GEOLOGY OF THE WHITE RIVER NATIVE COPPER DEPOSIT, YUKON TERRITORY

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ABSTRACT

The White River copper deposit, in upper Triassic Nikolai Greenstone of southwestern Yukon, is representative of the native copper-basalt association. Native copper and chalcocite are the most abundant ore minerals but a substantial amount of bornite is known, as well as lesser amounts of chalcopyrite, pyrite, digenite, covellite, cuprite and native silver. These minerals are found in crosscutting fractures, amygdules, gas release tubes, small crackle zones, and as local disseminations in basalt; and although concentrated near the margins of a single glomeroporphyritic unit, are neither confined to that unit nor to a single zone within it.

Two stages of copper mineralization are postulated: Stage I mineralization is thought to account for most of the native copper as a product of continental weathering of Nikolai basalts. Stage II mineralization is a much later event characterized by copper sulphides in crosscutting structures.

Native copper and copper sulphides of Stage II appear to form a stable and primary product of a low grade (regional) metamorphism indicated by such minerals as chlorite, epidote, prehnite, pumpellyite, calcite analcite and apophyllite which have essentially the same mode of occurrence as primary copper minerals. Consequently, metamorphism (prehnite-pumpellyite facies) is interpreted to have been the mineralizing process. Whole-rock potassium-argon dating suggests an age no older than 120 m.y. for the metamorphic mineralizing event; hence, stage II mineralization post-dated host rock formation by at least 80 m.y. It is probable that many other copper occurrences in Nikolai Greenstone have formed in a similar manner. Also, it is likely that some of these mineralizing fluids could have moved higher in the stragigraphic sequence and precipitated copper minerals in other units.

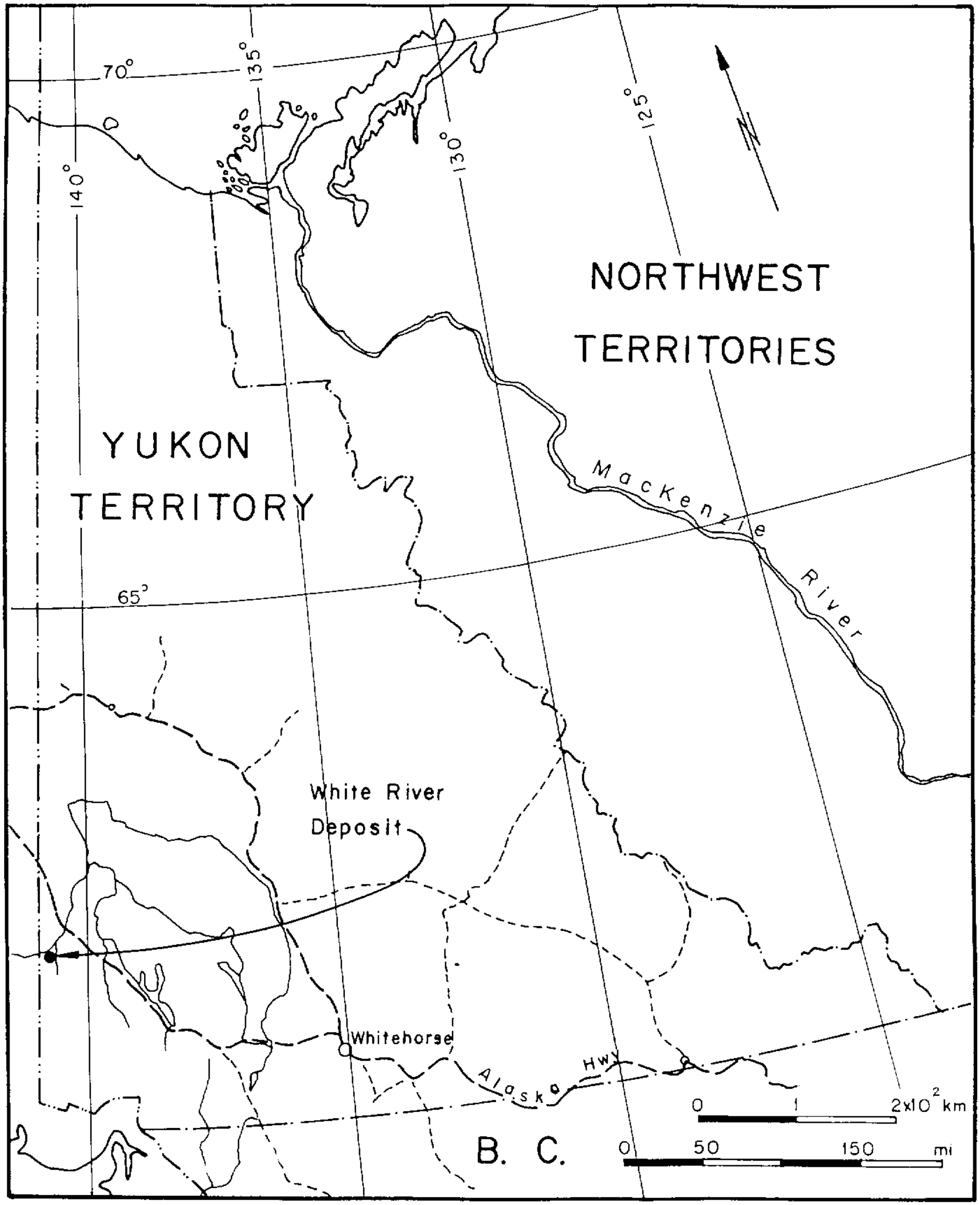

Figure 1: Location of White River native copper deposit.

Introduction

The White River copper deposit, owned by Silver City Mines Ltd. (now renamed Galaxy Silver Mines Ltd.), is about 220 air miles (352 km) northwest of Whitehorse, Yukon, and 6.5 miles (10.4 km) east of the Alaska border on the east bank of the White River (Figure 1). The property is about 16 miles (25.6 km) upriver from the point where the Alaska Highway crosses White River. Published reference to the deposit has been made since near the turn of the century (e.g. Knopf, 1910; Cairnes, 1915), and the occurrence has been cited as representative of a native Cu-basalt association that is recognized on a world-wide scale (Cornwall, 1956). White River copper deposit is renowned locally in Yukon by the fact that a 2,590 pound (1,173 kgm) slab of native copper forming part of the original discovery has been erected for display near the local museum in Whitehorse. Most recent exploration activity on the property has been under the auspices of Silver City Mines Ltd. Our field work during the summer of 1975 has made substantial use of survey and mapping information contained in several private reports by Dr. W.V. Smitheringale, Sr., and early exploration progress reports by R.J. Cathro, all submitted to Silver City Mines Ltd., Vancouver.

General Geology

Geology of the area is described by Muller (1967). Rocks in the Kluane Mountains range in age from Devonian to Cenozoic, and all with the exception of some Cenozoic units are folded and cut by southwesterly dipping thrust faults of regional extent. The White River property is in a small thrust slice of Permian and Triassic rocks bounded on the east by the Duke River overthrust and on the west by an unnamed thrust surface. Both faults dip gently to the southwest.

Permian rocks in the general area include a lower predominately volcanic unit and an upper sedimentary unit. The volcanic unit is characterized by pyroclastic and some flow rocks with minor amounts of intercalated greywacke, argillite and limestone. The sedimentary unit consists of argillite, sandstone, conglomerate, limestone and chert (see Read and Monger, 1976). Triassic Nikolai Greenstone is mainly amygdaloidal and/or porphyritic basaltic flow rocks that range in colour from red-brown to dark green, and are commonly 1,000 feet or more in total thickness. Native copper-copper sulphide deposits in the region are associated spatially with the Nikolai Greenstone.

Elsewhere in the area small mafic and ultramafic intrusions of probable Permian age have associated with them showings of Cu-Ni sulphides (Campbell, 1976). Much of the area immediately to the east of the White River property is underlain by Cretaceous intrusive rocks of intermediate composition.

No detailed account of the geology of the White River native copper deposit has been published to date. The most widely available description is a brief compilation of published literature and private reports summarized in a proprietary file, "Northern Cordilleran Mineral Inventory" prepared by the consulting firm, Archer, Cathro and Associates Limited, Vancouver, and kindly made available to the writers.

General geology of the property is shown in Figure 2 which is in part modified from unpublished maps by Dr. W.A. Smitheringale, Sr. The main mineralized area of particular concern in our detailed study is indicated by the small rectangle labelled "drill area".

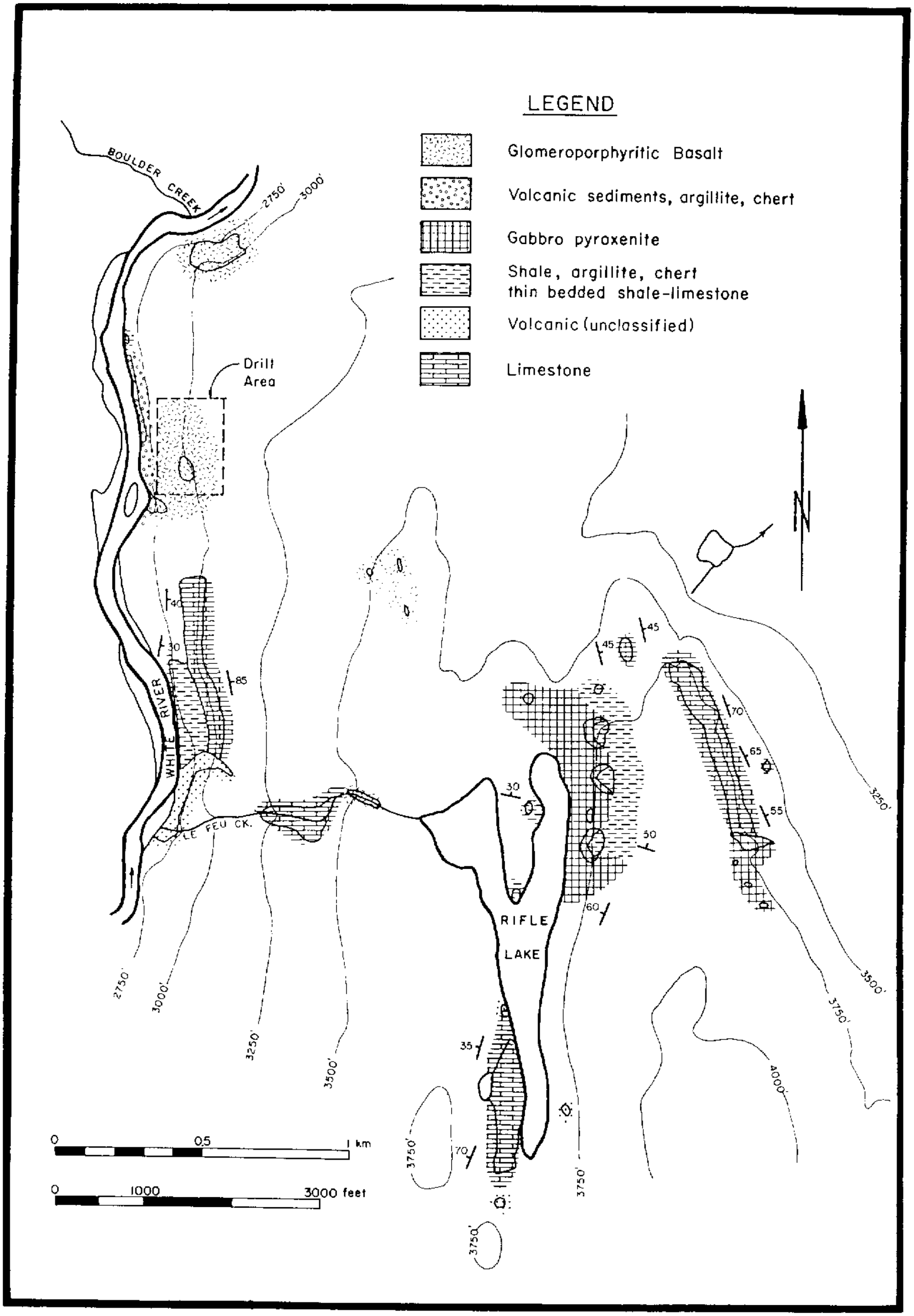

Figure 2: General geology of the area including White River native copper deposit. Modified from W.V. Smitheringale, Sr.

Host for the White River copper deposit is the Upper Triassic Nikolai Greenstone, a unit long recognized for the number of native copper-copper sulphide occurrences located within or stratigraphically near it (e.g. Knopf, 1910; Read and Monger, 1976). Within the general area the unit ranges up to several thousand feet thick (1,000 m). In the White River thrust segment the true thickness is unknown but probably is very much less than the maximum value of 3,000 feet (916 m) quoted by Read and Monger (1976). In general, all units of the Nikolai Greenstone are basaltic, the main mappable features being presence or absence of amygdules and/or phenocrysts and/or glomerophenocrysts, and colour variations. These features are not necessarily uniform even in a single flow. For example, both top and bottom of a flow might be amygdaloidal but the interior need not be; a flow top might be oxidized to a red-brown colour whereas the remainder of the flow could be dark green. Because of these variations considerable emphasis during mapping and core logging was placed on recognition of flow tops as a means of correlation and as an aid to structural interpretations of the volcanic sequence.

TABLE I

STRUCTURAL SUCCESSION OF UNITS WHITE RIVER COPPER DEPOSIT

Unit	Apparent Thickness [feet]	[metres]
5. Glomeroporphyritic Basalt No. 2	60 (min)	18.5
4. Grained Basalt	130	40
3. Glomeroporphyritic Basalt No. 1	250	76.9
2. Red and Green Amygdaloidal Basalt	100 (min) 200 (max)	30.7 61.4
1. Porphyritic Basalt	40 (min)	12.3

Five mappable units summarized in Table I are shown in the projected sections of Figures 3 and 4. Of these units, 3 and 5 are indistinguishable in hand specimen but in the field are separated, structurally at least, by a recognizably different rock, Unit 4. Limestone to the east of the mineralized volcanic sequence (Figure 2) is Permian in age based on fossil evidence (R.V. Kirkham, personal communication, 1977), and probably is in fault contact with the Nikolaï rocks on the west. Position of the volcanic rocks described here, within the total Nikolai succession, is uncertain.

All units consist of many flows. A brief description of each unit follows.

PORPHYRITIC BASALT (Unit 1): Porphyritic basalt is a sequence of unknown thickness at the base of the structural succession containing the mineralized zones. The rock is a fine-grained volcanic rock with 5 to 15 percent plagioclase phenocrysts about one mm long and many amygdaloidal sections 1 to 2 feet thick. Colour is green, grey-green, or red-brown. Glomerophenocrysts are rare and smaller than in Units 3 and 5, i.e. about 3 to 5 mm in diameter.

RED AND GREEN AMYGDALOIDAL BASALT (Unit 2): This unit is fine-grained with no glomerophenocrysts and relatively few plagioclase phenocrysts. It consists of intercalated dark red-brown and dark green layers and is commonly highly amygdaloidal (about 15 volume percent amygdules). Most amygdules are 2 to 3 mm in diameter and consist of either chlorite, calcite or zeolites on the White River property. Minimum thickness of the unit is 100 feet but it could be as thick as 200 feet.

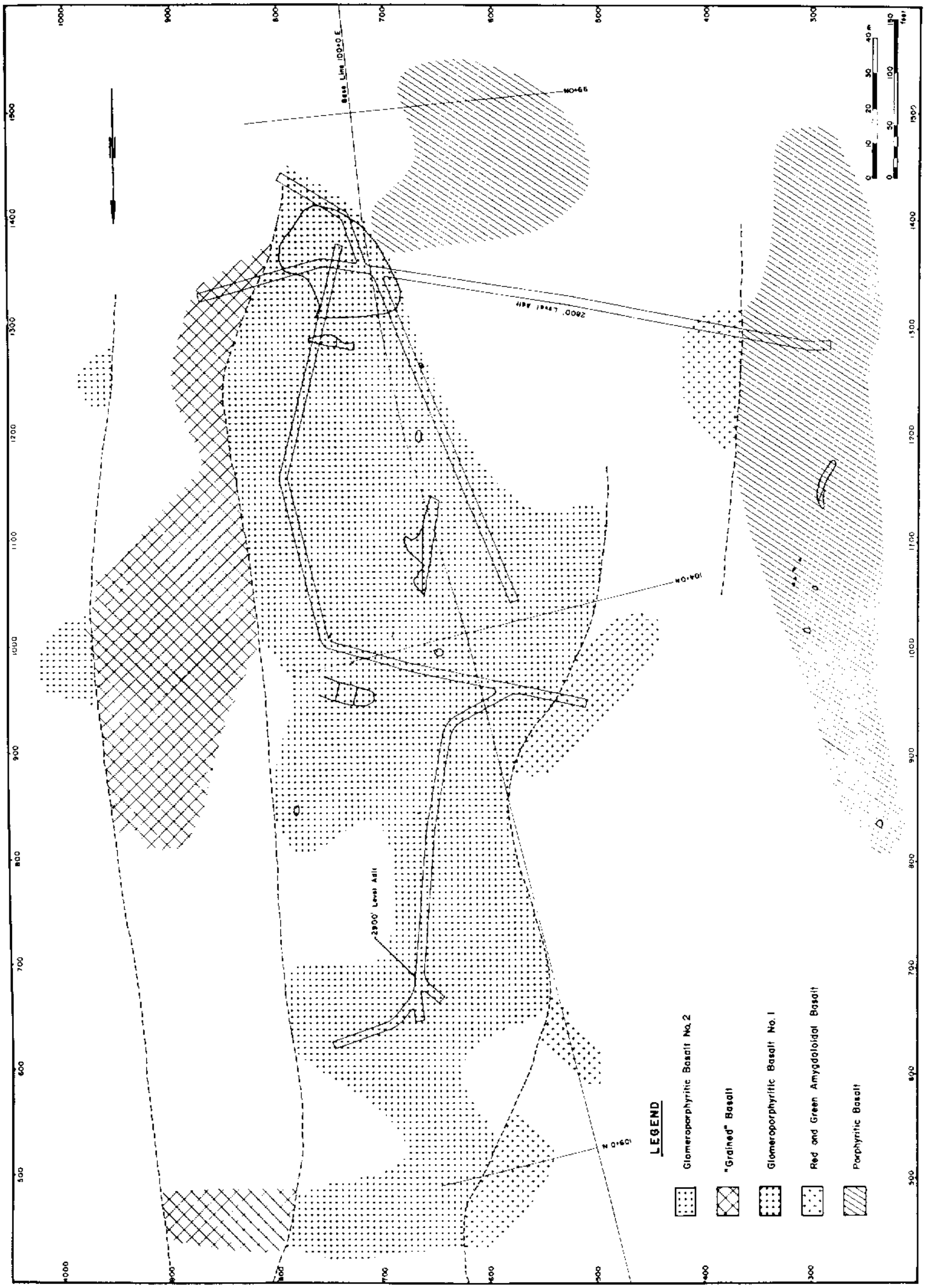

Figure 3: "Projected" plan showing slightly generalized lithologic contacts based on contact information projected along the average dip direction to the 2,900 foot level (890 m level). The 2,800 and 2,900 levels are outlined as are projected positions of outcrops. Portals are at the extreme west of the two levels.

GLOMEROPORPHYRITIC BASALT NO. 1 and NO. 2 (Units 3 and 5): Glomeroporphyritic basalt is either green, grey-green or some shade of red-brown.It is porphyritic (about 10 percent plagioclase phenocrysts up to 4 to 5 mm long) and characteristically contains widely spaced plagioclase glomerophenocrysts in which stubby to lath-shaped phenocrysts are arranged in clusters with a crude radial or star-like form. Diameters of these glomerophenocryst are of the order of 1 cm. Flow margins in the unit are amygdaloidal with chlorite the main mineral forming amygdules. Unit 3 has an apparent thickness through the main mineralized zone of 250 feet but appears to thin somewhat with depth. The minimum established thickness of Unit 5 is about 60 feet. The unit is certainly thicker but outcrops and drill data are too sparse to provide more information. Most of the known copper minerals are concentrated in Glomeroporphyritic Basalt No. 1 (Unit 3) although it should be pointed out that all units contain some native copper and/or copper sulphides.

"GRAINED" BASALT (Unit 4): This unit, referred to in the field as a "gabbro" is a volcanic rock with a high proportion of stubby phenocrysts about 3 to 4 mm long and a correspondingly small amount of matrix. The *megascopic* appearance is that of a medium-grained phanerite; the matrix is apparent in thin section. Amygdules 2 to 3 mm in diameter are present, mainly formed of chlorite or calcite, but are not nearly as abundant as in other units. Apparent thickness of the unit is about 130 feet.

GREENSTONE: A greasy appearing volcanic rock termed greenstone in the field was recognized only as thin layers within other units, particularly Glomeroporphyritic Basalt No. 1 (Unit 3). On very close examination small phenocrysts and amydules (up to 3 mm in long dimension) can be seen, or relicts of phenocrysts remain. Most specimens contain at least a few very small blebs of native copper and it is for this reason that the rock type has been considered of some importance in the past. Detailed examination has shown the rock to be an altered vitrophyre, the greasy lustre arising from alteration of volcanic glass. Apparent thicknesses of individual layers commonly range from about 5 to 20 feet.

Structure and Volcanic Stratigraphy

Geology of the mineralized zone is shown in plan and section in Figures 3 and 4 respectively (after Bentzen and Sinclair, 1978). Figure 4 is a "projected" vertical section through the 2,900 adit (adit designation is in feet above sea level). It is termed "projected" because all drill hole information within 150 feet (45.8 m) of the plane of section has been projected along the average strike to the plane of section. The section was generated originally from a computerized data file of drill hole and outcrop information and was output using a Calcomp drum plotter.

The cross section is to all intents and purposes perpendicular to the trend of the volcanic flows on the property, and provides a fairly clear indication of the general disposition of individual volcanic units. Superficially the sequence is homoclinal, but such an interpretation is a gross oversimplification because in areas of outcrop to the north (along the shore of White River) part of the same volcanic succession can be seen cut by fault surfaces that are subparallel to the "tabular" volcanic units. Comparable faults certainly exist in and near the mineralized zones, and, in fact, can be recognized in drill core and in adits. However, these faults cannot be projected with confidence, even over short distances; consequently, the extent to which they complicate the simple homoclinal structure indicated in Figure 2 cannot be ascertained. Field evidence from flow tops indicates that the succession is rightside up.

Contacts in general dip steeply to moderately to the east. Irregularities apparent in the contacts could arise from several causes; (a) data are projected within a total zone width of 300 feet and the section might not be perpendicular to local strikes over this short distance, (b) surveyed elevations are only approximate, (c) drill holes (unsurveyed) are assumed to be perfectly straight, and (d) faulting may have produced local irregularities in the "apparent" contacts. Despite these sources of uncertainty the accompanying section provides useful insight into the general structure of the mineralized zone and approximate orientation of individual units. The contact between Porphyritic Basalt and the Red and Green Amygdaloidal Basalt No. 1 is thought to be a fault, at least in part, based largely on the abundance of broken core observed during drill core logging.

Strikes and dips of some marker surfaces or units can be determined by solutions to three-point problems where sufficient drill intersections are available. A number of such calculations done at various locations in and near the mineralized zone, where effects of faulting are thought to be minor, show the strike to be essentially northerly. Dips are all to the east and range from moderate to steep. Precise dip values calculated from three-point

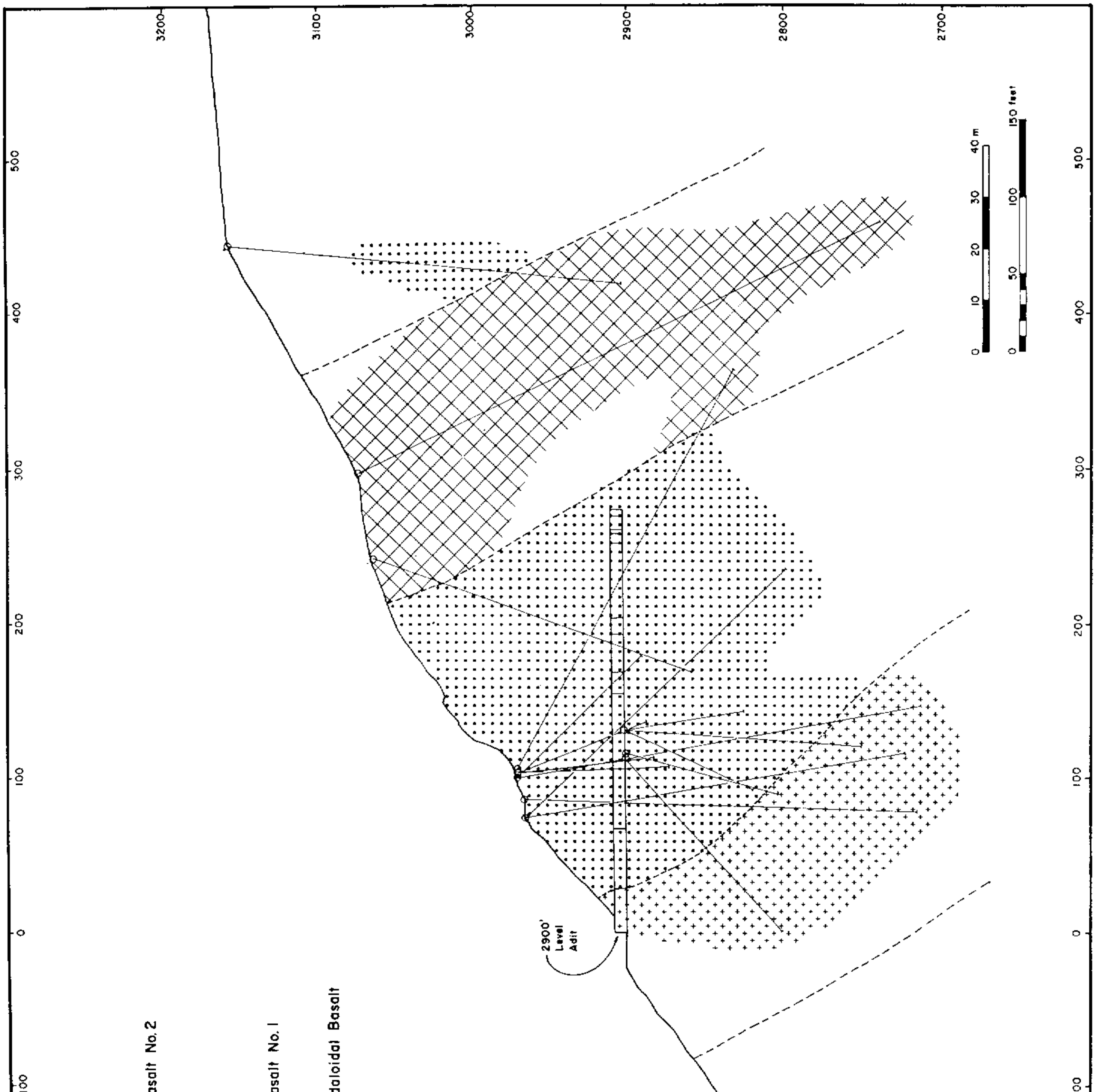

Figure 4: Projected vertical section through 2,900 adit. Contact information within 150 feet (46 m) of the plane of section was projected to the plane of section along the average strike direction.

problems are not particularly significant because of the short distances over which they have been calculated and the approximate methods used to determine locations in space.

A projected plan is shown in Figure 3. This plan was computer-generated by projecting critical drill hole information in the average dip direction of the homoclinal sequence to the 2,900 level. Thus, particular details of the plan can be slightly in error, but the distribution shown for mappable units is generally correct and the "projected" plan, considered with the "projected" vertical section, provide the first clear understanding of the general geometry of the volcanic succession in the immediate vicinity of the White River copper deposit.

Petrography

All mappable volcanic units have many petrographic (as well as chemical) features in common, that seem to require a common genesis. Even the field units Grained Basalt and Greenstone were found to be simply textural modifications of porphyritic and/or amygdaloidal basalts. The Grained Basalt, for example, simply contains a high proportion of plagioclase phenocrysts and a complementary low proportion of matrix, and superficially has the appearance of a phaneritic rock rather than a porphyry.

Perhaps a more significant point is that the Greenstone unit, an easily recognizable field unit with a greasy lustre, is simply a basalt in which phenocrysts are set in what was a glassy matrix, now devitrified. Virtually all such rock contain copper minerals (especially native copper) as disseminated grains or as irregular veinlets, and "greenstone" in the past was interpreted as hydrothermally altered volcanic rock. Our petrographic work shows it is equally plausible to interpret greenstone as a metamorphosed volcanic glass.

Primary minerals recognized in these rocks are plagioclase, augite, magnetite, hematite and rare apatite. A few pseudomorphs of serpentine after olivine were recognized but no olivine remains in specimens we examined. These primary minerals are commmonly set in an ill-defined matrix that originally ranged through microcrystalline to cryptocrystalline to glassy, from place to place. This matrix has been altered to varying degrees. The red-brown colour of parts of the volcanic succession can be seen to derive from partial oxidation of abundant magnetite to hematite. However, even where a deep red-brown colour occurs only a fraction of the magnetite has been oxidized.

The extent of deuteric processes is unknown. It may be that the principal vestige of deuteric alteration is serpentine as pseudomorphs after olivine. However the rock has been altered extensively by low grade regional metamorphism and any deuteric effects that might have existed are no longer obvious.

Approximate mineral abundances based on thirty-one specimens examined in detail are indicated in Table II. A rapid perusal of this table shows that the primary minerals are in the relative proportions expected for basaltic rocks. Of particular interest though is the prevalence of alteration minerals. Abundant chlorite and calcite, and the somewhat more localized occurrence of prehnite, pumpellyite, analcime, etc. indicate that the rock has undergone substantial alteration.

TABLE II

APPROXIMATE RANGES OF MINERAL PERCENTAGES IN THIRTY SAMPLES OF NIKOLAI GREENSTONE

		Approximate Range [Volume Percent]
Primary Minerals	Plagioclase	25-60
	Augite	7-25
	Magnetite	4-10
	Hematite	
	Apatite	Tr. 2
Metamorphic Minerals	Calcite	Tr-7
	Chlorite	5-25
	Epidote	Tr-1
	Prehnite	Tr-3
	Analcime	Tr-5
	Pumpellyite	Tr-2
	Laumontite	Tr
	Quartz	Tr
	Native Copper	0-3.5
	Copper Sulphides	0-5
	Serpentine	Tr
	Pyrite	0-2
	Sericite	0-8

Primary Minerals

Plagioclase is the most abundant mineral in the rocks studied. It occurs as lath-shaped phenocrysts about 1 to 3 mm long, locally arranged as glomerophenocrysts, and as an important component of the ground mass where it forms microlites. It commonly displays a subophitic texture with augite. Locally plagioclase is replaced extensively, although in many places it is relatively fresh. Sericite, chlorite and less abundant calcite or epidote commonly partly replace plagioclase. Where fresh, plagioclase phenocrysts are zoned normally with cores about An-80 and rims about An-60. Plagioclase in a hornblende-bearing dyke (?) rock of limited occurrence has a composition of An-54. Some microlites are about An-45.

Augite, the only pyroxene recognized, is present in highly variable amounts. It forms anhedral grains with either an intersertal or subophitic relation to plagioclase. Grains are normally in the range 0.2 to 0.6 mm diameter. Augite is surprisingly fresh in most cases but locally is replaced by chlorite.

Magnetite is ubiquitous in Nikolai rocks as anhedral grains normally 0.2 to 0.4 mm diameter. It is variably altered to hematite. Most magnetite is intersertal to plagioclase but locally it forms skeletal crystals.

The former presence of olivine is recognized by pseudomorphs of serpentine with well developed olivine crystal morphology now outlined by iddingsite. Olivine does not appear to have been abundant. Individual crystals were mostly in the range 0.5 to 1.0 mm diameter.

Hornblende has been found in only a single rock unit located in two short drill hole intersections, both intersections have been interpreted as dyke rock, perhaps the same dyke. Hornblende crystals are acicular phenocrysts up to 4.5 mm long in a matrix of plagioclase microlites with trachytic texture (Plate I).

Apatite is a minor accessory mineral observed in several specimens in very small amounts as minute crystals.

Hematite formed largely prior to complete consolidation of the rocks in which it occurs, by oxidation of magnetite. Hematite forms rims around magnetite and extends diffusely outward from magnetite cores into thin intergranular coatings that locally give rise to a deep red-brown colour, particularly in flow tops.

Secondary Minerals

Alteration minerals are present in all rocks examined, although their amounts vary as does the intensity of alteration of primary minerals. In many cases the principal alteration effects noted are infilling of voids by chlorite, calcite, prehnite, epidote, etc. and related opaque minerals. The voids were vesicles, gas release tubes, small scale irregular fractures and more extensive planar openings (perhaps joints) some of which cross cut the trend of the volcanic strata. Any openings that existed at the time of metamorphism were potential sites for deposition.

In addition to open space fillings, alteration effects are particularly evident in glassy or very dense matrix material which is now generally completely devitrified and/or altered to chlorite most commonly. A more advanced stage of alteration involves replacement of primary minerals, principally plagioclase, mainly by chlorite and lesser amounts of epidote and calcite.

These alteration minerals are properly referred to as metamorphic minerals, and a most interesting aspect of them is the presence of native copper and copper sulphides as what appears texturally to be a natural and original part of the assemblage. Common stable assemblages are chlorite-calcite, and quartz-epidote. Locally, the critical assemblage prehnite-pumpellyte is found. A fairly common assemblage is prehnite-native copper (Plate I). Sulphides and native copper are discussed in detail in a later section.

Chemical Analyses

All volcanic rocks investigated are basaltic in composition. Whole rock chemical analyses done on apparently unmineralized representative samples from drill core are listed in Table III. Data were obtained by X-ray fluorimetry by J.A. McLeod. No precision estimates are given but 3 specimens were sampled and analyzed in duplicate (Nos. 34, 58 and

TABLE III

X-RAY FLUORESCENCE ANALYSES OF NIKOLAI BASALTS*

Sample	14	34	34A**	58	58A**	71	99	213	217	233	233A**	248	Mean	Std. Dev.	Std. Err.
SiO_2	49.119	49.659	49.150	49.369	49.252	47.991	47.078	47.532	50.073	48.549	47.293	50.179	48.937	0.917	0.268
Al_2O_3	14.646	15.032	15.167	15.736	15.719	16.518	13.878	16.887	13.611	15.143	14.992	13.750	15.090	1.034	0.298
FeO	14.564	12.507	12.785	11.770	11.472	11.937	13.269	12.879	13.423	13.804	13.356	13.173	12.912	0.889	0.257
CaO	6.283	6.017	5.994	6.182	6.251	10.584	6.584	7.483	4.606	8.591	8.348	6.533	6.952	1.575	0.455
MgO	3.641	3.973	3.824	4.000	3.841	4.060	4.603	3.999	3.370	4.647	4.504	4.282	4.062	0.388	0.112
MnO	.164	.139	.139	.245	.247	.257	.185	.254	.184	.207	.201	.179	0.200	0.043	0.0123
TiO_2	2.858	2.607	2.631	2.214	2.212	2.658	2.346	2.735	3.184	2.775	2.709	2.483	2.618	0.277	0.0801
K_2O	1.191	.659	.647	1.531	1.558	.415	.254	1.470	.850	1.000	.999	1.549	1.010	0.459	0.132
Na_2O	3.548	3.971	4.044	3.571	3.627	2.246	3.502	2.681	4.613	1.502	1.149	3.492	3.187	1.002	0.289
P_2O_5	.415	.432	.388	.385	.378	.446	.398	.426	.437	.437	.451	.427	0.414	0.033	0.010
H_2O	1.768	2.564	2.636	2.485	2.543	2.058	3.066	2.403	2.252	2.352	2.459	2.263	2.404	0.319	0.092
TOTAL	98.198	97.560	97.406	97.399	97.101	99.170	97.164	98.750	96.603	99.007	96.761	98.311			

** indicates a duplicate sample

*Analyst: J.A. McLeod

233) and the slight compositional variations shown between duplicates indicates a high quality of reproducibility in the analytical technique. Accuracy is presumed to be adequate because of the high quality working curves that were obtained for standards of comparable composition.

Chemically the Nikolai analyses are intermediate between alkali olivine basalts and tholeiites (see Figure 5). However, their general characteristics are more compatible with a tholeiitic classification as most authors have recognized (e.g. Read and Monger, 1976).

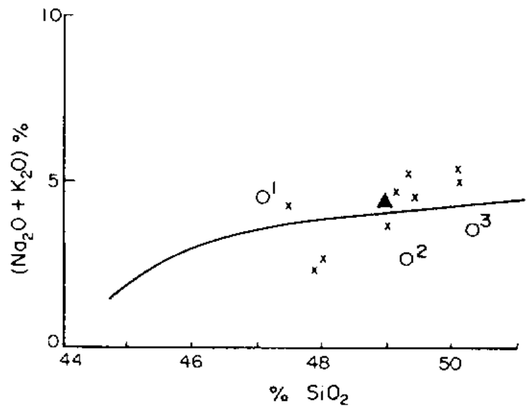

Figure 5: Alkali-silica plot of data for Nikolai Greenstone analyses of Table III. The average is shown as a solid triangle open circles 1, 2 and 3 are average analyses of alkali olivine basalt, oceanic tholeiites and continental tholeiites respectively.

Trace Metal Content

Samples analyzed for major elements were also analyzed for Rb, Sr, Zn, Cu and Ni. Results are listed in Table IV. No data are available regarding accuracy and precision of these particular analyses; however, for values in the 100 ppm range the method routinely provides a counting precision of about 5 percent (two relative standard deviations) in the U.B.C. laboratory where the analyses were done.

The specimens do not seem particularly abnormal with respect to trace elements presented here and, in fact, data are similar to those for comparable rocks in Alaska (E. Mackevett, Jr., personal communication, 1978). One interesting aspect of the copper data arises in comparing them with assay results for mineralized samples taken by one of us (A.B.). Note that the average value of copper in the apparently unmineralized samples analyzed is 147 ppm or about 0.015 percent compared with two assays of 0.005 percent copper --

both assayed samples contained minute amounts of visible native copper! Despite the imprecision of the assay values (because they are near the detection limit of the assay method) an important implication of these results is that "mineralized" rock can contain substantially less copper than does apparently unmineralized rock. One possible explanation of this seeming paradox is that some so-called mineralized rock with visible Cu minerals results not by the addition of but by a "reorganization" during metamorphism, of the Cu already in the rock, and perhaps in some cases seen as net loss of copper occurred during this reorganization.

TABLE IV

SOME MINOR ELEMENT ABUNDANCES IN NIKOLAI BASALTS*

Sample	Rb	Sr	Zn	Cu	Ni	Rb/Sr
14 Golmeroporphyry	15.33	258.78	90.0	94.5	95.0	.0592
34 Flow margin Glomeroporphyry	8.05	206.42	91.5	61.5	88.0	.0389
58 Glomeroporphyry	22.80	220.23	126.5	217.5	86.0	.1035
71 Greenstone	3.74	232.54	138.0	97.5	83.0	.0160
99 Glomeroporphyry	3.57	90.79	95.0	173.0	79.0	.0393
213 Glomerporphyry	19.06	289.15	142.0	233.0	104.5	.0659
217 Glomerporphyry	5.32	80.63	177.0	177.0	89.0	.0659
233 Greenstone	6.06	196.50	118.0	185.0	89.0	.0309
248 Glomeroporphyry	16.76	207.74	161.5	88.0	79.5	.0807
Mean ($\bar{x}$)	11.19	198.09	126.61	147.44	88.1	
Std. Dev. (s)	7.32	69.94	31.16	62.63	8.0	

*Analyst: J.A. McLeod, by X-ray fluorescence

Economic Geology

Opaque minerals identified in polished section of samples from the White River deposit are listed in Table V with their approximate average percentages in copper-bearing rock. Magnetite and hematite form an integral part of the country rock; other opaque minerals are part of the mineralization suite although a possibility exists that much of the native copper is a product of Mesozoic weathering.

The local, seemingly erratic, occurrence of copper minerals obscures the geometry of relatively rich mineralized zones. To offset this difficulty we have prepared a plan view of the 2,900 level showing the positions of projected copper mineral occurrences relative to projected lithologies (Figure 6). To

TABLE V

OPAQUE MINERALS AND THEIR RELATIVE ABUNDANCES WHITE RIVER COPPER DEPOSIT

Native Copper	55%
Chalcocite (incl. djurleite)	22
Bornite	9
Magnetite (in host)	8
Hematite	3
Pyrite	1
Digenite	1
Covellite	0.5
Chalcopyrite	0.5
Cuprite	tr
Malachite and Azurite	tr
Native Silver	tr

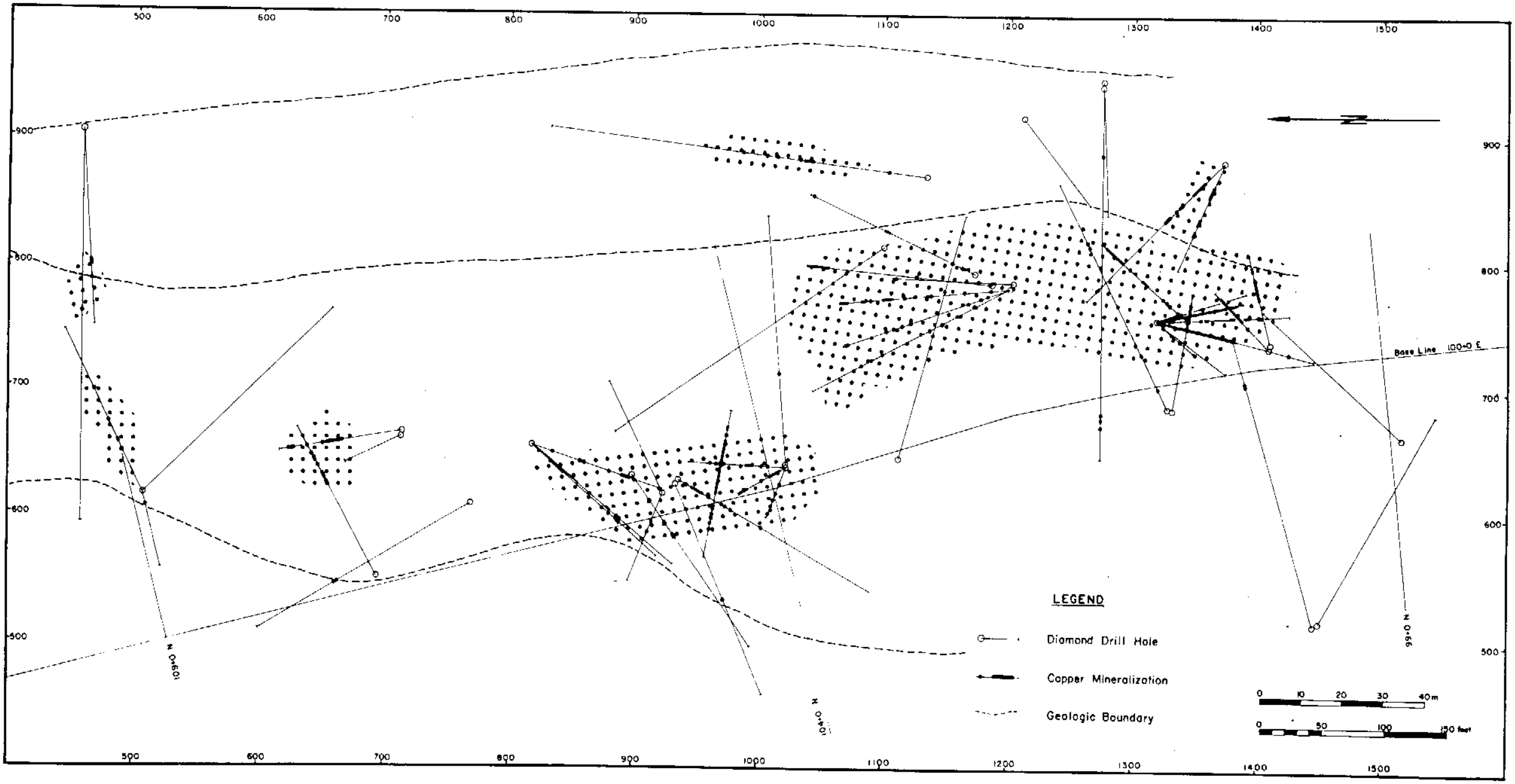

Figure 6: The occurrence of copper minerals noted in drill core and projected to the 2,900 level. Compare with Figure 3. Black dots are copper occurrences, black bars are copper occurrences too numerous to show individually. The hachured area shows the generalized distribution of copper mineral concentrations.

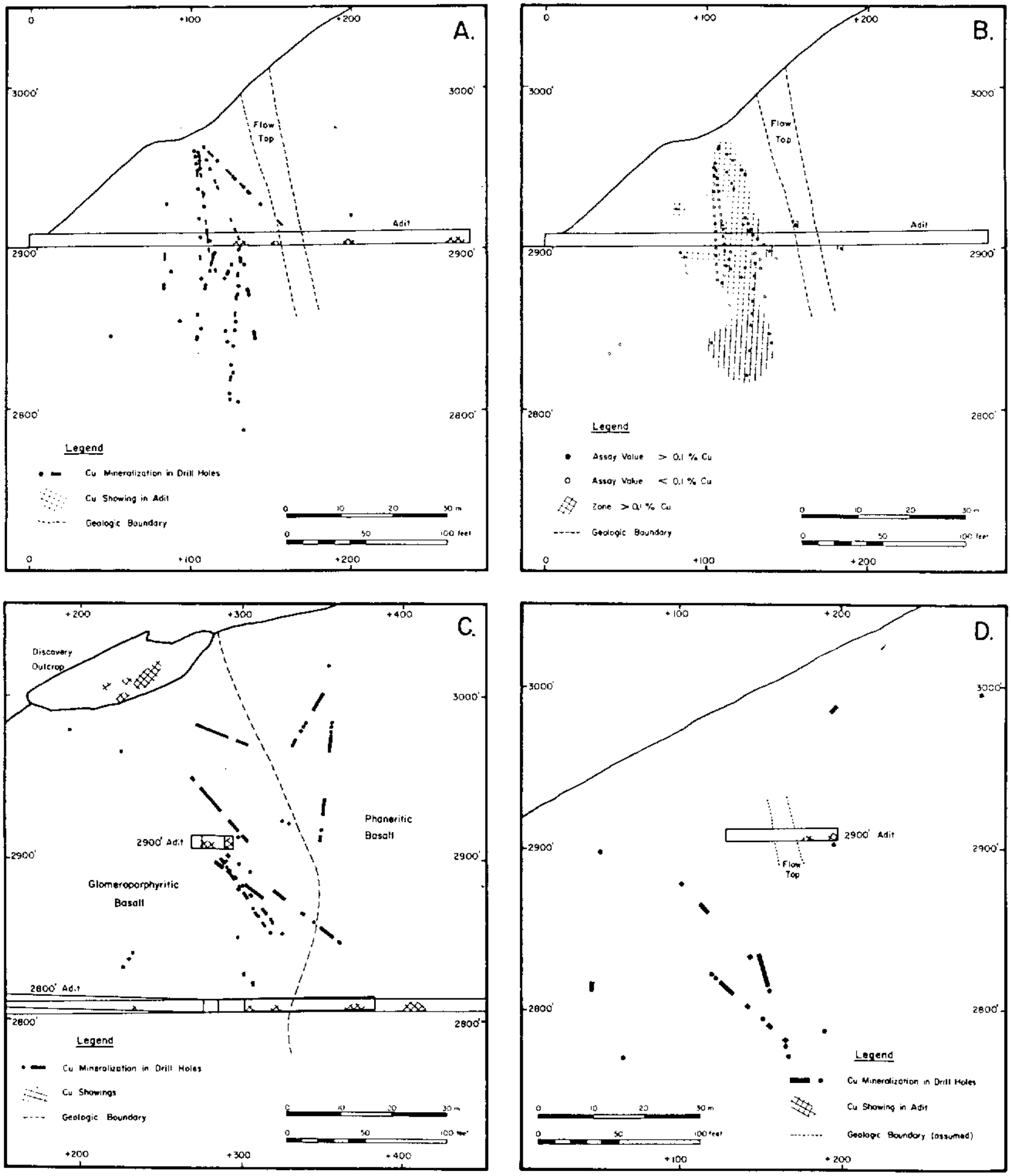

Figure 7: Cross sections showing positions of minerals (or assayed samples) noted in drill core within 150 feet (46 m) of the plane of section and projected along strike to the plane of section.

(a) Projected E-W section through 2,900 portal showing concentration of copper minerals relative to flow top. The section cuts 105 + 0N on the baseline of Figure 3.

(b) Same section as (a) showing projected assay values for split core samples. Patterned zone is interpolated as greater than 0.1 percent Cu.

(c) Projected E-W section through discovery outcrop showing copper mineral occurrences. Note concentration of copper minerals relative to contact of glomeroporphyritić basalt and phaneritic (grained) basalt. Section is through 101 + 5N on Baseline of Figure 3.

(d) Projected E-W section through 108 + 0N on baseline of Figure 3 showing copper mineral concentrations.

further clarify the geometry of mineralized zones we show in Figure 7 a series of projected sections, three of which are simply projections of reported "occurrences" of copper minerals in drill core logs and one of which represents projected assay values. In all cases, planes of projection are roughly perpendicular to the strike of the volcanic sequence, and only data within 150 feet of each section were projected.

An evaluation of these diagrams leads to a conceptual picture of the copper-rich masses as tabular zones, erratic in detail, localized near the two contacts of Unit No. 3 (Glomeroporphyritic Basalt No. 1). Of course, copper minerals are found sporadically in all the volcanic units, but the major concentrations have a clearly defined general tabular shape.

Copper minerals occur in several distinct forms in the White River deposit, viz. (1) apparently disseminated, mainly in greenstone, (2) in amygdules, and (3) in veinlets. In all these occurrences copper minerals are associated intimately with metamorphosed volcanic rock, and appear to be a natural and primary part of a metamorphic mineral assemblage that includes prehnite, pumpellyite, chlorite, epidote, calcite and locally, apophyllite or analcime, as illustrated in Plate I.

Copper minerals seem to be distributed erratically within the showing. Locally grades attain 2 to 3 percent Cu over distances of 25 or so feet (8 m) but such occurrences are rare, in part because of the localized nature of mineralized rock and in part because such occurrences, scattered in the first place, have been cut and segmented by faults. Metallic copper minerals are widely dispersed but the associated copper grade generally is not high across sample lengths of 10 feet or more.

Both native copper and chalcocite occur in veinlets many of which crosscut the general trend of volcanic rocks. In some places disseminated and amygdaloidal copper minerals are concentrated near mineralized crosscutting veinlets. Whatever their origin, copper minerals are unquestionably in large part epigenetic in their present locale. As indicated above and illustrated in Plate I native copper and copper sulphides are intimately associated spatially with low grade metamorphic mineral assemblages of the prehnite-pumpelleyite facies.

Mineralography

Opaque minerals recognized in the White River copper deposit are listed in Table V with an indication of their approximate average amounts in specimens examined in detail. On the average, hand specimens used for the mineralographic study contained about 15 percent opaque minerals (by volume) which is higher than most of the deposit except for selected high grade zones.

Native copper is by far the most abundant ore mineral on the property and occurs mainly in veins, some of which are several centimetres wide at least locally and many of which are predominantly copper over many metres of length or, conversely, contain a very small proportion of native copper. Calcite and epidote are common in veins low in native copper (Plate I). Prehnite is a fairly abundant vein-filling mineral and commonly shows a mammillary form along the two walls of a vein with local small openings (vugs) that occur intermittently along the length of the vein. In a number of cases small octahedral native copper crystals have been observed in vugs of this sort (Plate I). The better mineralized zones contain numerous parallel veinlets which widen locally to form "nuggets" that have irregular hackly extensions into the wallrock. A dichotomous situation exists for native copper-bearing veins, the two abundant types being those largely native copper and those largely gangue minerals with a small proportion of native copper.

A small proportion of native copper veinlets or seams contain an important amount of cuprite, perhaps 10 percent. In virtually all such veins observed by the writers vein margins are diffuse, with cuprite concentrated near the margins of native copper "nuggets". Because of the irregular margins, thicknesses are difficult to measure accurately, but most veinlets do not exceed 5 mm.

Native copper also occurs in two other forms that in total account for a very small percentage of

TABLE VI

DUPLICATE ASSAY RESULTS OF CHIP SAMPLES TAKEN OVER 10 FOOT LENGTHS

Sample No.	% Cu in Replicates A	% Cu in Replicates B
40/9/17	0.022	0.022
40/19/12	0.025	0.027
40/5/18	0.005	0.005
40/5/17	0.005	0.005

Analyst: Mr. P. Kemp, Mineral Eng. Dept., University of British Columbia.

copper in the deposit. The most significant of these is disseminations mainly in Greenstone but also in other units. Virtually all Greenstone (altered vitrophyre) contains at least some native copper as small disseminated grains in devitrified glass or less commonly as a replacement of plagioclase. It is interesting to note that chip samples taken over a distance of 10 feet of Greenstone containing visible but small amounts of native copper, assay substantially less than the average geochemical abundance of copper in Nikolai specimens (Tables IV and VI). The third mode of occurrence of native copper is in amygdules and gas release tubes where it is found only rarely as a minor constituent of what are mainly calcite-chlorite and epidote-filled structures.

Chalcocite is the most abundant sulphide in the deposit and occurs in two principal mineral associations that are mutually exclusive; chalcocite-native copper described previously, and chalcocite-bornite. Bornite is commonly much more abundant than is apparent megascopically, principally because it is intergrown intimately with chalcocite. Bornite has been observed only in association with chalcocite and chalcopyrite. The association chalcocite-bornite is most common in veinlets and as infilling in what appear to be very small crackle zones. This latter form is particularly characteristic of high grade sections. Copper-bearing amygdules generally contain about 80 percent chalcocite and 20 percent bornite intergrown in vermicular fashion. Disseminated chalcocite is commonly adjacent to veinlets and is especially abundant in zones near chalcocite-bearing amygdules. Bornite occurs in several samples with chalcopyrite, the two intergrown with crystallographic texture and consisting of about 8 percent (by volume) chalcopyrite. Chalcopyrite occurs also in association with rare pyritic zones and as isolated blebs in a few amygdules. The association with pyrite has a somewhat unusual textural form in that fairly regular lamellae of chalcopyrite occur in pyrite crystals. Digenite although widely dispersed throughout the specimens examined is present only in small amounts, partly as a reaction zone between chalcocite and bornite. In some cases digenite is clearly supergene, in other cases it might be hypogene. Covellite, on the other hand, is entirely supergene in origin, and occurs along margins of some chalcocite grains.

Pyrite is present only rarely. It has been found in two short drill intersections that may represent a one to two foot layer with potential as a marker unit. It has also been noted in an outcrop 50 feet (46 m) south of the 2,900 portal. In all cases it has associated with it small amounts of chalcopyrite. Very minor amounts of pyrite have been found in amygdules formed largely of calcite and quartz.

Both magnetite and much hematite appear to have formed at the time the host crystallized, independently of copper mineralization. Magnetite is commonly intersertal, less commonly skeletal: it is the common iron oxide of green volcanic rocks. Even a small amount of oxidation to hematite imparts a distinctive red-brown colour to the rock. Most red-brown rocks investigated microscopically still retain a substantial portion of the original magnetite as cores to hematite patches. A few crystals of specularite have been noted associated with copper minerals. This specularite may simply represent hematite that has been recrystallized as a result of the later mineralizing process. On the other hand some hematite may have formed by oxidation of magnetite by the mineralizing fluids. Djurleite is suspected but has not been confirmed by X-ray analysis.

Trace amounts of native silver have been found associated with native copper. The silver has been observed in two anhedral grains completely enclosed within native copper. A preliminary investigation by scanning electron microscopy indicates that the native silver is abnormally high in mercury. It is interesting to note that the famous Kennecott copper sulphide deposits are characterized by relatively high silver and mercury contents (MacKevett, personal communications, 1978).

Copper oxides identified in hand specimen and polished section are cuprite, malachite and azurite. Cuprite appears to be contemporaneous in origin with native copper in some places, but could be partly related to weathering processes as undoubtedly are malachite and azurite.

Geothermometry

Several independent approaches to geothermometry of the White River copper deposit were investigated. Textural studies indicate that native copper, copper sulphides and the non-opaque minerals chlorite, calcite, epidote, prehnite, pumpellyite and apophyllite were all deposited in their present form during metamorphism of Nikolai basalts. Consequently, all these minerals must have formed under somewhat comparable temperature conditions. The low grade metamorphic assemblage prehnite-pumpellyite is stable in the range 300°C to 400°C (Liou, 1971). Several examples of this assemblage with native copper as a primary stable member have been observed in the White River deposit, particularly in drill hole number 104. The stability field of this assemblage is not greatly dependent on pressure.

Several textures among the copper sulphides are interpreted as resulting from exsolution. In particular, a crystallographic texture of chalcopyrite blades in bornite has a minimum temperature of formation by exsolution of about 220°C (e.g. Brett, 1963) at eight mole percent chalcopyrite. In White River specimens the chalcopyrite content of such a mixture is close to eight mole percent. A second texture in White River copper sulphides that could also arise by exsolution is a vermicular intergrowth of bornite and chalcocite, particularly common in some amygdules (Plate I). If this vermicular texture originated by exsolution it indicates a minimum temperature of formation of 200°C (Brett, 1963).

We attempted fluid inclusion studies of several specimens of transparent minerals but found that most inclusions were either too small to work with or leaked on heating. However, one primary inclusion in calcite from a vein containing 85 percent (volume) calcite and 15 percent prehnite produced acceptable results (sample 40/2/3). The inclusion is small, about 0.02 mm in longest dimension, and contained two phases, gas and liquid. The ratio of bubble equatorial area to maximum planar area of the inclusion is about 0.25. Slow warming from the frozen state produced beginning of melting at -13.0°C. With final disappearance of ice at -4.9°C, indicating a fluid composition of about 7.7 weight percent NaCl equivalent (Potter et al, 1978). These results could not be duplicated during cooling because of metastable retnetion of fluid to -54°C. Heating resulted in gradual decrease in bubble size and eventual disappearance between 270°C and 275°C. These figures were reproducible over several trials. The uncertainty range of 5° is due to the very small size of the fluid inclusion. Minute inclusions in apophyllite are abundant but are too small to deal with effectively. The general implications of these geothermometric studies is that metamorphism and mineralization occurred at temperatures of about 300°C to 400°C.

Age of Mineralization

The Nikolai Greenstone is Upper Triassic in age (Read and Monger, 1976) thus placing a lower limit on the possible age of mineralization. Throughout the preceding account we have presented evidence to the effect that metamorphism and mineralization were related if not identical processes. Hence, to date one is to date the other.

In an effort to date regional metamorphism we selected four samples for whole rock potassium-argon analyses. Two specimens were chosen from the White River deposit and two specimens supplied by Dr. P.B. Read were from Nikolai Greenstone exposures about 50 miles to the south near Burwash Creek. Analytical data and model ages for these samples are given in Table VII. The two White River samples have similar ages with an average value of about 119 m.y. The two specimens provided by Dr. Read have much younger model ages, averaging

TABLE VII

ANALYTICAL DATA AND K/Ar MODEL AGES METAMORPHOSED NIKOLAI GREENSTONE

Specimen	Location	%K	Rad. Argon %	Ar^{40}/K^{40}	Apparent age [m.y.]
D40-5-58	White River Deposit	1.119 ± .001	73.9	7.377 x 10^{-3}	122 ± 3
D40-5-213	White River Deposit	1.289 ± .022	73.7	6.961 x 10^{-3}	115 ± 3
RL-74-75*		0.467 ± .009	36.4	5.239 x 10^{-3}	87.5 ± 3.5
RL-79-22*		0.097 ± .006	24.6	5.613	96.3 ± 5.8

* Supplied by Dr. P.B. Read, Vancouver, B.C.

about 90 m.y. It may be that both pairs of ages are correct, leading to the conclusion that ages of regional metamorphism differed in the two areas by about 30 m.y. On the other hand, the White River model age could be somewhat high due to incomplete resetting of the K-Ar clock during metamorphism, or, the two southern samples could be "younged" by an indeterminant amount because they are adjacent to the Duke River thrust fault of regional extent. We tend to favor the older ages as being closest to the true age of metamorphism because numerous post-kinematic plutons in comparable terrane to the northwest have ages of 105 m.y. to 114 m.y. (Richter et al., 1975). Whatever the detailed interpretation it is apparent that formation of Nikolai Greenstone and a period of copper mineralization (metamorphism) were separated in time by at least 80 m.y.

Genesis of White River Copper Deposit

Several hypotheses have been proposed for the origin of more-or-less comparable deposits elsewhere. For example, Stroiber and Davidson (1959) attribute the enormous native copper deposits of the Keweenawan peninsula to the regional hydrothermal metamorphism. A more explicit metamorphic origin was attributed to these same deposits by Jolly (1974) who suggested that copper was derived from low in the Keweenawan basalt succession by dehydration metamorphic reactions and precipitated higher in the section by hydration metamorphic reactions. He presented a crude mass balance calculation to show that Keweenawan basalts affected by dehydration metamorphism were an adequate source of both an aqueous ore fluid and copper.

An alternative suggestion by Kirkham (1972) is that native copper deposits such as the Keweenawan deposits and the White River occurrence owe their origin to a period of extensive weathering of continental basalts in an arid climate. According to this model copper in solution is obtained by normal weathering processes, and subsequent precipitation occurs at or near the surface in a highly oxygenated environment. The low temperature character of the mineralization is later destroyed by annealling during regional metamorphism.

It seems likely that White River copper deposit has formed in a manner similar to the many other copper occurrences observed in the Nikolai basalts (Read and Monger, 1976). Consequently, regional consideration should be taken into account. MacKevett (personal communication, 1978) notes that native copper deposits in the Nikolai of Alaska tend to be tabular, roughly parallel to individual flows, and can be interpreted readily as products of sub-aerial weathering in an arid climate as suggested by Kirkham (1972). Such an interpretation could apply to the White River deposit. We know of no criteria to prove or disprove this weathering model for much of the native copper. It is apparent to us however, that at least some of the native copper was formed at the same time as epigenetic secondary minerals as illustrated in Plate I.

The copper sulphide occurrences, are distinctly different in their mode of occurrence, commonly concentrating in obvious cross cutting structures and are more obviously connected with regional metamorphic mineral assemblages than is most of the native copper. We find no difficulty attributing crystallization of epigenetic iron and copper sulphides as cogenetic with formation of silicates and carbonate under conditions of prehnite-pumpellyite facies of regional metamorphism.

The model therefore assumes two stages in development of the White River copper deposit, an early stage of weathering resulting in the formation of a roughly tabular zone consisting principally of native copper; and a much later superimposed mineralizing event related to regional metamorphism resulting in development of sulphides.

There are no specific criteria emerging from this study of the White River deposit to prove the precise nature of the early stage of mineralization. Features that support the suggestion are:

1) The continental nature of the Nikolai Greenstone and the abundant evidence of oxidation throughout the sequence,
2) The tabular form of principal mineralized zones, and
3) The concept that a roughly comparable origin can apply to the bulk of known copper occurrences within Nikolai rocks.

Evidence relating to copper and iron sulphides and at least a small part of the native copper to prehnite-pumpellyite metamorphic is fairly convincing. Examples of native copper, and copper and iron sulphide intricately intergrown with obvious metamorphic minerals are abundant, and a few examples are illustrated in Plate I. This dual metallogeny of copper is consistent with the dichotomous nature of occurrence of native copper in the White River deposit -- veins rich in native copper relate to the early stage and veins poor in native copper relate to the later stage. Although we interpret the existence of two mineralizing events no direct evidence exists in the form of obvious cross cutting relations; that is, we have seen no example of sulphides clearly cross cutting Stage I native copper. The explanation of this absence appears to be in the vein-form where the Stage I copper itself and the relative ease with which Stage I copper would anneal during the regional metamorphism that gave rise to Stage II mineralizing effects.

There are some interesting implications of the genetic model proposed above. Most important is the fundamental nature of the Stage I copper. Without Stage I copper it is possible that no significant sulphide concentrations would form during regional metamorphism. That is, it may be that suggestions by others, principally Jolly (1974), that copper is concentrated from normal basaltic rocks may not apply either to the native copper or to copper in sulphides. The most important source for copper to form sulphide might be in the native copper concentrates, and, in fact, metamorphism may be an agent for dispersing copper previously concentrated by weathering processes. These statements, although largely speculation, are consistent with the known copper occurrences in the Nikolai Greenstone and should be considered because of their implication to exploration.

Another speculation to be considered is the source of sulphur in the copper and iron sulphides. Sulphur would appear to be derived from without the Nikolai Greenstone or we might expect to find copper sulphides pervasively throughout the unit. Despite the high copper content of the Nikolai Greenstone (approx. 150 ppm) the unit is not mineralized pervasively with copper sulphides. An external source for not only the sulphur but also the ore fluid is suggested by the cross-cutting nature of structures mineralalized with sulphides and the likelihood that they represented open systems relative to the Nikolai Greenstone. The occurrence of hydrocarbons in some mineralized amygdules (Knopf, 1910) further suggests an open system and external source for the ore fluid. It is possible of course that some contribution was made to the ore fluid by metamorphic waters as suggested by Jolly (1974) for the Keweenawan deposits. A particular source in the case of White River deposit might have been devitrification of volcanic glasses now represented by Greenstone. However, the weight of evidence would seem to require that most of the ore fluid be derived externally, probably from below.

The foregoing discussion leads to the development of a genetic model for the White River copper deposit, summarized briefly as follows:

(1) Continental extrusion of tholeiitic Nikolai basalts rich in copper.

(2) Surficial weathering to oxidize Nikolai basaltic rocks, take copper into solution and to transport it to sights of supergene deposition where native copper deposits formed (Stage I).

(3) Later regional metamorphism of Stage I native copper about 80 m.y. or more after formation.

(4) Local tectonic disruptions produce through-going structural systems along which connate water, perhaps largely from underlying Permian sediments, perhaps in part of metamorphic origin, are channelled.

(5) Where these sulphide-bearing waters contact Stage I native copper, the copper is mobilized and reprecipitated, largely as sulphide but locally as native copper. All admixed with a variety of metamorphic silicates and carbonates.

This model is in part speculative, but is consistent with known facts in the area.

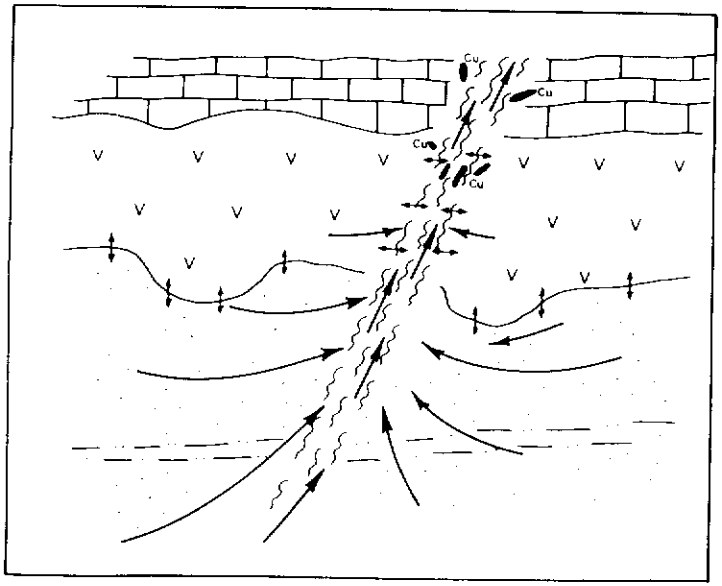

Figure 8: Conceptual model for development of White River copper deposit. Effect of folding is not shown on the diagram. The Nikolai Greenstone (V), underlying Permian rocks (stippled) and overlying limestone are represented schematically. Long arrows indicate general flow of water into appropriate structures. Smaller double-headed arrows indicate fluid-rock interchange involving particularly, extraction of copper from Nikolai Greenstone and subsequent redeposition in new sites indicated by labelled black ellipses (Cu).

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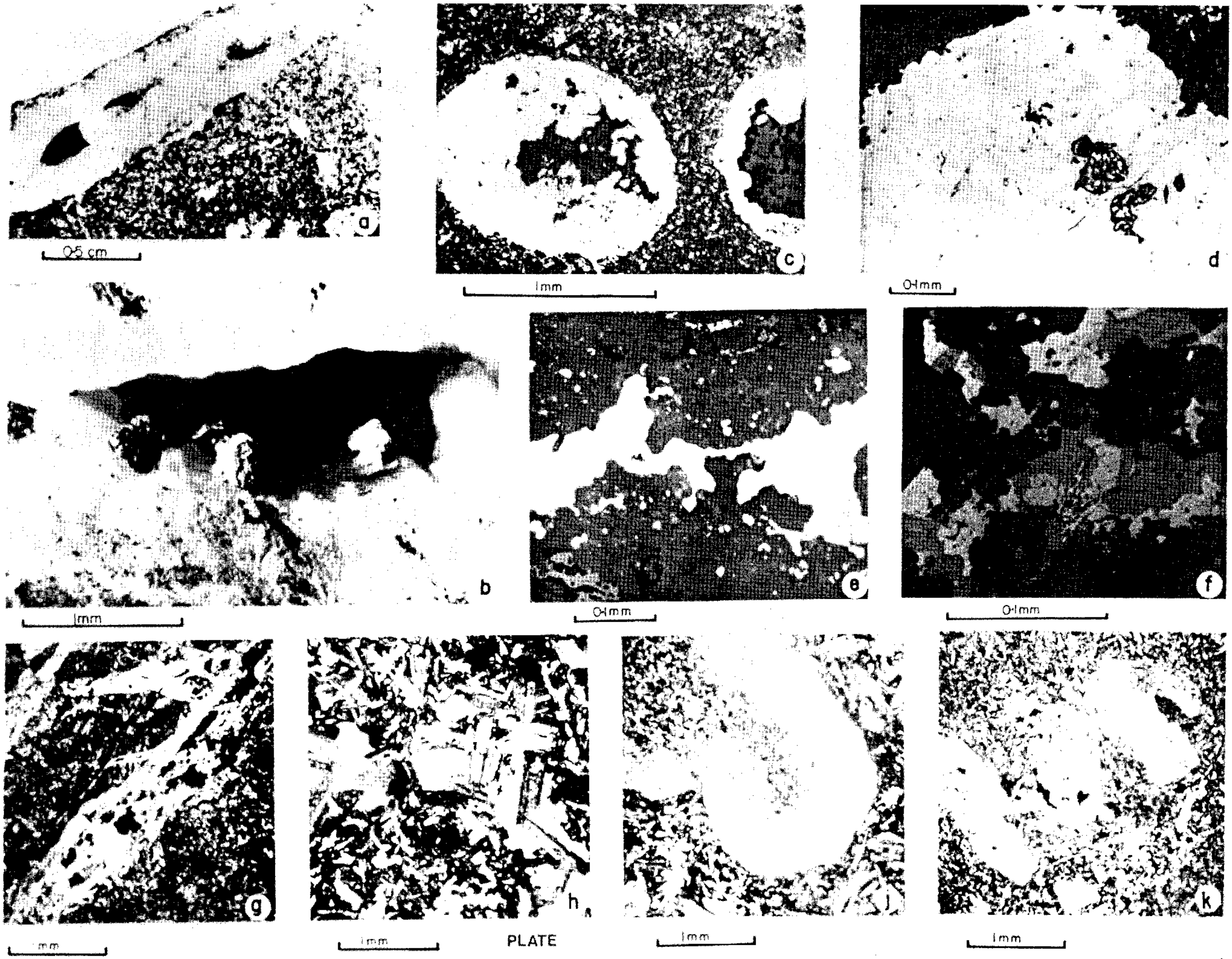

PLATE

PLATE CAPTIONS

(a) Vuggy prehnite-native copper vein in drill core of glomeroporphyritic basalt.

(b) Details of a vug from (a) showing relationship of crystals and irregular masses of native copper to prehnite. Octahedral crystals of native copper (dark) project into the vug (black). Irregular dark patches surrounded by white are small masses of native copper enclosed in prehnite.

(c) Polished section of amygdules of chalcocite (white) with central zone of chlorite (dark) within glomeroporphyritic basalt. The small white specks throughout the basalt are disseminated grains of chalcocite.

(d) Polished section of part of an amygdule containing about 80 percent chalcocite (white) and 20 percent bornite (pale grey) intergrown with a vermicular texture. Note the two small inclusions of chlorite in the chalcocite.

(e) Polished section of native copper (white) and calcite (grey) as a vein filling.

(f) Polished section of chalcocite (pale grey) and bornite (middle grey) in gangue (black). Elongate hematite crystals are enclosed in sulphides in the centre of the photograph.

(g) Thin section of native copper (black) calcite and prehnite (both white) in a vein cutting chloritized glomeroporphyritic basalt.

(h) Thin section of glomerophenocrysts of plagioclase in a fine-grained matrix.

(j) Thin section of prehnite (white) amygdule with chlorite (mottled) in olivine-bearing amygdaloidal basalt.

(k) Thin section of hornblende porphyry dyke showing hornblende phenocrysts (white) in a very fine-grained matrix with trachytic texture.

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