineralizing fluids.

The copper grades are fairly consistent from north to south along the deposit with the best grades most closely associated with the presence of bornite and intense biotite alteration. Gold grades are variable with higher grades (exceeding 5 g/t Au) closely associated with the abundant bornite, magnetite and hematite in both the northern and southern parts of the Central zone. In contrast, lower gold grades correlate with the intense Ca-K-silicate altered core region. The most intense levels of late SAC alteration show a negative correlation with both copper and gold grades.

Southwest Zone

The Southwest zone is entirely masked by glacial cover in the southern part of the Galore Creek intrusive-volcanic complex. Drilling in 1991 outlined a tabular zone of mineralization, 400 m long and up to 140 m wide. Mineralization dips 60° to the south and has been traced to a depth of 200 m.

In the Southwest zone, a diatreme breccia body about 350 m across cuts a megaporphyry (I9a) intrusion. Megaporphyry (I9b) and syenite dikes cut the breccia and the Southwest zone. Mineralization within the breccia body forms a distinct east-trending linear body that transects the diatreme contact. The highest copper-gold grades and widest sulphide intercepts occur near the western diatreme pipe contact. This mineralization coincides with a geometric irregularity or overhang in the diatreme contact that physically hindered ascending mineralizing fluids to cause them to pond along an east-trending structure.

Alteration in both the breccia and surrounding intrusion is intense but primary textures are well preserved throughout. The K-silicate alteration is most intense in the breccia matrix and consists of biotite, K-feldspar, and magnetite locally intergrown with specular hematite, anhydrite, calcite, albite and apatite. Clasts show a similar but more variable alteration and typically contain a higher proportion of hydrothermal K-feldspar. The I9a intrusion outside the breccia shows moderate to strong K-silicate alteration dominated by hydrothermal K-feldspar with minor biotite, hematite and magnetite.

Copper mineralization occurs mainly as fine-grained, disseminated chalcopyrite within the breccia matrix. Some mineralization extends outward from the breccia as narrow chalcopyrite fracture-fillings in the I9a megaporphyry. Pyrite (4% to 6%) accompanies chalcopyrite although the high contents of chalcopyrite and pyrite tend to be antipathetic. Better copper and gold grades correlate closely with the abundance of biotite, magnetite and early hematite. The Cu:Au ratio is variable. Locally, average gold grades greater than 1 g/t accompany low copper levels and generally higher than average pyrite content.

The alteration mineralogy of the Southwest zone is generally similar to that of the northern and southern parts of the Central zone with more abundant calcite. Some clasts contain mineralized veinlets, truncated by matrix, while others show intense sericitic alteration that contrasts with the K-silicate alteration in the matrix of the breccia. These clasts record earlier mineralizing and alteration events, which based on the intrusive clast types, may correspond to the main-stage copper mineralization in the Central zone.

Junction Zones

Recent exploration at the North Junction and Junction zones considerably extended the known mineralization in both zones, but with diminished grades and widths. Both deposits dip west, strike 020° to 030°, and contain copper-gold mineralization in intensely altered volcanic rocks. Together these two zones are interpreted to have been a single deposit that was originally 1400 m in length before it was faulted. The mineralization is hosted by fine to coarse lapilli tuff and feldspar phyric flows. Alteration consists of K-feldspar flooding, pervasive fine-grained hydrothermal biotite (up to 10%), fine-grained garnet and anhydrite. A large mass of late-mineral I9b megaporphyry truncates mineralization west of the zones.

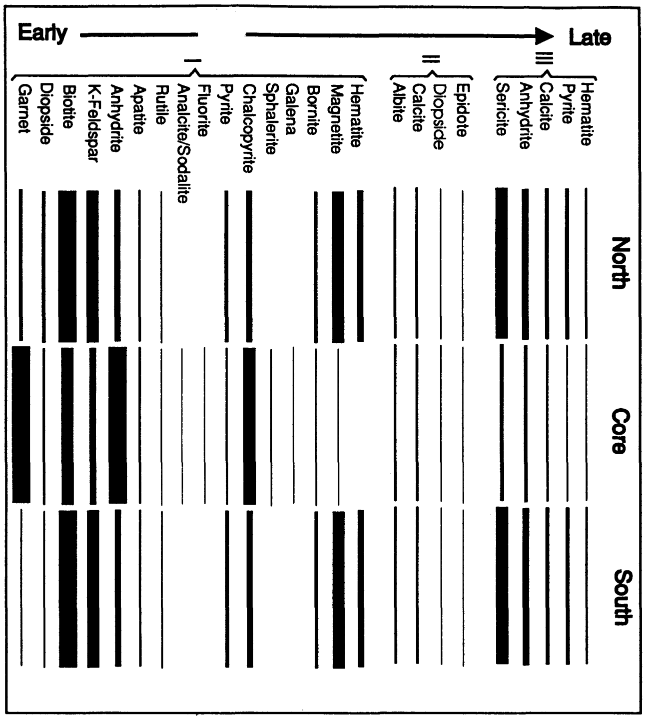

FIGURE 9. Mineral paragenesis for alteration and mineralization in the Central zone at Galore Creek, divided into the north, core, and south parts of the zone. Three groups of minerals are shown representing stages that are based on paragenetic relationships, with the relative importance of each mineral indicated by the width of the bar. The paragenetic order of minerals within each group is approximate, and several minerals in each group formed throughout much of their respective stage; for example, anhydrite in stage I.

Mineralization consists of disseminated chalcopyrite and bornite. Assays for gold from the old coarse reject samples and from recent drilling returned a consistently higher gold content at the North Junction zone (0.5 g/t Au to 2.0 g/t Au) compared with the Junction zone (0.1 g/t Au to 0.2 g/t Au). The higher gold grades correlate with the presence of bornite in the North Junction zone, where mineralization occurs in several irregular bodies, 45 m to 120 m wide, with grades that locally exceed 2.0% Cu below 200 m. The smaller and lower grade Junction zone is less intensely altered, contains less bornite, and higher pyrite.

Other Zones

The Butte and the West Rim zones are located along the western margin of the Galore Creek complex. In both zones, the mineralization dips to the west, has a northeast strike, and occurs as disseminated chalcopyrite and bornite. At the West Rim zone, previous drilling intersected 48.8 m of 0.8% Cu and surface sampling in 1991 indicated increasing copper grade to the north. Drilling in 1991, however, showed that this mineralization was truncated at depth by I9b megaporphyry intrusions. At the Butte zone, mineralization, consisting of bornite with minor chalcocite and chalcopyrite, occurs in K-feldspar-flooded and biotite-altered pseudoleucite-bearing volcanic rocks. At surface, mineralization grades up to 2.18% Cu and 0.5 g/t Au across 86.6 m. As at the West Rim zone, mineralization is truncated at depth by postmineral (I11) intrusions.

Copper-gold mineralization was discovered in 1991 at the new Middle Creek zone, about one kilometre west of the Central zone. Mineralization consists of finely disseminated bornite, chalcopyrite and magnetite, associated with pervasive fine-grained biotite and garnet in an altered, intermediate tuffaceous unit. The size of the mineralized zone is unknown, but it is apparently constrained by able metal.

Preliminary metallurgical test work i 92 on four composite core samples from 1991 drill holes complimented previous work in 1967 on a 45 tonne underground sample. Results from this testwork indicate that conventional flotation on material from the Central zone will obtain a 25% Cu concentrate grade with copper recoveries of 90%, and with gold recoveries between 64% and 74%. Environmental baseline studies were initiated in 1991 and included water quality testing, hydrology surveys, and acid-base accounting.

Conclusions

Recent exploration at Galore Creek has modified previous interpretations of the geology and mineralization. The major igneous and hydrothermal events can now be summarized as follows:

1. The development of a volcanic centre in the late Triassic to earliest Jurassic dominated by alkaline magmatism.
2. Intrusion of an early I3 syenite into the volcanic pile at the intersection of two major regional faults, striking east and northeast.
3. Formation of magmatic-hydrothermal breccias (lower Dendritic Creek breccia) within and adjacent to the I3 intrusion.
4. Generation of the main stage mineralization and hydrothermal alteration. This resulted in pervasive and intense Ca-K-silicate alteration around the I3 intrusion in the core of the Central zone, passing out into K-silicate alteration to the north and south, and propylitic alteration in surrounding rocks.
5. Emplacement of I4 intrusions, followed by the culmination of the main stage mineralizing event. Petrological similarities among the pseudoleucite-bearing I3 and I4 syenites (and the minor I1 and I2 phases) suggest close genetic ties among these intrusions and pseudoleucite-bearing volcanic rocks in the area.
6. Overprinting sericite-anhydrite-carbonate (SAC) alteration, particularly on the fringes of the Central zone, probably during waning magmatic-hydrothermal activity. More than one period of SAC alteration may have occurred.
7. Emplacement of intermineral phases, I5 and possibly some of the I10 and I11 phases. The relative timing of intermineral intrusions and SAC alteration is uncertain and is complicated by the possibility that several periods of SAC alteration may have occurred.
8. Intrusion of late mineral phases, I8, I9a/b and I11a, associated with minor alteration and mineralization. Intrusion of largely unmineralized phases into mineralized zones effectively dilutes the resource.
9. Emplacement of diatreme breccias that host significant mineralization in the Southwest zone, as well as the weak mineralized breccia bodies in upper Dendritic Creek and Dry Creek.
10. Emplacement of the I12 Lavender porphyry, possibly coincident with late, widespread purple K-feldspar veins.
11. Formation of late, magnetite-rich and sulphide-poor, magmatic-hydrothermal breccias (e.g., West Fork). Copper sulphides in the similar Saddle zone breccia demonstrate that mineralization continued late in the history of the Galore Creek intrusive-volcanic complex.
12. Deformation, mainly faulting, and postmineral igneous activity during Cretaceous to mid-Tertiary time.

Galore Creek is classified as a silica-undersaturated alkaline porphyry Cu-Au system (Lang et al., 1994). It demonstrates a complex succession of intrusive and hydrothermal events with the greatest intensity of hydrothermal alteration and mineralization (Central zone) developing early in its history. Younger igneous events all contributed some mineralization, but the only substantial late mineralization event appears to have occurred in the Southwest zone diatreme breccia. A multi-phase intrusive-hydrothermal history at Galore Creek may have contributed to the relatively high copper and gold grades compared to other, simpler alkaline porphyry deposits in British Columbia.

Part of the alteration r ralogy in the core region of the Central zone may be classified as n-type. Such a classification, however, does not apply to the whole Central zone, which is dominated by K-silicate alteration. Furthermore, classification of the Central zone as a skarn obscures the relationship between the Ca-K-silicate and K-silicate alteration, and the overall characteristics of the alkaline porphyry. The deposits at Galore Creek share many of the general features of the British Columbia alkaline porphyry Cu-Au deposits (Fox and Cameron, 1991). More research is needed to fully explain the large size and high average copper grade of the Central zone, the presence of abundant garnet in the Ca-K-silicate alteration, as well as the relationship between the various alteration types and copper-gold grades.

The presence of a volcanic sequence that hosts apparently comagmatic intrusions, dominated by dikes and sills, and associated magmatic-hydrothermal and diatreme breccias suggests that the Galore Creek system formed at a relatively high, subvolcanic level. Galore Creek is the only deposit of the alkaline suite that was emplaced into its own volcanic carapace, and therefore, where a relatively high level of emplacement can be documented. No data are currently available to provide a more precise estimate of paleodepth.

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