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The Geology and Geochemistry of the Carolin Gold Deposit, Southwestern British Columbia, Canada

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ABSTRACT

The Carolin gold deposit of southwestern British Columbia is characterized by pyrrhotite, pyrite, arsenopyrite, albitic alteration, and quartz veining. Gold is associated mainly with sulphides, and the ore contains sporadic trace enrichment of Sb, Mo, Zn and Cu.

The mesothermal, replacement-type mineralization is both lithologically and structurally controlled. It is hosted by turbiditic wackes, siltstones, and conglomerates of the Jurassic Ladner Group, close to their unconformable, locally sheared contact with greenstones of the Triassic (?) Spider Peak Formation, and their faulted contact with ultramafic rocks of the Coquihalla serpentine belt. The host rocks were tectonically inverted and subsequently folded. However, the vertical pyrite-pyrrhotite zoning in the deposit suggests it is upright and therefore postdates the structural overturning event. Mineralization is concentrated along the hinge of a disrupted antiformal fold, and the orebodies exhibit a saddle-reef-like morphology.

Individual ore horizons are associated with potassium and barium depletion envelopes and a drop in K_2O/Na_2O ratios. The deposit as a whole is enveloped by zones of potassium depletion, sodium enrichment, and mineral alteration that extend several hundred metres into the country rocks. The alteration mineralogy comprises a wide, outer chloritic ± sericite zone and a narrow, inner albitic zone. The albitic zone includes sulphide-rich horizons that carry gold.

In this district, lithogeochemical sampling is a viable regional exploration method for discovering similar, sodium-enriched gold deposits. The potassium and barium depletion envelopes surrounding the auriferous horizons form valuable exploration drill targets.

RESUME

Le gisement d'or de Carolin au Sud-Ouest de la Colombie Britannique est caractérisé par la présence de pyrrhotite, pyrite, mispickel, une altération albitique et des veines de quartz. L'or est surtout associé avec les sulfures, et il contient des traces sporadiques de Sb, Mo, Zn et Cu.

La minéralisation mésothermale de type de remplacement est contrôlée par la lithologie et la structure. Elle est encaissée par des wackes de courants de turbidité, des aleuronites et des conglomérats du Groupe Jurassique de Ladner, près de leur contact discordant, et parfois cisaillé, avec les roches vertes Triassiques (?) de la Formation de Spider Peak et de leur contact faillé avec les roches ultramafiques de la ceinture de serpentine de Coquihalla. Les roches hôtes ont été tectoniquement renversées et ensuite plissées. La zonation verticale de pyrite-pyrrhotite du gisement suggère que le gisement est droit et il est plus jeune que l'événement de renversement structural. La minéralisation est concentrée le long de la charnière d'une faille antiforme rompue et les gîtes montrent une morphologie semblable aux voûtes anticlinales.

Les horizons individuels de minerai sont associés avec des enveloppes appauvries en potassium et baryum et une baisse du rapport de K_2O/Na_2O. Le gisement luimême est enveloppé par des zones d'appauvrissement en potassium, d'enrichissement en sodium, et une altération qui s'étend quelques centaines de mètres dans les roches encaissantes. La minéralogie de l'altération renferme une large zone extérieure de chlorite ± séricite et une étroite zone intérieure d'albite. La zone albitique comprend les horizons riches en sulfures qui contiennent l'or.

Dans cette région, l'échantillonage lithogéochimique est une méthode viable d'exploration régionale pour découvrir des gisements d'or semblables à Carolin qui sont enrichis en sodium. Les enveloppes appauvries en potassium et baryum qui encadrent les horizons aurifères forment une cible valable pour le forage d'exploration.

INTRODUCTION

The Carolin gold mine lies approximately 120 km east of Vancouver and 20 km northeast of Hope in southwestern British Columbia (Figure 1). The deposit forms part of the "Coquihalla gold belt" which, in addition to the Carolin mine, comprises 4 former producers and 19 minor gold occurrences (Ray, 1983). Most of the gold in the belt is hosted in narrow, tension-fracture-filled quartz veins. However, at Carolin mine the mesothermal, epigenetic mineralization forms saddle-reef-like orebodies characterized by the introduction of sulphides, albite, quartz and gold.

At the time of intial development, the Carolin deposit comprised reserves of 1.5 million tonnes grading 4.4 g/t Au (at a cut-off grade of 2.7 g/t Au). The mineralization is hosted by Jurassic metasedimentary rocks of the Ladner Group, close to both their unconformable contact with Early Triassic (?) greenstones of the Spider Peak Formation and their faulted contact with ultramafic rocks of the Coquihalla serpentine belt (Figure 1).

EXPLORATION AND MINING HISTORY

The Carolin mine claims were first staked in 1915, and the mineralized surface exposures of the "Idaho zone", the gold deposit which later comprised the Carolin mine operation, were originally described by Cairnes (1929). In 1973, the property was purchased by Carolin Mines Ltd., who conducted a major exploration and drilling program; by 1974, the mining potential of the Idaho zone was realized. The mill, with a 1360 tonne per day capacity, was completed in 1981 and milling on a large scale began in December 1981. Details on the initial mining methods and milling procedures are given by Samuels (1981). Between 1982 and 1984, Carolin mine produced a total of 1354 kg of gold from 799 119 tonnes of ore milled. However, due to poor gold recoveries, environmental concerns and low world gold prices, the mine closed at the end of 1984.

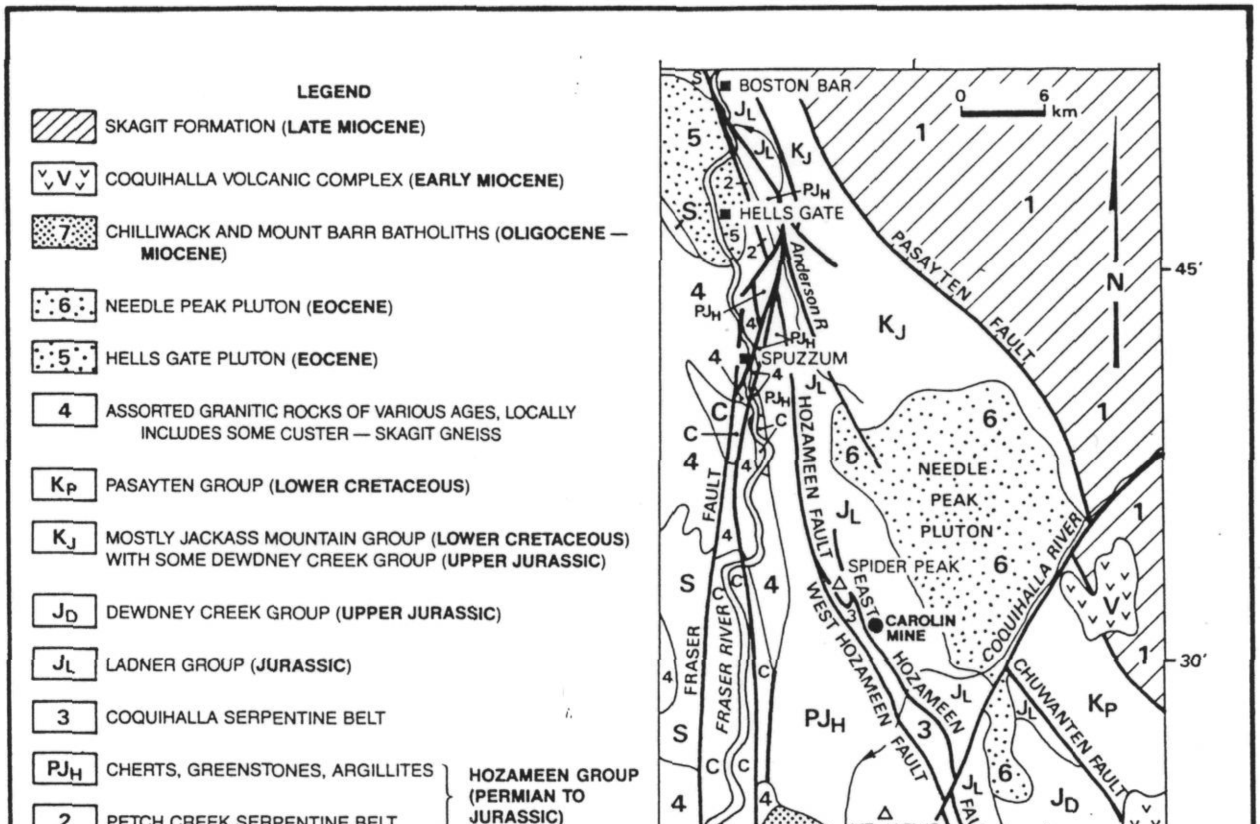

Figure 1. Regional geology of the Hope – Boston Bar area showing location of the Carolin mine. (Adapted after Monger, 1970; Ray, 1986a).

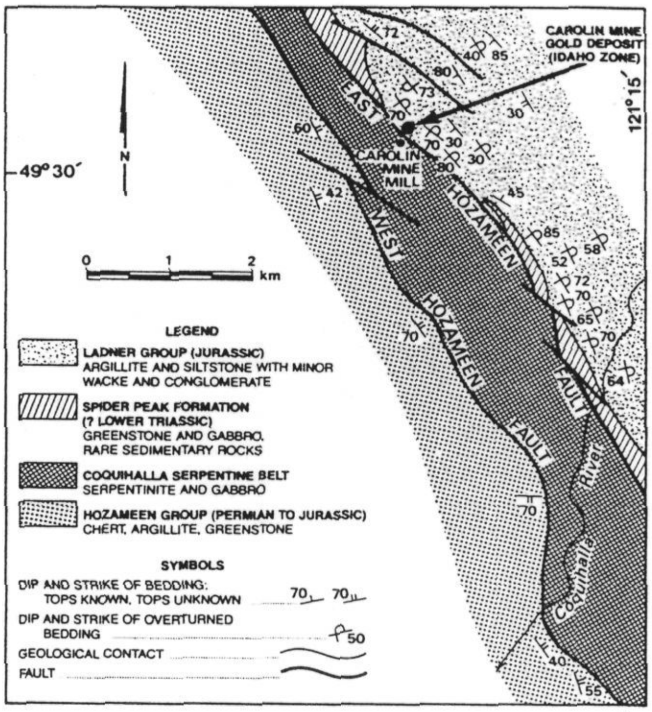

Figure 2a. Geology of the Carolin mine-Coquihalla River district.

REGIONAL GEOLOGY

The regional geology of the Carolin mine – Hope area is shown on Figure 1. The area is situated within the Cascade Mountains physiographic unit (Holland, 1976), at the southern end of the Coast Plutonic Complex close to its eastern boundary with the Intermontane Belt. The mine, like most gold occurrences in the Coquihalla gold belt, lies close to the faulted eastern margin of the Coquihalla serpentine belt (Figures 1 and 2a). This steeply dipping, north-northwest trending ultramafic unit separates two distinct crustal domains. To the west is a highly deformed oceanic assemblage of greenstones, cherts, argillites, minor ultramafic rocks and rare limestones of the Hozameen Group (Daly, 1912). The Hozameen Group ranges from Permian to Middle Jurassic in age (Haugerud, 1985) and probably represents a dismembered ophiolite succession (Ray, 1986a).

East of the Coquihalla serpentine belt are turbidite and successor basin deposits of the Pasayten Trough (Coates, 1970) which range from Early Jurassic to Early Cretaceous in age (Coates, 1974) and have an estimated maximum thickness of between 9000 and 12 000 m. Marine siltstones, argillites, and minor wackes and conglomerates of the Lower to Upper Jurassic Ladner Group (Cairnes, 1924; Ray, 1986a) are the oldest sedimentary rocks in the Pasayten Trough. The Ladner Group has an estimated maximum thickness of 2000 m and comprises a broad, upward fining stratigraphic sequence. This consists of a locally developed lower unit characterized by coarse clastic sedimentary rocks, a middle unit of largely well-bedded, turbiditic siltstone, and a thick upper unit dominated by poorly bedded, carbonaceous, pyritiferous and slaty argillites (Figure 2b). The lower, coarse clastic unit in the Ladner Group is economically important because it hosts many of the gold occurrences in the Coquihalla gold belt, including the Carolin deposit (Shearer and Niels, 1983). The lower unit is best developed near the mine where it is approximately 200 m thick (Figure 2b), but to the north and south it rapidly pinches out. The base of the Ladner Group is marked locally by a conglomerate, generally <10 m thick.

The Ladner Group is interpreted to represent an easterly derived turbidite prism deposited in a deep water marine environment. The middle and upper units were laid down under low energy conditions, but deposition of the lower unit involved high density turbidite currents, chaotic slumping, and mass gravity transport. The lower unit is believed to represent deep water channel slope or turbidite fan sediments, and the conglomeratic horizons may represent olistostromes and debris flow deposits (Ray, 1986a).

Unconformably underlying the Ladner Group, and forming a basement to rocks in the Pasayten Trough, is the Spider Peak Formation (Figure 2b). This has a maximum stratigraphic thickness of 500 m and is a predominantly volcanic greenstone sequence of possible Early Triassic age (Ray, 1986a). The formation is traceable for more than 15 km along the eastern, faulted margin of the Coquihalla serpentine belt, and generally forms a thin, discontinuous strip separating the belt from the Ladner Group further east (Figure 2a). Greenstones in the formation represent a geochemically homogeneous suite of subalkaline, spilitized sea floor basalts (Table 1) that probably formed within a spreading ridge environment (Ray, 1986a).

The Coquihalla serpentine belt exceeds 50 km in discontinuous strike length (Figure 1) and reaches its maximum development in the Carolin mine – Coquihalla

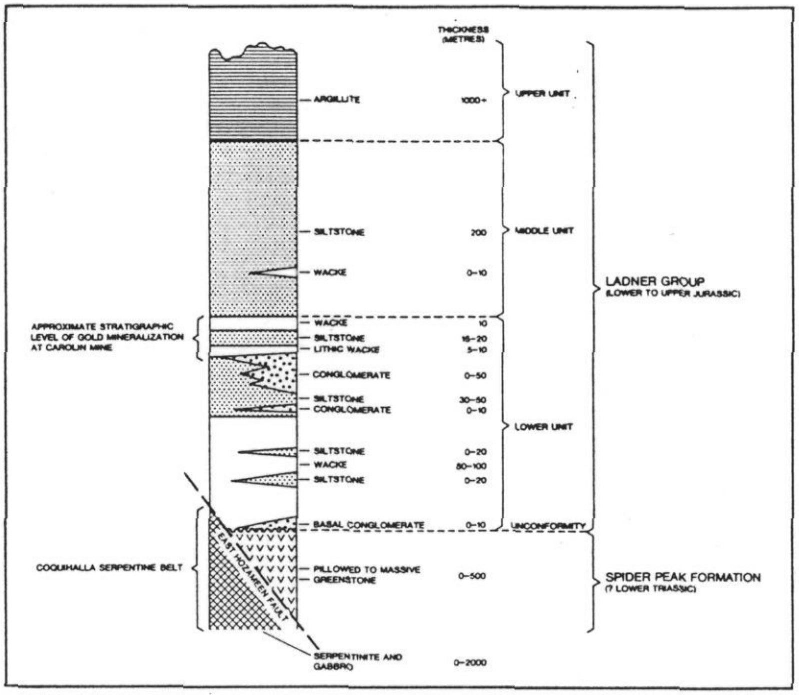

Figure 2b. Stratigraphy in the Carolin mine area.

River area, where it exceeds 2 km in outcrop width (Figure 2a). The eastern and western margins of the belt are sharply defined by two major breaks: the East and West Hozameen Faults (Figures 1 and 2a). The belt narrows to the north and south until the Hozameen and Ladner Groups are separated only by a single fracture, the Hozameen Fault (Figure 1). Dark, highly sheared to massive serpentinite characterizes the belt. However, coarse to fine grained intrusive rocks of gabbroic composition are also common; these rocks form subparallel lenses up to 250 m wide, generally occupying fault-bounded boudins within serpentinite. In several localities adjacent to the East Hozameen Fault, the serpentine belt also contains tectonic slices of magnesite and fuchsite-bearing quartz carbonate rock ("listwanite") up to 100 m in width. An average of geochemical analyses from twelve serpentinite samples from the belt is given in Table 1.

The East Hozameen Fault, due to its proximity to many gold occurrences, including the Carolin deposit, has been studied in detail (Cairnes, 1929; Cochrane et al., 1974; Anderson, 1976; Cardinal, 1981, 1982; Ray, 1982, 1983, 1984, 1986a, 1986b; Wright et al., 1982). The fault generally dips steeply eastward, but locally reverses attitude to a westward dip. The western margin of the serpentine belt, the West Hozameen Fault (Figures 1 and 2a), represents a regionally important, subvertical fracture, but it is not apparently associated with gold mineralization. The composite Hozameen Fault system is believed to have undergone an early period of easterly directed thrusting, followed by regional dextral transcurrent movement (Ray, 1986a).

Sedimentary rocks in the Pasayten Trough are cut by a variety of small intrusive bodies ranging in composition from gabbro to granodiorite to syenite (Cairnes, 1924; Ray, 1982) as well as one major intrusion, the Needle Peak Pluton (Monger, 1970). This granite-granodiorite intrusion exceeds 200 km^2 in area (Figure 1) and has been dated at 40 Ma by K/Ar methods (Wanless et al., 1967, Monger, 1970). It is spatially associated with swarms of sodic felsic sills and dikes which are widespread in the Ladner Group, but are absent west of the Hozameen Fault system (Ray, 1986a). These felsic bodies apparently predate the last major dextral transcurrent movement along the fault.

GEOLOGY OF THE CAROLIN MINE AREA

The surface geology around Carolin mine (Ray, 1986a) is shown on Figure 3. To the east are metasedimentary rocks of the Ladner Group and massive to pillowed volcanic greenstones of the Spider Peak Formation. These are separated from serpentinites of the Coquihalla serpentine belt further west by the East Hozameen Fault. The gold-bearing Idaho zone, which forms the Carolin deposit, outcrops approximately 150 m east of this fracture (Figure 3). The unconformable contact between the older Spider Peak Formation and the Ladner Group is not exposed in the mine area. Consequently, the existence of a basal conglomerate in the Ladner Group at the mine is unproven (Figure 2b), although it is exposed elsewhere in the district. The Ladner Group succession at Carolin mine comprises an approximately 200 m thick heterogeneous, coarsely clastic lower unit, which is overlain in turn by an approximately 200 m thick middle unit of siltstone, and an upper slaty argillite unit more than 1000 m thick (Figure 2b). Graded bedding is widespread in the siltstones and wackes; other less common features include cross-bedding, flame structures, chaotic slumping and rip-up clasts.

TABLE 1. ANALYSES OF VARIOUS ROCK TYPES FROM THE CAROLIN MINE DISTRICT.

					Unmineralized, albite bearing Ladner Group wackes		Idaho Zone - Carolin Mine			
	Spider Peak Formation (1)	Coquihalla Serpentine Belt (2)	Ladner Group unmineralized wacke (3) 25459*	Ladner Group unmineralized siltstone (4) 30225*	(5) 26691*	(6) 30179*	No. 2 Orebody mineralized wackes (7) 26686*	(8) 26684*	No. 1 Orebody mineralized wackes (9) 26842*	(10) 26843
SiO_2	49.71	39.14	56.42	57.17	55.20	57.33	65.67	50.56	69.80	54.20
TiO_2	1.57	0.06	0.97	0.76	0.79	1.16	0.43	0.74	0.35	0.75
Al_2O_3	14.48	1.67	15.90	17.43	15.32	17.55	14.35	14.18	10.76	17.22
Fe_2O_3	1.19	4.74	8.13	8.82	7.48	7.99	3.73	6.57	3.11	9.97
FeO	8.82	2.39	-	-	-	-	0.63	1.98	2.36	8.43
MgO	6.93	37.64	3.01	5.15	1.90	3.92	0.60	1.75	1.16	2.48
CaO	6.27	0.23	2.51	1.95	5.71	0.10	1.76	7.06	3.37	1.95
Na_2O	4.87	<0.06	4.19	2.38	6.04	7.53	7.77	7.39	6.25	8.12
K_2O	0.26	<0.01	1.70	1.63	0.54	0.48	0.11	0.35	0.17	0.20
MnO	0.18	0.11	0.17	0.08	0.16	0.07	0.42	0.13	0.06	0.11
H_2O^+	3.10	11.90	-	-	-	-	0.32	0.56	0.15	1.97
Total	97.38	97.95	93.0	95.37	93.14	96.13	95.79	91.27	97.54	105.4
Au	-	-	-	<0.3 ppm	<0.3 ppm	<0.3 ppm	11.8 ppm	2.4 ppm	7.4 ppm	5.4 ppm
Ag	-	-	-	<0.3 ppm	<0.3 ppm	<0.3 ppm	2.6 ppm	1.8 ppm	<0.3 ppm	<0.3 ppm
As	-	-	-	<20 ppm	24.0 ppm	<20 ppm	2.67%	1.02%	718 ppm	649 ppm
Cu	-	-	-	72 ppm	53 ppm	54 ppm	13 ppm	99 ppm	35 ppm	91 ppm
Hg	-	-	-	138 ppb	<15 ppb	54 ppb	<15 ppb	23 ppb	16 ppb	19 ppb
Zn	-	-	-	112 ppm	81 ppm	99 ppm	51 ppm	78 ppm	-	-
Mo	-	-	-	<4 ppm	<4 ppm	<4 ppm	80 ppm	16 ppm	<2 ppm	2 ppm
Sb	-	-	-	<10.0 ppm	<10.0 ppm	<10.0 ppm	18.5 ppm	12 ppm	<10 ppm	<10 ppm
BaO	-	-	-	184 ppm	240 ppm	80 ppm	45 ppm	63 ppm	40 ppm	60 ppm
Co	-	-	-	25 ppm	19 ppm	12 ppm	10 ppm	15 ppm	-	-
CO_2	-	-	-	1.7%	4.5%	0.42%	2.20%	7.62%	4.36%	1.76%
S	-	-	-	0.11%	0.04%	0.05%	0.30%	0.7%	0.97%	1.87%

*Laboratory sample number. - = Analysis not completed for element.
1 - Average of 10 greenstone samples from the Spider Peak Formation (after Ray, 1986a).
2 - Average of 12 serpentinite samples from the Coquihalla serpentine belt (Ray, In prep.).
3 - Unmineralized wacke (Ladner Group - lower unit), 2.3 kilometres north of Carolin mine.
4 - Unmineralized, thin-bedded siltstone (Ladner Group - middle unit), 500 metres east of Carolin mine.
5 - Albitized, unmineralized wacke with calcite veining, Drill hole IU-49.
6 - Albitized, unmineralized wacke adjacent to the surface exposure of the Idaho zone.
7 - Albitized, sulphide-bearing wacke in the hangingwall of Gold Zone A, Drill hole IU-49 (see Figs. 6A and 6B).
8 - Albitized, sulphide-bearing wacke with ankerite veins. Central portion of Gold Zone A, Drill hole IU-49 (see Figs. 6A and 6B).
9 - Albitized, sulphide-bearing wacke. Gold Zone C, Drill hole IU-53 (see Figs. 6A and 6B).
10 - Albitized, sulphide-bearing wacke. Gold Zone C, Drill hole IU-53 (see Figs. 6A and 6B).
All analyses completed at the B.C. Ministry of Energy, Mines and Petroleum Resources, Geochemical Laboratory, Victoria, B.C.
Analytical methods used in Table 1: – Major elements by Flame AAS with a precision of 0.75% relative standard deviation.
– Ag, Co, As, Cu, Zn, Mo, and Sb, by Acid extraction Flame AAS. – H_2O by gravimetric methods.
– Hg by Cold Vapour AAS. – BaO by Fusion AAS. – CO_2 and S by Induction Furnace.

Gold mineralization at Carolin mine is hosted in the lower heterogeneous coarse clastic unit of the Ladner Group succession, approximately 150 to 200 m stratigraphically above the unconformable contact with the Spider Peak Formation (Figure 2b; Shearer and Niels, 1983). The lower unit includes discontinuous wedges of interbedded greywacke, lithic wacke, sedimentary breccia, and conglomerate, together with intercalated sequences of siltstone and minor argillite. The lithic wackes contain variable amounts of angular rock and mineral fragments averaging 1 cm in diameter. Basic and intermediate volcanic clasts predominate although some quartz, carbonate, and feldspar fragments, and rare clasts of altered acid volcanic rock are also present.

Polymictic conglomerate horizons within the lower unit seldom exceed 30 m in thickness. They vary from densely packed, clast-supported sedimentary breccias with angular lithic fragments, to conglomeratic mudstones containing isolated, well-rounded pebbles, cobbles and boulders up to 30 cm in diameter. The clasts are set in a mudstone or siltstone matrix which often displays soft sediment disruption and chaotic slumping. One distinct conglomeratic horizon in the mine district reaches 50 m in thickness and is traceable for 1.5 km along strike (Ray, 1986b, 1986c). This unit exhibits an overall reverse grading; its lower section consists of a densely packed, green-coloured breccia which passes stratigraphically upwards into a conglomeratic mudstone containing rounded cobbles and boulders up to 30 cm across. The clasts in the conglomeratic mudstone are predominately altered basalt with lesser amounts of chert, gabbro, diorite, granite, granodiorite, porphyritic andesite, flow-banded dacite, and limestone. Conodont microfossils of Middle to Late Triassic age were extracted from one limestone boulder within a conglomeratic mudstone horizon located approximately 250 m north of the Idaho zone surface outcrop (M.J. Orchard, Geological Survey of Canada, written communication, 1986; G.S.C. Loc. No. C-103719).

The middle sedimentary unit of the Ladner Group at Carolin mine mainly comprises grey to black, generally well-bedded siltstone (Figure 2b). Beds vary from 1 cm to 10 cm in thickness and commonly display grading. The slaty argillites in the uppermost unit (Figure 2b) form black to grey, generally non-bedded sedimentary rocks that are locally pyrite- and organic-rich; they are composed mainly of very fine grained quartz, altered plagioclase, and chlorite with variable amounts of sericite, carbonate and exceedingly fine grained, opaque organic material. Cleavage is defined by the subparallel alignment

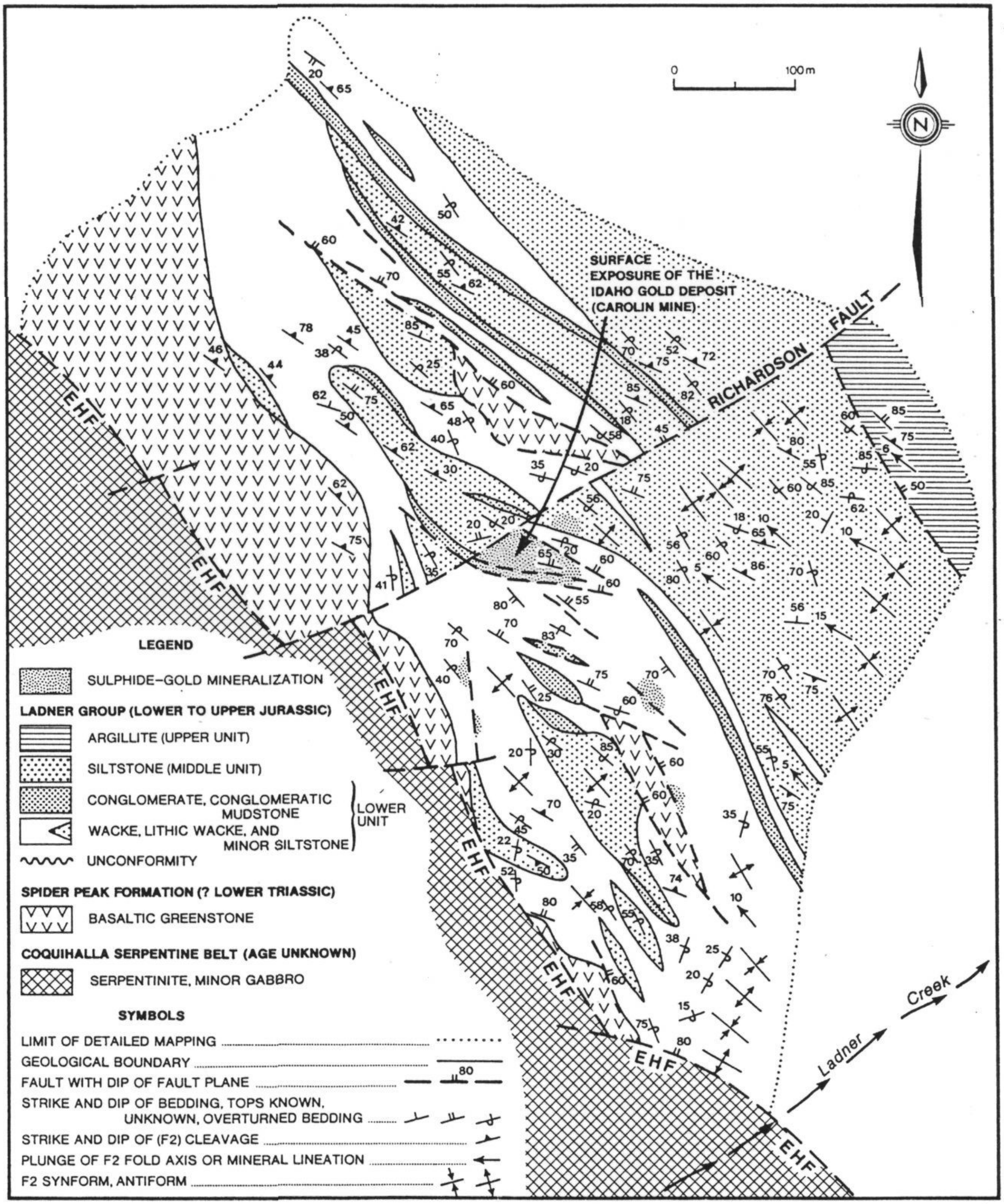

Figure 3. Surface geology of the Carolin mine vicinity. (Adapted after Ray, 1986c). EHF = East Hozameen Fault.

of chlorite and elongate growth of the quartz and pyrite crystals.

The Spider Peak Formation in the mine area generally lies adjacent to the East Hozameen Fault, often separating the Ladner Group to the east from the Coquihalla serpentine belt in the west (Figure 3). However, two narrow fault-bounded slices of the Spider Peak Formation were mapped within the Ladner Group north and south of the Idaho zone surface outcrop (Figure 3). The basalts in the Spider Peak Formation are generally massive, but both tectonic and aquagene breccia textures are locally present. Close to the Ladner Group unconformity these rocks contain amygdules, faint layering, and pillow structures. Despite the intense alteration, ophitic textures and some original pyroxenes are locally preserved, although most of the mafic minerals and feldspars are replaced by chlorite, epidote, sericite, and carbonate. Some outcrops are characterized by randomly orientated, late crystals of stilpnomelane up to 1.5 cm long.

Serpentinite in the Coquihalla serpentine belt consists largely of lamellar antigorite and massive lizardite. Pseudomorphs after pyroxene and olivine are relatively abundant but unaltered olivine is rare.

The East Hozameen Fault in the mine area dips steeply northeast and sharply crosscuts the Ladner Group stratigraphy. Graded bedding in the Ladner Group reveals that most of the stratigraphic sequence, including that hosting the gold-bearing Idaho zone, is structurally overturned (Figure 3). Consequently, the Spider Peak Formation now tectonically overlies the stratigraphically younger Ladner Group.

The surface exposure of the Carolin deposit (the Idaho zone) is a highly faulted and altered zone up to 40 m in outcrop width (Figure 3). It is characterized by manganese and iron oxides, intense albitic alteration, disseminated sulphides, and a dense network of irregular, variably deformed quartz veins. The replacement-type sulphide-albite-quartz mineralization is preferentially hosted in the more permeable, competent rocks such as wackes, lithic wackes, conglomerates and siltstones (Figure 2b). The thin units of slaty argillite in the mine sequence are generally unmineralized (Ray et al., 1983).

Most of the post-ore faults in the mine area strike northwest (Figure 3), subparallel to the East Hozameen Fault and the regional slaty cleavage. However, a younger set of east-northeast striking normal faults are also present; this includes the northerly dipping Richardson Fault which cross cuts the Idaho zone.

STRUCTURAL HISTORY OF THE CAROLIN MINE AREA

Two major structural events are recognized in the mine area. The first of these (F1) resulted in tectonic inversion of both the Ladner Group and the Spider Peak Formation, although no related folds or structural planar fabrics are recognized. The Hozameen Fault is believed to represent an easterly directed thrust zone that originally dipped west (Ray, 1986a). Tectonic inversion was caused by easterly overthrusting of the Hozameen Group onto rocks of the Pasayten Trough. Ultramafic rocks from beneath the Spider Peak Formation were emplaced within the thrust zone to produce the Coquihalla serpentine belt.

The second deformational event in the mine area (F2) produced the dominant folds in the district (Figure 3); this folding is economically important because the mineralization at Carolin mine is structurally controlled within the hinge zone of a major F2 antiform (see below, Figure 5a). The F2 event resulted in upright and overturned minor and major folds, the latter having wavelengths of 60 m to 110 m and amplitudes of 25 m to 50 m (Ray, 1982). These folds vary from concentric to similar in style; some have disrupted, faulted hinges and limbs, along which quartz veins are locally injected. The F2 event was accompanied by the development of an axial planar slaty cleavage in the siltstones and argillites; the bedding-cleavage intersection lineations are oriented subparallel to F2 fold axes (Figure 3). Cleavage and mineral lineations are generally absent in the wacke units.

Subsequent to the F1 overthrusting, three generations of faulting are recognized. The first either preceded or accompanied gold mineralization and resulted in northwest trending dislocation zones along some F2 fold hinges. The second generation was post-ore and produced both high angle reverse and normal faults that strike northwest and cut the deposit (Figure 5a). The youngest set is easterly striking and includes the Richardson Fault (Figure 3).

Stereoplots of the bedding and cleavage data in the mine area (Figures 4-1 and 4-2) show that most F2 folds are overturned to the southwest and have southeasterly striking axial planes that dip steeply northeast. A plot of lineation data (Figure 4-3) demonstrates that the F2 fold axes in the mine area have a mean plunge of 12° in a northwesterly direction. This is essentially similar to the estimated 20° northwesterly plunge of both the Carolin mine orebody and the axis of its controlling antiformal structure (Shearer and Niels, 1983). The second generation, northwesterly striking faults which cut the deposit (Figure 4-4; Shearer and Niels, 1983), were controlled by, and follow the slaty cleavage rather than the sedimentary bedding. These northwest striking faults tend to be preferentially concentrated along the hinges and limbs of the F2 folds.

GEOLOGY AND MINERALOGY OF THE CAROLIN DEPOSIT

During the first year of mining, the precise geological controls of the gold mineralization were unknown. Surface geological mapping over the deposit (Ray, 1982) revealed the presence of numerous upright and asymmetric, large scale F2 folds (Figure 3) and it was speculated that the geometry of the deposit was influenced by these structures. Subsequent underground mapping demonstrated that the mineralization is both lithologically and structurally controlled (Shearer and Niels, 1983); mineralization is preferentially concentrated in the more permeable, competent sedimentary beds within the hinge of a complex F2 antiformal fold (Figures 5a and 5b). A boulder and pebble conglomerate marker horizon within the Ladner Group was recognized underground at the mine (Figure 5a); this unit may correlate with the distinctive green breccia and conglomeratic mudstone horizon mapped on surface (Figure 3).

A geological cross-section across the Carolin deposit is shown in Figure 5a. The deposit plunges gently north-

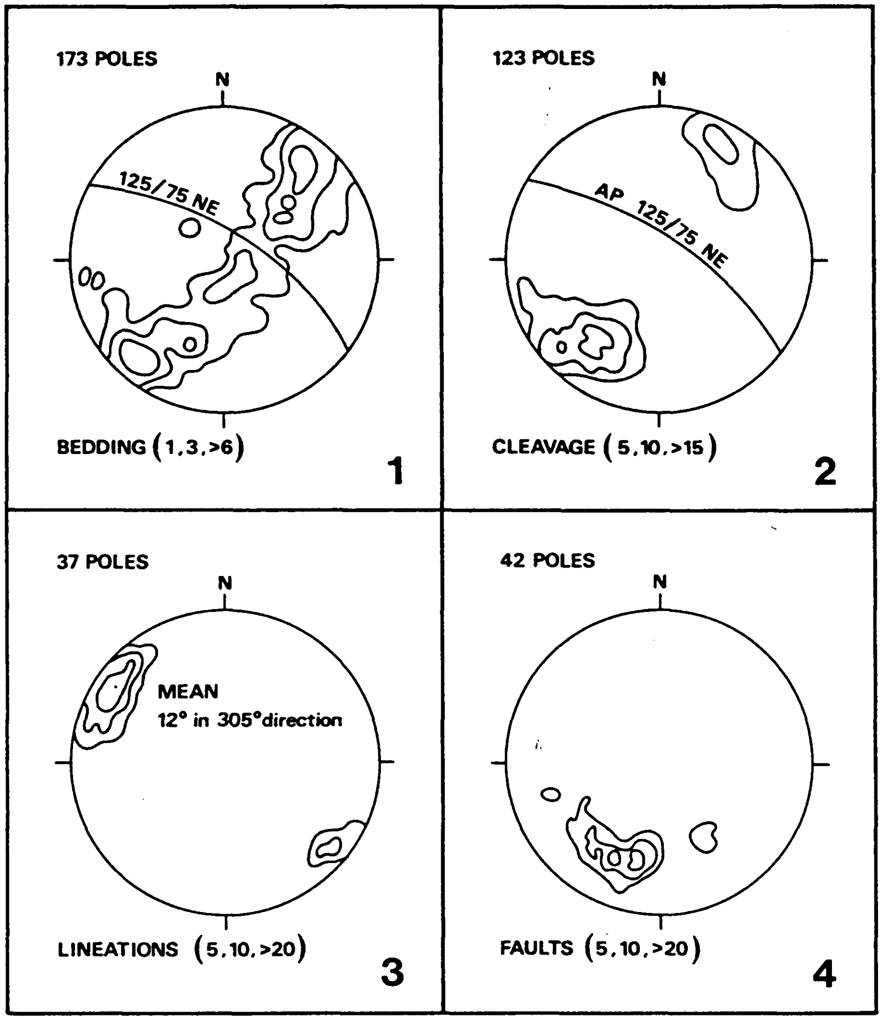

Figure 4. Lower equal area projections of structures in the Ladner Group exposed in the Carolin mine area. Poles to: 1 -bedding; 2 -slaty cleavage; 3 -bedding-cleavage intersection lineations; 4 -second generation faults (post ore). Numbers in brackets are contour intervals in percent.

west, subparallel to the plunge of the F2 fold axes in the area (Figure 4-3). The ore most amenable to open longhole stoping is located in the thickened region of the fold hinge, while mineralization on the fold limbs tends to be too narrow for profitable mining. At least three saddle-reef-like orebodies have been outlined to date, an upper No.2, a middle No.1, and a lower No.3 orebody (Figures 5a and 5b). Deep drilling has revealed several additional auriferous zones below the No.3 orebody.

Significant mineralogical and geochemical differences are noted between the No.1 and No.2 orebodies, and the deposit as a whole probably possesses a vertical mineralogical zoning. Shearer (1982), concluded that the upper No.2 orebody is pyrite-rich, while the lower No.1 orebody is pyrrhotite-rich. The No.1 orebody is hosted mainly in greywacke and possesses extremely uniform gold grades while the No.2 orebody is hosted in siltstone and has erratic gold values. This probably reflects differences in the original permeability of the host rocks. Little is known about the deep No.3 orebody except that it resembles the overlying No.1 orebody in its mineralogy and host rock lithology. The silver/gold ratio in the deposit averages 1:10, but varies locally from 1:1 to 1:22.

The Carolin deposit is cut by numerous northerly striking faults (Figure 5a), some of which contain carbonaceous material (Shearer, 1982). The deposit is also truncated to the north by the younger, easterly striking and northerly dipping "Hangingwall Shear". No mining has taken place north of the shear, and the location of the postulated down plunge extensions of the orebodies across the shear is unknown. The Hangingwall Shear may be an underground continuation of the normal Richardson Fault (Figure 3), which suggests that the northerly extension of the deposit is downthrown to the north.

Favourable metasedimentary lithologies for hosting gold-sulphide-albite-quartz mineralization in the deposit include wackes, pebble conglomerates and siltstones. Coarse grained, pervasive albitization is present throughout both the ore zones and the adjacent wall rocks. However, the exceedingly fine grained chloritic and sericitic alteration related to the mineralizing event is generally well developed in the host rocks, but not so abun-

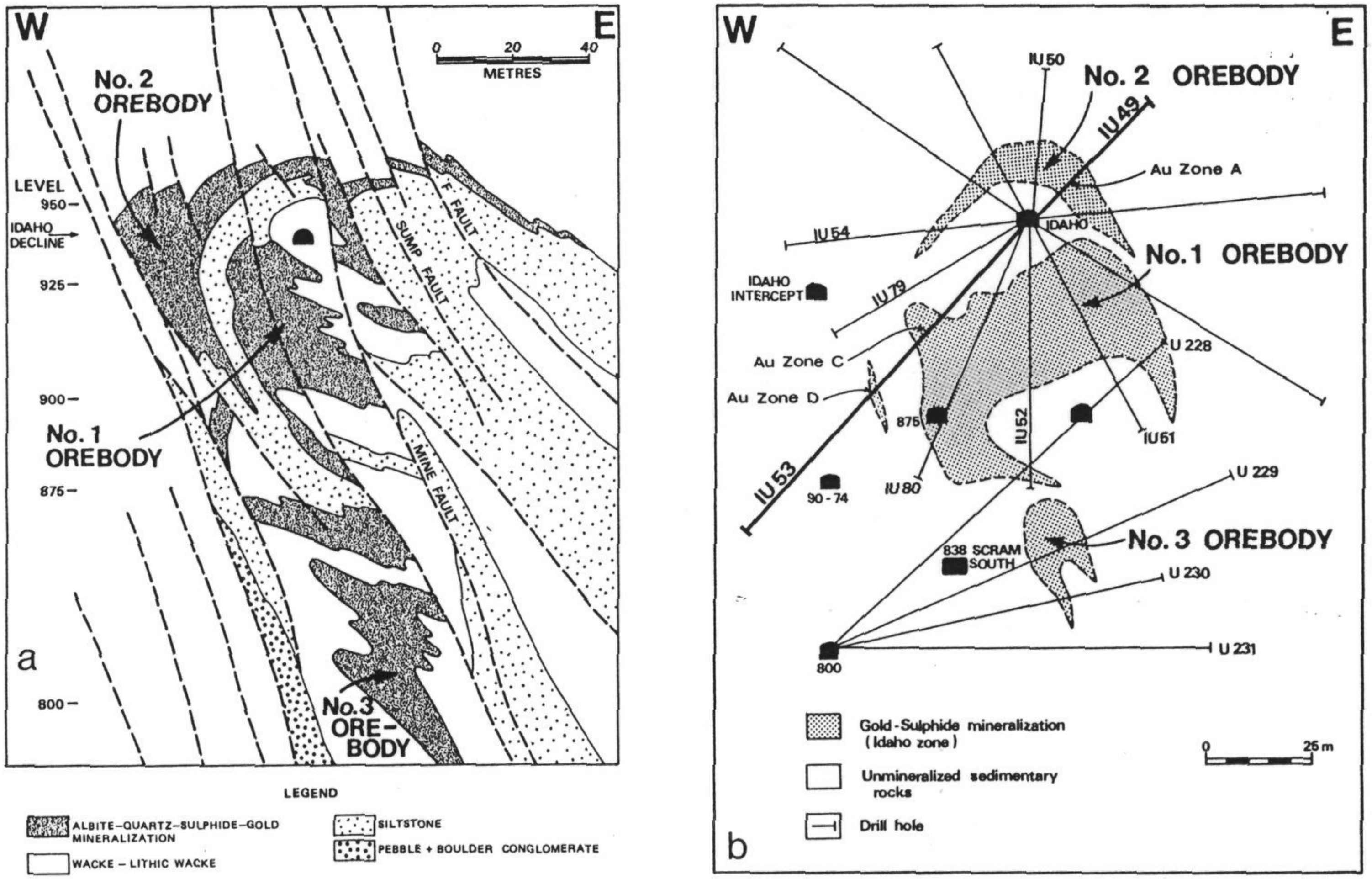

Figure 5. (a) E-W geological cross-section of the Carolin deposit at 766 North, showing location of the No. 1, 2, and 3 orebodies. (Adapted after Shearer and Niels, 1983).
(b) E-W cross-section through the Carolin deposit at 837 North. Note location of drill holes IU-49 and IU-53, and auriferous zones A, C and D.

dant in the ore. The ore groundmass consists largely of quartz and albite (An 3-5), with variable amounts of carbonate, chlorite, very fine sericite and opaque minerals; the ore is cut by numerous irregular veins of albite and quartz. The opaques range from 1% to 15% by volume and average approximately 6% to 8%; they are mainly pyrrhotite, arsenopyrite, pyrite, and magnetite. Less common opaques, in decreasing abundance, include sporadic traces of chalcopyrite, bornite, gold and sphalerite (Kayira, 1975). Pyrite and arsenopyrite generally form coarse euhedral to subhedral crystals, while pyrrhotite and magnetite occur as finer grained disseminations and clusters. Kayira (1975) concluded that the paragenesis of the opaque minerals was (i) magnetite, (ii) arsenopyrite, (iii) pyrite, (iv) gold, (v) pyrrhotite, (vi) sphalerite, and (vii) chalcopyrite; a partial overlap in the deposition of arsenopyrite, pyrite and pyrrhotite was noted. However, Shearer (1982) in his study of both the pyrite-rich and pyrrhotite-rich portions of the deposit presented the following paragenesis: (i) magnetite, (ii) arsenopyrite and some gold, (iii) contemporaneous deposition of pyrite, pyrrhotite and some gold, (iv) minor magnetite, and finally (v) traces of chalcopyrite and gold.

The majority of the magnetite in the ore represents early, first generation material; it forms small, disseminated, rectangular grains and is probably unrelated to mineralization since it shows no spatial association with either gold or sulphides. Arsenopyrite is the earliest sulphide associated with gold (Shearer, 1982). Some arsenopyrite crystals are partly rimmed with small blebs of pyrite and pyrrhotite, while the euhedral pyrite crystals in the ore locally include small grains of pyrrhotite. The pyrrhotite is magnetic and often contains exsolution rods of pyrite. Shearer (1982) notes the presence of some minor, second generation magnetite which is related to mineralization and is associated with pyrrhotite and arsenopyrite. Gold generally forms very small grains up to 0.02 mm in size, commonly as inclusions within the pyrite and arsenopyrite or rims on pyrite and chalcopyrite. Some gold and chalcopyrite rim pyrrhotite (Shearer, 1982). Minute grains of gold are also seen, within or along grain boundaries of some quartz, carbonate and albite crystals. Although visible gold is rare throughout the Idaho zone, it is seen as thin plates and smears along some fault surfaces. Rarer forms of visible gold include leaf-like masses, small scales and rods.

Rocks in the Idaho zone are commonly pale coloured due to weak silicification and intense, pervasive albitic alteration. The auriferous zones are generally associated with albite and quartz veining and disseminated sulphides, although not all areas containing these features are necessarily enriched in gold. The widespread albitization produces a sodium-rich envelope that extends hundreds of metres from the deposit. There are at least three generations of albitization. The earliest is fine grained and was probably coeval with sulphide-gold-quartz mineralization; this first phase albite is weakly altered and disseminated throughout the ore groundmass, being intimately intergrown with sulphides and fine quartz crystals. This early phase is cut by numerous thin, deformed veins of poorly twinned, second generation albite. The youngest albite forms irregular veinlets and disseminated masses throughout the ore zone, comprising coarse, fresh, well-twinned crystals (An 3-5) up to 8 mm in length with locally deformed twin planes. In places, small angular, disrupted fragments of sulphide-rich ore are entirely engulfed by the third generation albitic material.

The deposit is cut by numerous white quartz veins generally <15 cm wide which form a complex, irregular network. Sigmoidal gash fracturing, and the variation in vein deformation suggests the multistage quartz injection occurred during recurrent structural deformation, and three phases of vein injection are recognized. Many of the early veins are folded. They contain strained quartz crystals elongated parallel to the F2 fold axial planes and slaty cleavage, and are interpreted to be either pre- or syn-F2 in age. The quartz crystals in the younger veins are generally unstrained and granoblastic. While some of the earlier quartz veins may be coeval with the mineralization, most appear to have been introduced immediately after gold, sulphides and albite. Some quartz veins contain minor amounts of carbonate, albite and clinozoisite, as well as minute flakes of pyrobitumen, whose optical and physical characteristics suggest a muturation equivalent to meta-anthracite (J. Kwong, B.C. Ministry of Energy, Mines and Petroleum Resources, written communication, 1983). In rare instances, small quantities of finely disseminated carbon are also present within the altered wallrocks immediately adjacent to some quartz veins.

Late veins and disseminations of calcite and ankerite are also sporadically present in the Idaho zone; the carbonate veining is not folded and it postdates albitization and quartz veining.

Preliminary studies of fluid inclusions from various quartz veins in the Idaho zone suggest the presence of three generations of low salinity, CO_2-rich fluids yielding homogenizing temperatures of approximately 320°C, 225° to 275°C, and 150° to 190°C respectively (J.B. Murowchick, University of Alberta, written communication, 1985). Nesbitt, et al. (1986) conclude from oxygen isotope studies that emplacement of quartz veins in the deposit involved deeply circulating meteoric waters that were highly enriched in $\delta^{18}O$ and somewhat enriched in δD relative to local meteoric water. Their work also suggested that the serpentinites in the Coquihalla serpentine belt adjacent to the mine were affected by these fluids.

The age of the Carolin mineralization is unknown. However, it apparently accompanied the main F2 folding in the area, which is believed to be a post-Mid Cretaceous to pre-Late Eocene event (J.W.H. Monger, Geological Survey of Canada, verbal communication, 1986). Despite its apparent young age, the deposit exhibits similarities in its mineralogy and alteration assemblage to some Archean gold deposits in eastern Canada and Australia. For example, pyrrhotite is locally associated with gold at several Archean deposits including the McIntyre and Sigma mines of Ontario and Quebec (Hodgson, 1983a, 1983b; Colvine et al., 1984). A vertical pyrite to pyrrhotite zoning, similar to that at Carolin mine is described in the Mount Charlotte deposit of western Australia (Phillips et al., 1983) and at the McIntyre mine (Langford, 1938). Gold is associated with widespread albitic alteration in the Timmins, Red Lake, Crow River – Pickle Lake, and Geraldton camps of Ontario (Horwood, 1945; Horwood and Pye, 1955; Pye, 1976; Davies and Luhta, 1978). However, unlike Carolin mine, gold and albitization in these Archean camps are spatially and possibly genetically related to intrusive felsic porphyritic bodies (Colvine et al., 1984). Although swarms of albite-rich felsic sills and dikes are present in the Carolin mine district, they appear to be related to the 40 Ma Needle Peak Pluton, and apparently postdate the regional F2 deformation. Consequently, these intrusions are probably too young to be related to the gold mineralization at the Carolin mine. At present the source of the gold and albite in the Carolin deposit is unknown; they may have been derived from either the rocks of the Coquihalla serpentine belt or the spilitized greenstones in the Spider Peak Formation.

GEOCHEMISTRY OF THE NO.1 AND NO.2 OREBODIES AT CAROLIN MINE

The geochemistry of several ore horizons in the Carolin deposit were studied by systematically analyzing 50 core samples from drill holes IU-49 and IU-53; these holes total 130 m in length and cut across the entire pyrite-rich No.2 orebody and a repeated hangingwall portion of the underlying pyrrhotite-rich No.1 orebody (Figure 5b). The objectives of this study were to determine the variations in major and trace element content throughout the holes and compare these variations to observed mineralogical changes. (The analytical and univariate statistical results are available in Open File at the B.C. Ministry of Energy, Mines and Petroleum Resources.) Four sulphide-rich auriferous zones were intersected which are designated zones A, B, C and D respectively (Figures 5b, 6a and 6b). The 9 m wide zone A represents the No.2 orebody intersection, while zones B, C and D, which total 18 m thick, are the repeated hangingwall portions of the No.1 orebody. Pervasive albitization is evident throughout the entire drillholes, in both the ore horizons and the surrounding host rocks. However, the latter are distinguished mineralogically by the general absence of sulphides and quartz veining, and the presence of intense chloritic and sericitic alteration.

The downhole variation of selected elements is shown on Figures 6a and 6b. In addition to the elements shown, analyses were completed for Cu, Hg, P_2O_5, Pb, SrO, TiO_2, FeO and total iron (Fe_2O_3T). Cu was very weakly anomalous (up to 310 ppm) in some mineralized zones, while P_2O_5 exhibited a consistent and marked drop in values in the gold zones. Hg, Pb and SrO showed no anomalous values throughout the drill holes, while Sb consistently showed enrichment (up to 20 ppm) in the hangingwall portions of all four gold-bearing horizons.

Univariate statistics were determined from the raw analytical results, and correlation matrices indicate that the gold in the ore horizons has a strong to moderate positive correlation with Na_2O, S, CO_2, Sb, Mo, Cu, As and Ag, and a strong to moderate negative correlation with Al_2O_3, MgO, K_2O, H_2O^+, P_2O_5 and BaO. No statistically significant correlation between gold and SiO_2, Fe_2O_3T, CaO, TiO_2, MnO or Pb is apparent in the ore zones. In the No.2 orebody (zone A, Figure 6a), the gold and silver are preferentially concentrated in the footwall and hangingwall, and a positive correlation between the two elements is apparent. The hangingwall section of this orebody is associated also with anomalous values of Mo and As (Figure 6a); by contrast, zones B, C and D in the No.1 orebody (Figure 6a) do not contain Ag or Mo, although they are associated with high Au and As values.

Compared to unmineralized Ladner Group siltstones and wackes outside the mine area, which average approximately 2.5% to 4% Na_2O (Table 1), most of the 130 m long drill hole section is anomalously enriched in sodium (Figure 6b). Increases in sodium correspond with decreases in potassium, suggesting that albitization led to the breakdown and removal of the original K-feldspar in the rocks. The close association between albitization and mineralization is illustrated by the sharp decrease in K_2O/Na_2O ratios as the individual ore zones are approached (Figure 6a).

Auriferous horizons A, B and C, are surrounded by potassium and barium depletion envelopes that are generally twice as wide as the associated ore zones. The positive correlation between the two elements suggests that the barium was originally contained within K-feldspar. All four auriferous, sulphide-rich horizons are associated with increases in sulphur and decreases in water (Figure 6b); the latter reflects the drop in the chlorite and sericite content of the ore compared to the wall rocks. Higher levels of magnesium and potassium in the wall rocks mark areas of more intense chloritic and sericitic alteration. The entire wallrock section drilled between the No.1 and 2 orebodies is intensely chloritic, and a 7 m wide zone of pervasive chlorite alteration, marked by increased magnesium values, is present immediately above the No.1 orebody (Figure 6b). This chloritic envelope is separated from the ore horizon by a thin (2 to 3 m) zone which is chlorite-poor, but contains abundant quartz veining.

The distribution of elements within and adjacent to the gold-bearing zones A, B and C, show many common characteristics, but the lowermost auriferous zone D, in the No.1 orebody is geochemically unique. Mineralization in zone D is associated with a decrease in silica and increases in calcium, barium and potassium. It is uncertain whether this reflects geochemical differences in the original sedimentary host rock, or whether the pyrrhotite-rich No.1 orebody contains two mineralogically and geochemically distinct suites.

GEOCHEMICAL ENVELOPES ASSOCIATED WITH THE CAROLIN DEPOSIT

Seventy-three lithogeochemical samples of Ladner Group wacke and siltstone were systematically collected from a wide area around the Carolin deposit to determine whether large scale element zoning is associated with the gold mineralization; the location of the samples is shown on Figure 7a. These were analyzed for a number of major and trace elements. (The lithogeochemical analytical and univariate statistical results are available in Open File at the B.C. Ministry of Energy, Mines and Petroleum Resources.) The study revealed that TiO_2, MnO, Cu, Pb, Zn, Co, Ni, Mo, Cr, Hg, Sb, Bi, Cd and SrO showed little or no systematic change in concentration throughout the sampled area, and are not apparently influenced by the gold mineralization. Failure to detect increased values of Sb and Cu over the deposit is probably due to the low concentration and sporadic distribution of these elements within the ore. However, some other elements, notably gold, arsenic, barium, potassium, sodium, silica, magnesium and calcium, showed systematic variation patterns and form enrichment or depletion zones within or around the deposit. These include relatively small and narrow

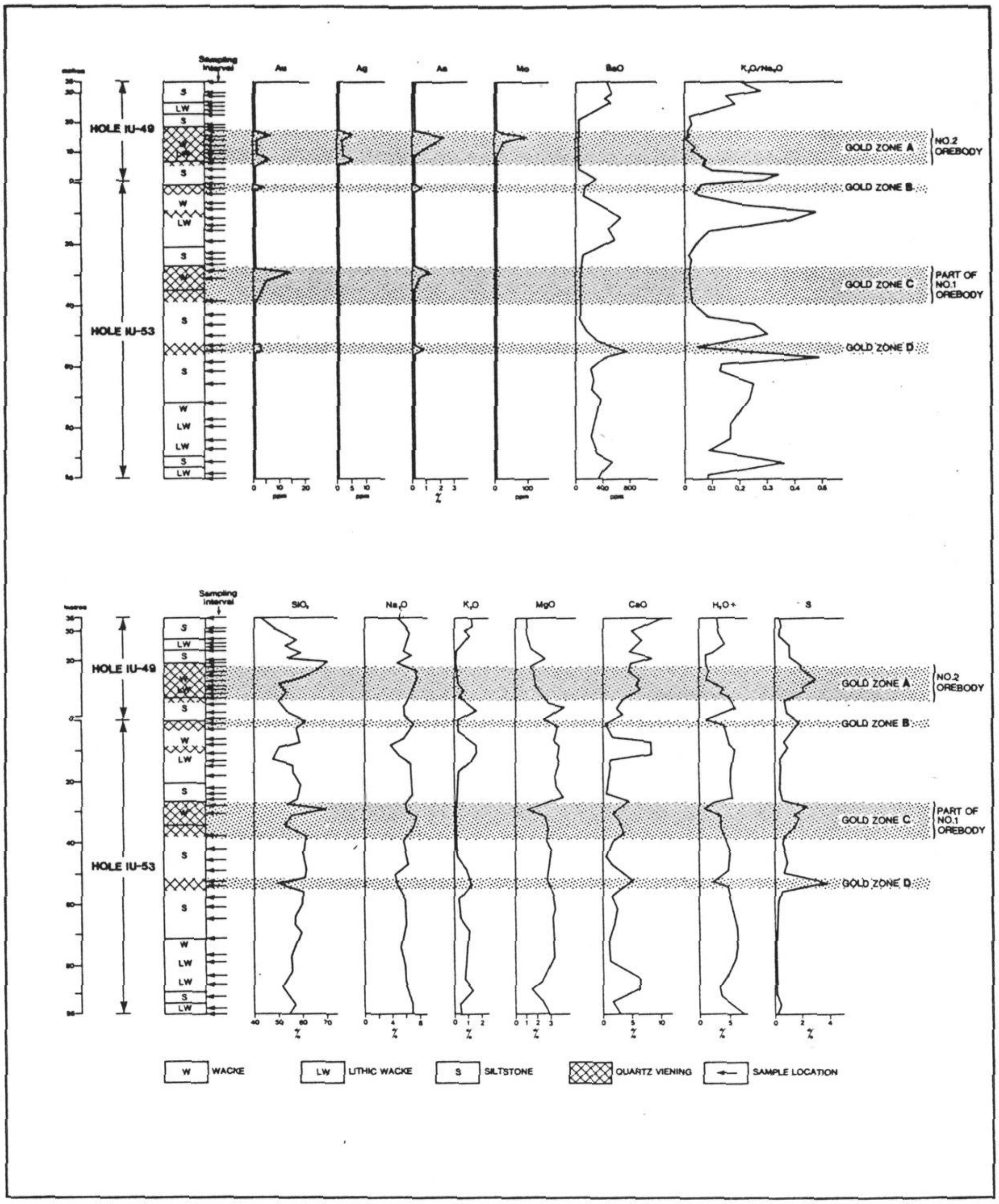

Figure 6. (a) Geology, trace element geochemistry, and K_2O/Na_2O ratios of holes IU-49 and IU-53, Carolin deposit. Note auriferous zones A, B, C and D. **(b)** *Geology and major element geochemistry of holes IU-49 and IU-53, Carolin deposit.*

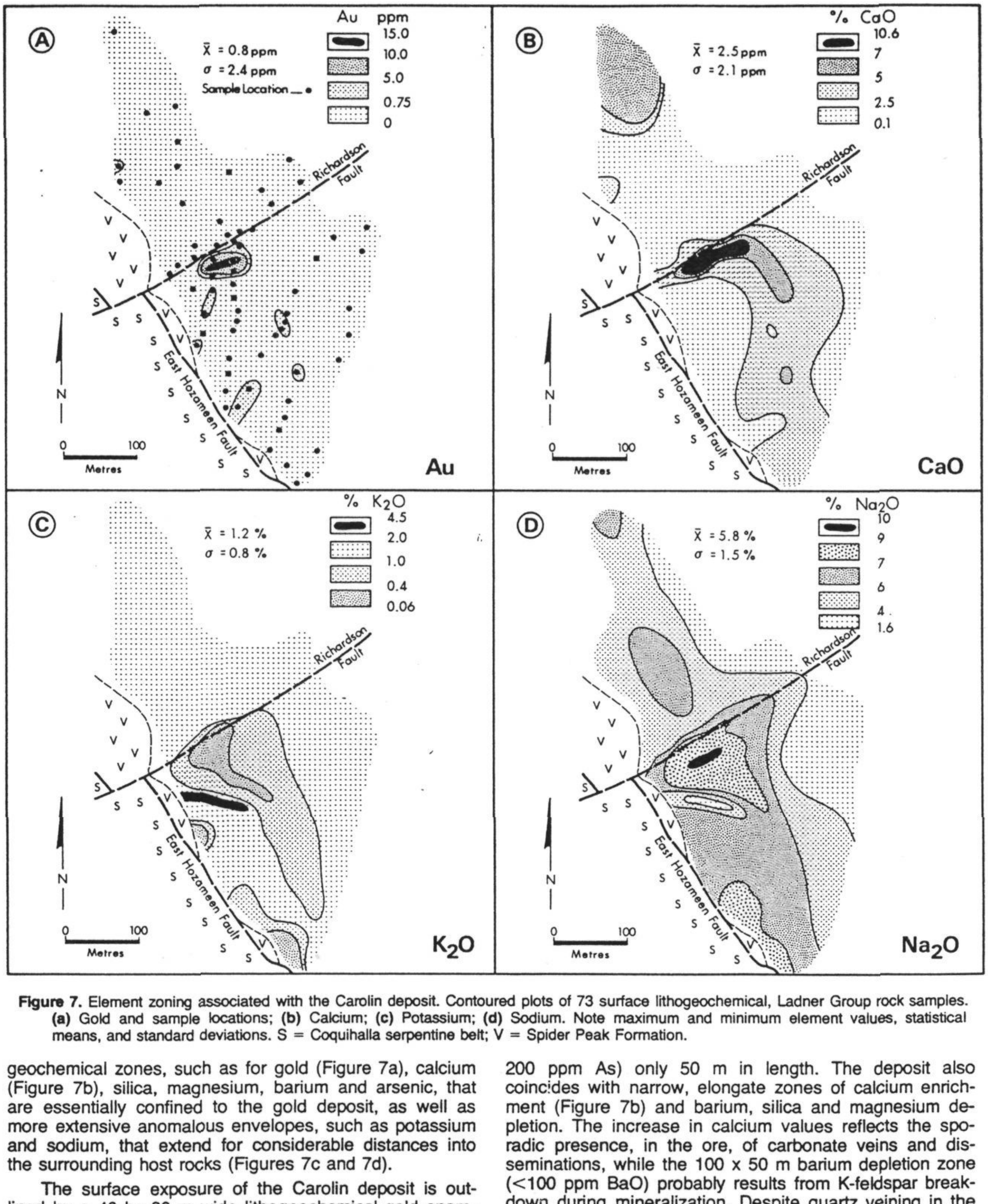

Figure 7. Element zoning associated with the Carolin deposit. Contoured plots of 73 surface lithogeochemical, Ladner Group rock samples. **(a)** Gold and sample locations; **(b)** Calcium; **(c)** Potassium; **(d)** Sodium. Note maximum and minimum element values, statistical means, and standard deviations. S = Coquihalla serpentine belt; V = Spider Peak Formation.

geochemical zones, such as for gold (Figure 7a), calcium (Figure 7b), silica, magnesium, barium and arsenic, that are essentially confined to the gold deposit, as well as more extensive anomalous envelopes, such as potassium and sodium, that extend for considerable distances into the surrounding host rocks (Figures 7c and 7d).

The surface exposure of the Carolin deposit is outlined by a 40 by 80 m wide lithogeochemical gold anomaly (Figure 7a), while arsenic which is only sporadically present in the ore, forms a smaller anomaly (500 to 18 200 ppm As) only 50 m in length. The deposit also coincides with narrow, elongate zones of calcium enrichment (Figure 7b) and barium, silica and magnesium depletion. The increase in calcium values reflects the sporadic presence, in the ore, of carbonate veins and disseminations, while the 100 x 50 m barium depletion zone (<100 ppm BaO) probably results from K-feldspar breakdown during mineralization. Despite quartz veining in the ore, the samples collected in this study showed that the deposit is associated with a drop in silica values (38% to

53% SiO_2) relative to the country rocks (53% to 69% SiO_2). However, this may reflect a sampling bias since quartz-veined material was not included for analysis. The magnesium content of the surrounding host rocks (2.5% to 5% MgO) is generally higher than that in the deposit (0.6% to 2.5% MgO). The magnesium increase in the host rock is due to the wide envelope of chloritic alteration that surrounds the deposit.

Potassium and sodium display the most extensive anomalous envelopes around the Carolin deposit (Figures 7c and 7d). Siltstones and wackes from the Ladner Group outside the mine district average 1.5% to 2% K_2O and approximately 2.5% to 4% Na_2O, while similar rocks from the mineralized horizons contain between 6% and 10% Na_2O and generally less than 0.4% K_2O (Table 1; Figures 7c and 7d). This study demonstrates that the Carolin gold deposit is surrounded by a 150 m by 250 m wide zone of potassium depletion (Figure 7c), and a sodium enrichment envelope approximately 500 m long and 300 m wide (Figure 7d). Unlike many other epigenetic gold deposits (Boyle, 1979), mineralization at Carolin mine is associated with a sharp decrease in K_2O/Na_2O ratios.

All zones of geochemical depletion and enrichment except sodium, are sharply truncated by the easterly striking Richardson Fault (Figures 7a, b and c). However, both the sodium enrichment and chloritization envelopes related to the Carolin mineralization extend north of the Richardson Fault (Figures 7d and 8) which could indicate the presence of a downthrown, down plunge, northerly extension of the deposit.

MINERAL ALTERATION AROUND THE CAROLIN DEPOSIT

Discovery of the extensive lithogeochemical enrichment and depletion envelopes around the Carolin deposit led to a detailed thin section examination of the surrounding host rock mineralogy (Figure 8). This study revealed that the deposit is surrounded by an elongate envelope of mineral alteration at least 200 m wide and 600 m long that variably overprints the Ladner Group host rocks. Four concentric zones of alteration are recognized (Figures 8 and 9a). These have gradational boundaries with one another and are of variable width, being characterized by different mineral assemblages and/or mineral textures; they are designated from outermost to innermost as zones 1, 2, 3 and 4 (Figures 8 and 9a). The two innermost alteration zones (3 and 4) are intimately associated with each other and only underlie a small area (Figure 8); the intense, coarse grained nature of the alteration in zones 3 and 4 makes it easily identifiable in hand specimen. By contrast, the outermost two alteration zones (1 and 2) are more extensive (Figure 8), but the alteration is finer grained, and generally only recognizable in thin section. Consequently, the existence of mineral alteration zones 1 and 2 was not recognized during the initial geological mapping around the deposit (Ray 1983; Shearer and Niels 1983).

Zone 1 is the outer and most extensive alteration envelope around the Carolin deposit (Figure 8), and is characterized by pervasive chloritization. However, the outer limits of Zone 1 cannot be precisely defined due to the variable chloritic alteration associated with the regional greenschist facies metamorphism in the district. Generally, the original clastic grains of twinned plagioclase (An 25-35) are clearly recognizable in the regionally metamorphosed Ladner Group wackes and siltstones outside the mine area. Within Zone 1, however, detrital quartz is generally the only recognizable original component in the wackes. The groundmass in these rocks is partially or completely replaced by fine chlorite, and the original feldspars are altered to exceedingly fine-grained sericite, kaolinite, epidote, and late carbonate. Ilmenite within the zone 1 rocks is rimmed or replaced by leucoxene, and actinolite appears in minor quantities (Figure 9a).

Zone 2 reaches 75 m in width (Figure 8) and the alteration is marked by the crystallization of fine-grained quartz, plagioclase, actinolite and epidote, and the groundmass is extensively chloritized and sericitized. However, the characteristic feature of Zone 2-type alteration is the appearance, within the fine grained chloritic and sericitic groundmass, of isolated porphyroblasts of twinned albitic plagioclase (An 3-12) up to 0.5 mm in length (Figure 9a); these are partially replaced by late sericite and carbonate. Original detrital quartz grains are still recognizable but locally the rocks contain recrystallized, fresh quartz elongated parallel to the foliation.

Transition from Zone 2 to Zone 3 is marked by a decrease in chlorite and sericite, and an increase in both the albite content and mineral grain size (Figure 9a). Zone 3-type alteration extends up to 75 m beyond the auriferous orebodies; albitization is both pervasive and veined, and it increases in intensity toward the gold horizons. Locally the rocks in Zone 3 are cut by quartz and carbonate veins.

Zone 4 is the central and smallest alteration unit recognized and it represents the gold-bearing horizons comprising the Carolin mine orebodies. Like Zone 3, it is marked by intense albitic alteration and quartz veining, but is distinguished by the presence of up to 15% sulphides, which includes pyrrhotite, pyrite and arsenopyrite. Locally these rocks carry late disseminations and veins of calcite and ankerite. Minor chlorite is widespread, and sericite replacement along narrow zones and fractures is common locally. Although these rocks are sodium-rich, X-ray studies have not detected paragonite (J. Kwong, B.C. Ministry of Energy, Mines and Petroleum Resources, written communiction, 1986).

The paragenesis of the alteration mineral assemblage at Carolin mine is shown in Figure 9b; the apparent general sequence is: (1) chloritization together with some sericitization and weak kaolinization; (2) the introduction of quartz, albite, sulphides and gold, (3) continuing introduction of albite, (4) emplacement of multiple phases of quartz veins, followed by (5) the late emplacement of veins and disseminations of calcite and ankerite. Weak sericitization and chloritization apparently took place throughout the sequence (Figure 9b).

CONCLUSIONS

The Carolin deposit, which lies within the Coquihalla gold belt, represents an epigenetic, replacement-type, turbidite-hosted gold deposit. Mineralization is marked by the introduction of sulphides, albite and quartz ± carbonate and by sporadic trace enrichment of Au, Sb, Mo, Zn and Cu. Sulphides, which average 6% to 8% of the ore, are

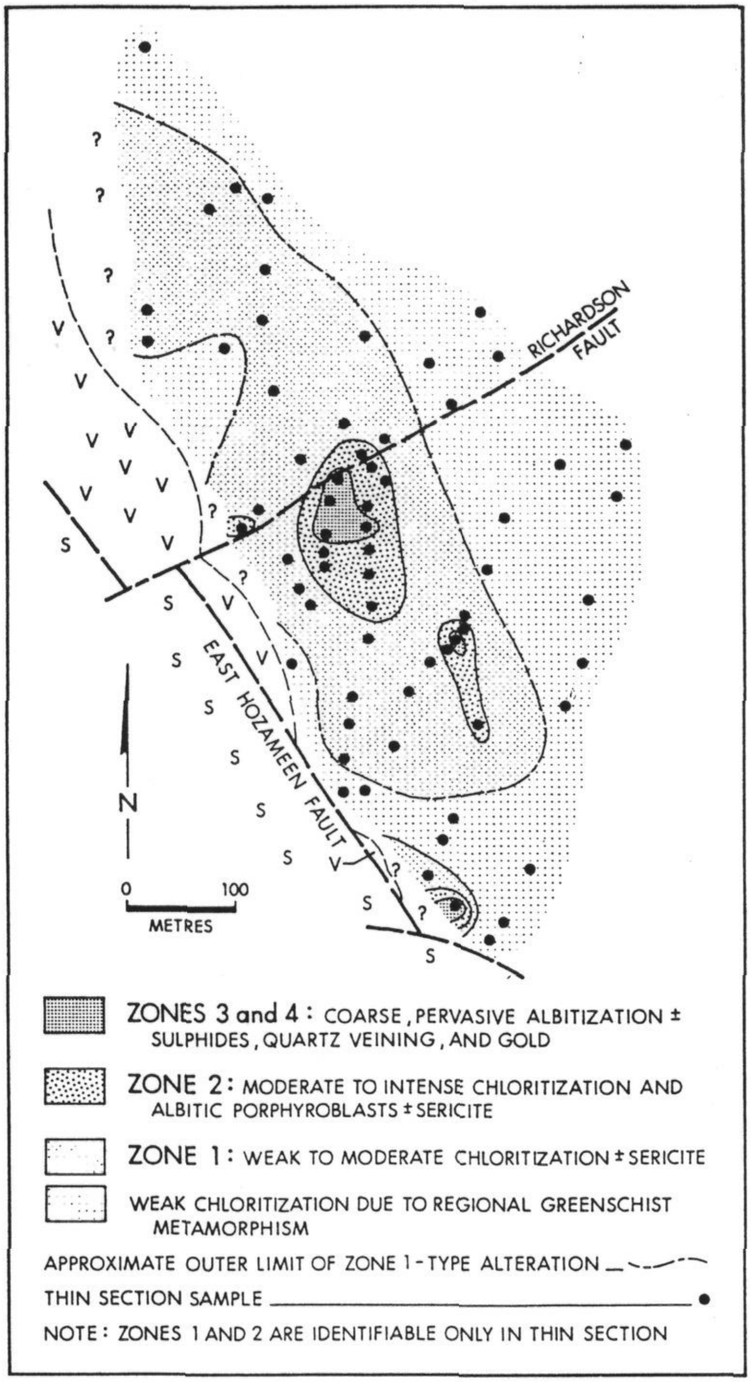

Figure 8. Distribution of mineral alteration zones associated with the Carolin deposit (from thin section modal estimates).

mainly pyrrhotite, arsenopyrite and pyrite. Generally, gold is intimately associated with the pyrite, arsenopyrite and trace quantities of chalcopyrite in the ore.

Gold mineralization is both lithologically and structurally controlled. It is hosted in wackes, siltstones and conglomerates in the basal part of the Jurassic Ladner Group, close to their unconformable contact with spilitized greenstones of the Triassic(?) Spider Peak Formation and their faulted contact with ultramafic rocks of the Coquihalla serpentine belt. In the mine area, the Ladner *Group and Spider Peak Formation were tectonically in*verted (F1) and subsequently deformed into large scale upright to asymmetric F2 folds. Mineralization apparently accompanies the regional F2 folding which is believed to

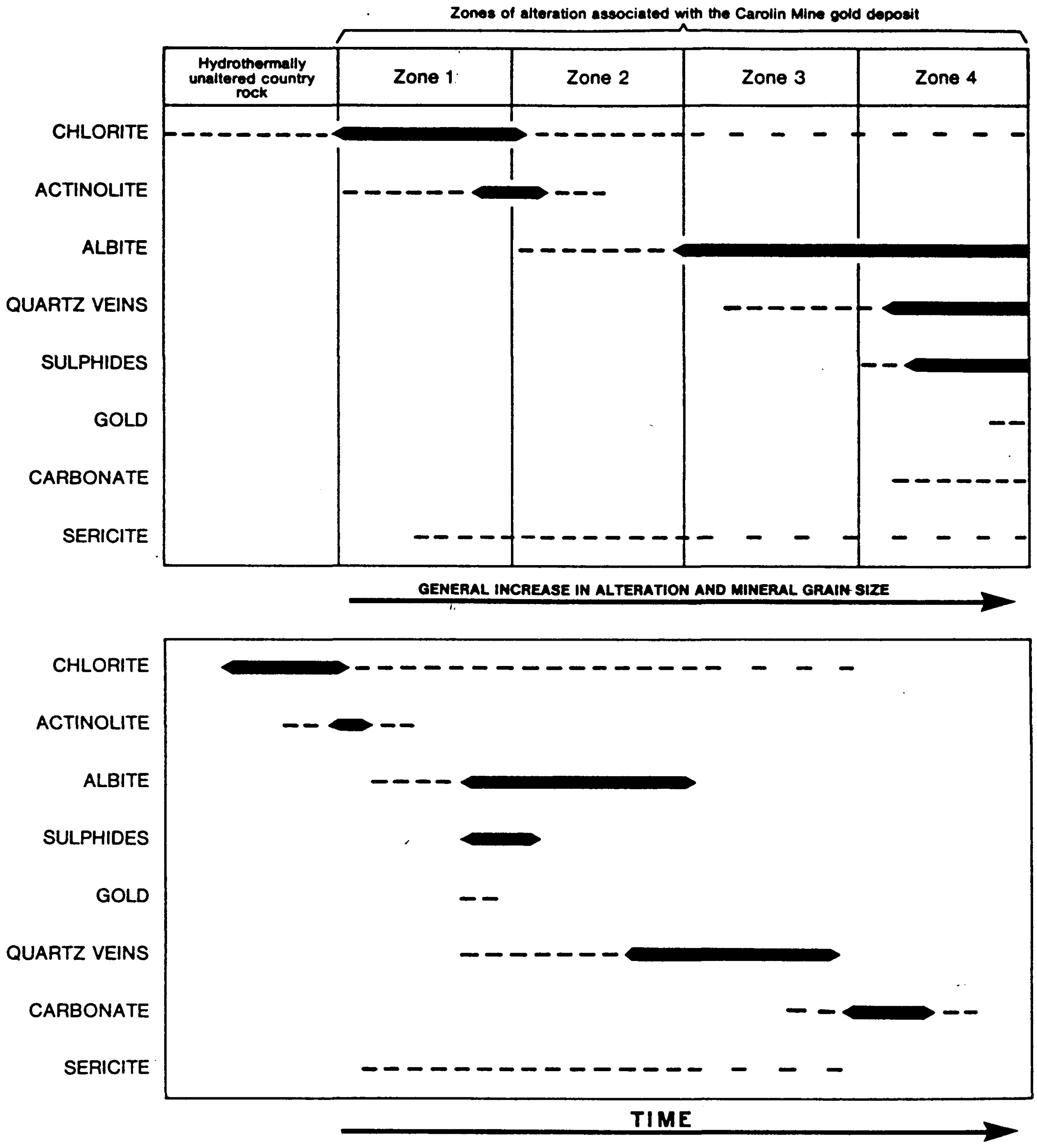

Figure 9. (a) (top) Schematic illustration of the four zones of mineral alteration associated with the Carolin mineralization. **(b)** (bottom) Paragenesis of the mineral alteration assemblages associated with the Carolin mineralization.

be a post-Mid Cretaceous to pre-Late Eocene event (J.W.H. Monger, Geological Survey of Canada, verbal communication, 1986). However, the precise age of the gold mineralization and its source are unknown.

The gold and sulphides at Carolin mine are preferentially concentrated in the more competent and permeable sedimentary beds along the tectonically thickened hinge region of a disrupted, asymmetric antiformal F2 fold. The three separate orebodies outlined in the deposit exhibit a saddle reef-like morphology and plunge gently northward, subparallel to the F2 antiformal axis. The deposit is pyrite-rich in its upper parts and pyrrhotite-rich at depth. This zoning suggests the deposit is upright, and younger than the F1 tectonic overturning that affected the host rocks.

The ore zones, which reach a maximum thickness of 30 m, are characterized by sulphides, intense albitic alteration, multiple phases of quartz veins and late carbonate veining. The paragenesis of the sulphides is: (1) arsenopyrite and some gold, (2) pyrite, pyrrhotite and some gold, (3) traces of sphalerite, and (4) traces of chalcopyrite and gold. A pre-sulphide phase of magnetite in the ore is apparently unrelated to the mineralization. Gold mostly forms grains up to 0.02 mm in size and visible gold is rare. The silver/gold ratio in the deposit averages 1:10.

Both the deposit and the individual ore horizons are associated with, or enveloped by, various geochemical enrichment and depletion halos that largely mimic zones of mineral alteration. The ore zones are surrounded by distinct potassium and barium depletion envelopes that are related to the breakdown of K-feldspar during albitization; these depletion envelopes are generally twice as wide as the associated gold-bearing horizons. On a mine scale, the Carolin deposit is enveloped by zones of potassium depletion and sodium enrichment that extend several hundred metres into the country rocks. The ore horizons and the deposit as a whole are associated with a sharp drop in K_2O/Na_2O ratios. This reflects the widespread pervasive albitization and accompanying destruction of K-feldspar that occurred during mineralization. The deposit also coincides with narrow, but distinct zones of calcium enrichment and silica depletion, but gold in the individual ore horizons shows no statistical correlation with these elements.

A halo of mineral alteration several hundred metres wide surrounds the deposit. This comprises a chloritic ± sericitic outer zone, and an albitic inner zone; the latter includes the sulphide-rich horizons associated with the gold. The paragenesis of the alteration assemblages is: (1) chlorite, sericite and minor kaolinite, (2) albite, quartz, sulphides and gold, (3) continuing albitization, followed by (4) multiphase quartz veining and silicification, and finally (5) the local introduction of calcite and ankerite as disseminations and veins.

Most of the quartz veins in the deposit appear to immediately postdate the introduction of the gold, sulphides and albite. Nevertheless, they are considered to be part of, and closely related to the mineralizing event. Consequently, the 150° to 320°C temperatures obtained from studies of fluid inclusions in quartz veins (Nesbitt et al., 1986; J.B. Murowchick, University of Alberta, written communication, 1986) are interpreted to indicate minimum temperatures for the Carolin mineralization. The hydrothermal system responsible for the Carolin deposit resulted in gold enrichment covering a present area of about 3000 m^2. However, the related geochemical and mineral alteration in the country rocks affected an outcrop area at least 40 times this size (approximately 130 000 m^2).

Lithological sampling to outline other areas of sodium enrichment represents a viable exploration tool for locating similar Carolin-type deposits in the district. The potassium and barium depletion envelopes that surround the individual ore horizons represent valuable drill targets; they could be used to locate downplunge extensions of the Carolin deposit north of the Richardson Fault.

On a district scale, the main controls of mineralization in the Coquihalla gold belt, including the Carolin deposit, are (1) the presence of competent host rocks that favour the development of a fracture-induced permeability, (2) close proximity to the East Hozameen Fault and the eastern margin of the Coquihalla serpentine belt, and (3) proximity to the Ladner Group-Spider Peak Formation unconformity, which is often the locus of faulting. More than 99% of the past total production from the Coquihalla gold belt has come from deposits less than 200 m from the East Hozameen Fault and the basal Ladner Group unconformity (Ray, 1984). In addition, Carolin-type mineralization is apparently controlled by the presence, in the Ladner Group, of F2 antiformal fold structures having disrupted hinges and limbs that provided conduits for the gold-bearing hydrothermal solutions.

ACKNOWLEDGEMENTS

This work resulted partly from a four-year mapping project of the Coquihalla gold belt by the British Columbia Ministry of Energy, Mines and Petroleum Resources. We thank the following for their assistance during this project: the management and staff of Carolin Mines Ltd. and Aquarius Resources Ltd., particularly P.W. Richardson and D.G. Cardinal; the staff at the British Columbia Ministry of Energy, Mines and Petroleum Resources, particularly B.N. Church, T. Hoy, W.J. McMillan, A. Panteleyev, W.R. Smyth, D.G. MacIntyre, W.M. Johnson, J. Kwong, and P.F. Ralph; M.J. Orchard and J.W.H. Monger of the Geological Survey of Canada; D. Bulinckx for typing the manuscript; J. Armitage, P. Chicorelli, and M. Lakin for drafting the figures; P. Desjardins for reliable assistance in the field; and D.G. Troop and K. Heather of the Ontario Geological Survey for their constructive reviews.

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