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Paper 83-2

Case History
Radiore 2 Mine Matagami, Quebec

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September, 1982

GM 69979

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Discovery and Exploration

Introduction

The Radiore 2 mine is located in the SE quadrant of Isle Dieu Township approximately 4 km east of the town of Matagami in northwestern Quebec (Fig. 1). The property is on the east side of the Bell River and access is now by means of a dirt road from kilometer 5 on the James Bay road.

The history of the mine begins in 1961 with the discovery of a massive sulphide lense on the property by Radiore Uranium Mines Ltd. Exploration drilling outlined a small orebody of approximately 150,000 tons grading around 3.0% of combined copper and zinc. During subsequent years numerous exploration programs were conducted in attempts to find sufficient ore to sustain a mining operation. Ownership changed a number of times but no significant amount of ore was found. Finally in 1979-80 the orebody was mined by Noranda Mines Limited.

In the first part of the paper we give a case history of exploration of the property, for much effort was expended to increase ore reserves. This is followed by the results of a M.Sc. thesis study on the geology and geochemistry made by one of us (Bonavia 1981) while the orebody was being mined. The study forms an integral part of the ABITIBI PROJECT at McGill University which is primarily involved with the genesis of ore deposits at Matagami and the development of new mineral exploration criteria for the district.

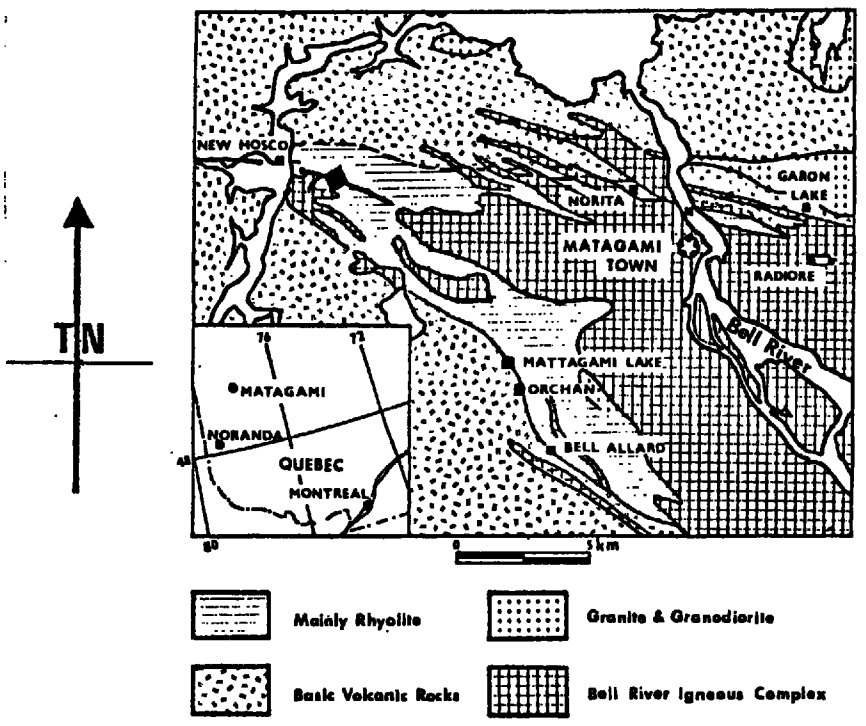


Fig. 1. Location and district geology map. Geology after Sharpe (1968).

Exploration History

Radiore Uranium Mines Limited

The ground was staked by Radiore Uranium Mines in March 1961, and a sulphide body, initially termed "East Zone", was first indicated by a Boliden EM Gun Survey carried out by the Company's geophysical crew. The original staking included 37 claims but, following detailed geophysical work, only the present 19 claims were retained and held under Development Licenses. The claim numbers are as follows:

C-182093 Claims 1 to 5
C-182094 Claims 1 to 5
C-182095 Claims 1 to 5
C-182096 Claims 1 to 3 and 5

Drilling commenced in 1961 and 38 holes totalling 10,631 feet were drilled in the immediate area of the East Zone and completed by 1962. M.E. Woakes (1961), resident geologist of Radiore Uranium Mines Ltd., logged the core and made the first description of the volcanic rocks. He meticulously described the hydrothermally altered volcanic rocks, and his description is the only complete remaining documentation of the original drilling, as part of the drill-core has been lost.

During February 1963 a magnetometer survey was carried out by Radiore Uranium Mines personnel on three small areas of the property not covered by an earlier magnetomer survey in 1958-59. In this survey an ABEM torsion magnetometer, Model M2-4, was used to measure the vertical componet of the magnetic field. According to Woakes (1964):

> "The results of the survey in each of the three areas covered are very similar. Relatively narrow, parallel bands of higher magnetic intensity trending WNW are separated by wider areas of uniformly lower magnetic intensity. In all cases these are extensions of similar zones delimited in the earlier magnetometer surveys.
>
> The zones of higher magnetic relief are interpreted as being basic intrusive offshoots from the main Bell River Complex, separated by greater thicknesses of volcanic material."

The orebody is outlined on this survey by a concentric anomaly of more than 18000 gammas of magnetic relief (Fig. 2).

The stratigraphy of the area was first described by Woakes (1964) (Fig. 3). He states:

> "The sulphide mass occurs as the north contact of a zone of very mixed and altered pyroclastic and tuffaceous rocks which are from 40 to 110 feet in thickness. Above and below this zone of pyroclastics are massive andesitic rocks which to the north are extensively intruded by various gabbroic, anorthositic and quartz dioritic rocks.
>
> The East Zone orebody is a lens of massive sulphides which dips almost vertically and strikes N 70° E. The north wall is essentially sharp against andesitic material while the south wall is less well defined since the massive sulphides tend to grade into more dispersed material in the pyroclastics."

Woakes (1964) also outlined the orebody and made the first ore reserve calculation (Fig. 4). Drill results indicate that ore grade mineralization bottomed at 310 feet. The total tonnage calculated from 20 drill hole intersections was 95,000 tons averaging 15 feet in thickness and grading 2.6% copper and 1.35% zinc with minor amounts of gold and silver. It has a maximum strike length of 375 feet, and overburden was estimated to be 15-25 feet thick. Almost 90% of the ore occurs above the 200 foot level and grades 2.7% copper and 1.4% zinc with an average thickness of 17 feet. Ore minerals comprising more than 90% of the lenses are pyrite, pyrrhotite, chalcopyrite, sphalerite and magnetite.

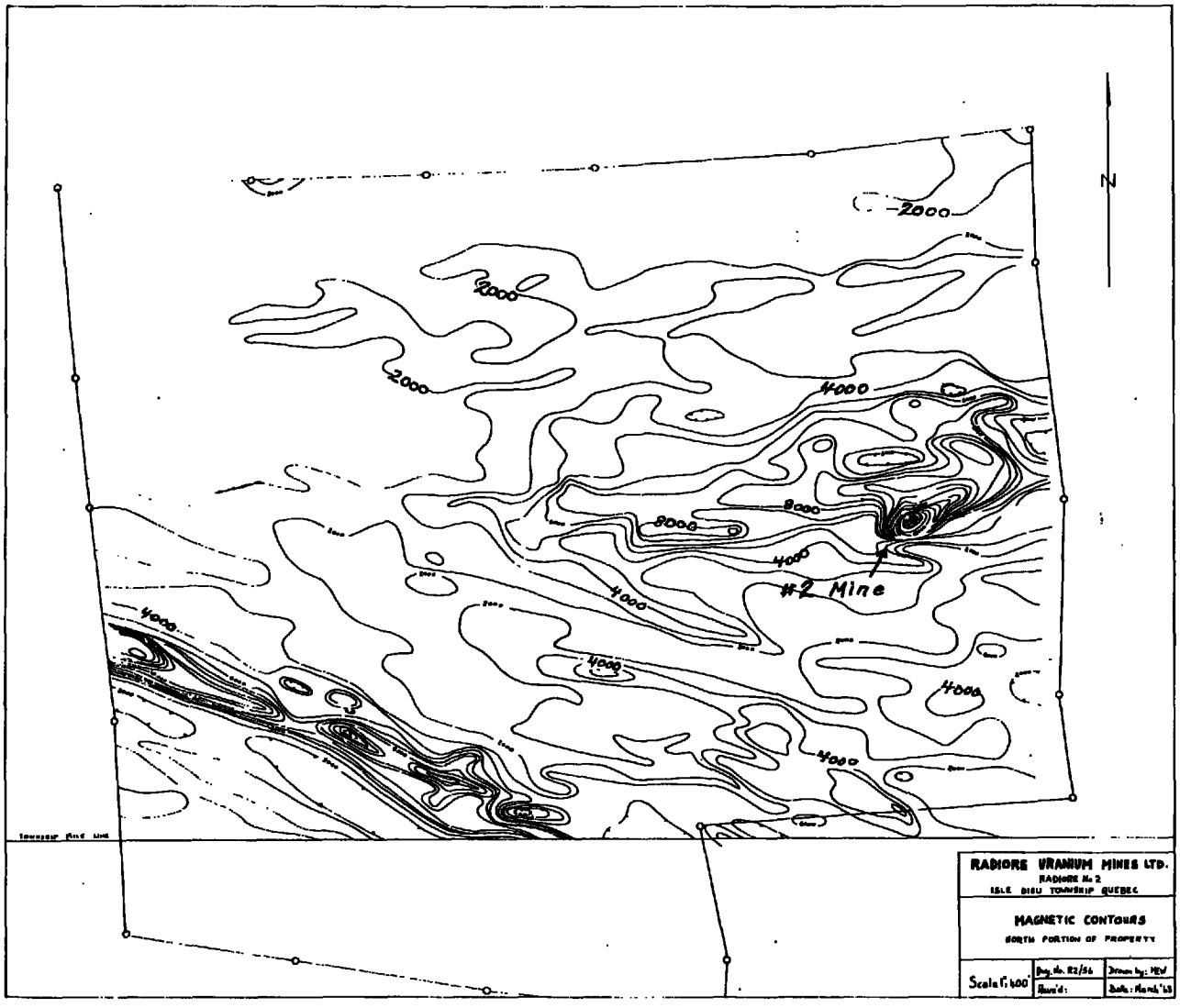


Fig. 2. Magnetometer survey of the Radiore 2 property made by Radiore Uranium Mines Ltd. in 1963.

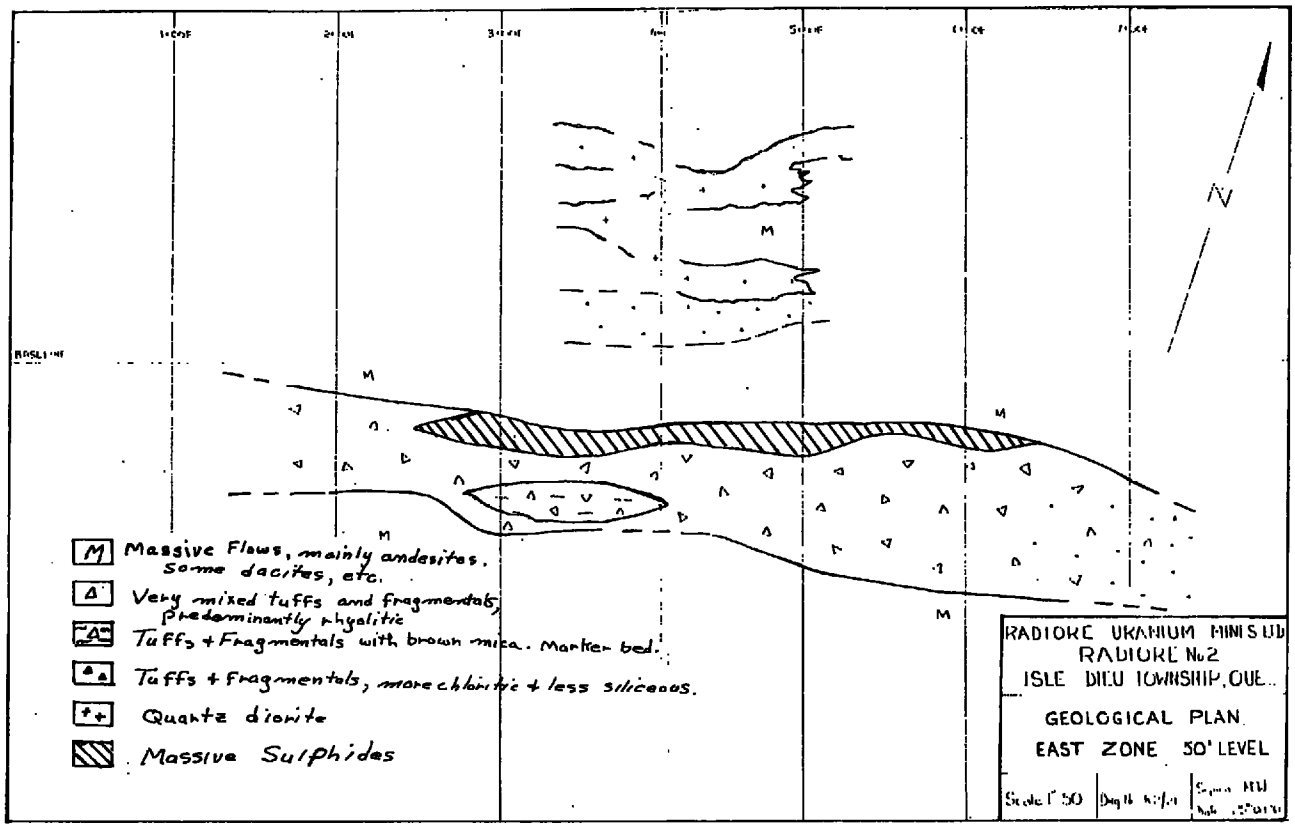


Fig. 3. Geological map of Radiore 2 made from drilling information by M.E. Woakes in 1961.

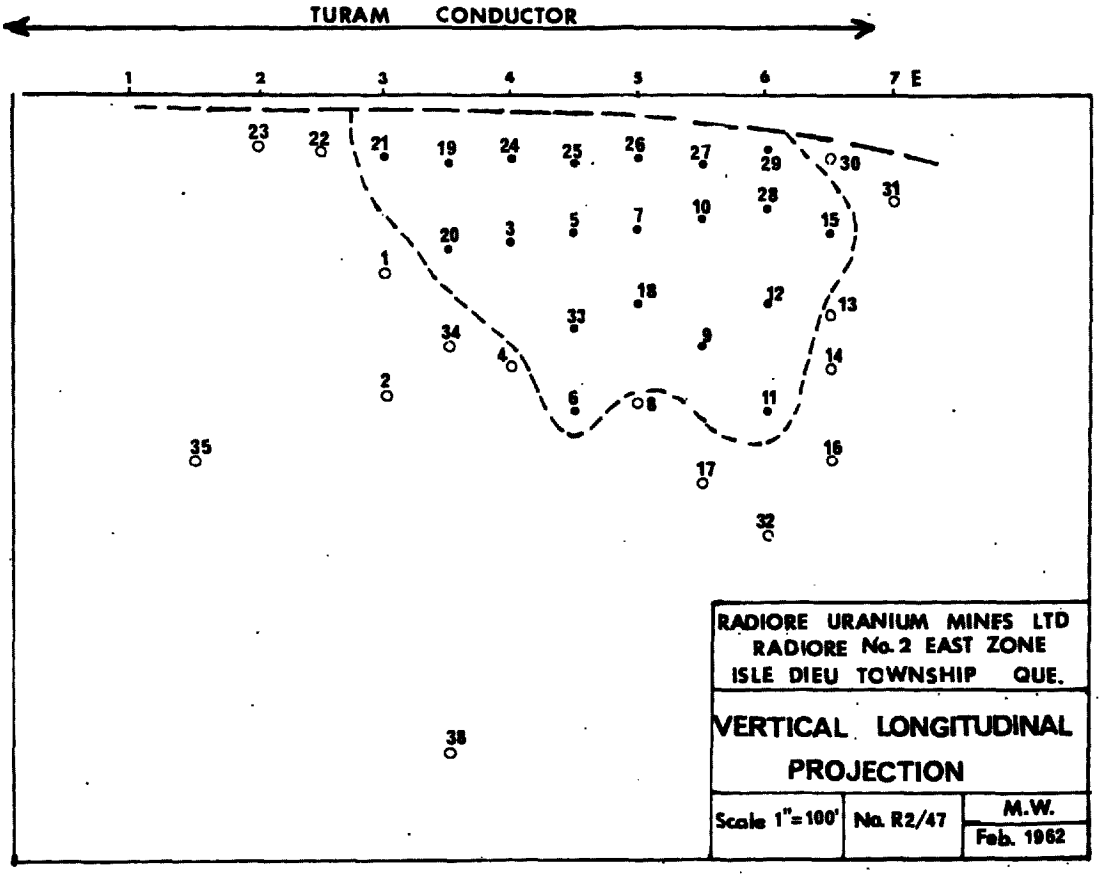


Fig. 4. Longitudinal section in the plane of the orebody showing drill hole intersections. Black dots are massive sulphide intersections; open circles are holes that contain only thin or no massive sulphide intersection. Drawn from M.E. Woakes map of February, 1962.

Exploration and development expenditures incurred during the initial period of investigation are reported in Table 1 (from Woakes, 1964).

Orchan Mines Limited

Orchan Mines acquired the Radiore 2 property in December 1970 for $175,000, of which $100,000 were received and the balance was due when the mine went into production. A re-examination of drill results suggested 139,400 tons averaging 2.2% coper and 1.1% zinc, and production, planned for late 1974, was deferred pending an improved copper price. However, workings went ahead and a ramp decline from the portal to 1682 feet was completed in January 1975, but stope preparation was suspended.

Noranda Mines Limited

In December, 1978 Noranda Mines Limited amalgamated Orchan Mines Limited: 1 Noranda share for 6 Orchan shares. Another examination of drill results was carried out and this showed the reserves to be 126,880 tons containing 2.41% copper and 1.24% zinc. The deposit was mined out by the first half of 1980.

When mining was completed a drilling program was initiated to explore for ore at depth. Down-hole geophysics was also employed. Late that year the company released to the press (Northern Miner, 1980) a report on the intersection of massive sulphides followed by disseminated sulphides at 2300 feet below surface. Exploration is still in progress to assess the potential of the discovery.

Previous Geological Studies

Mapping by J.I. Sharpe (1961-1963)

J.I. Sharpe mapped the geology of the Matagami mining district for his Ph.D. research at McGill University (Sharpe, 1964). This was done in conjunction with the Quebec Department of Natural Resources, and his published report (Sharpe, 1968) provided the first general outline of the geology of Radiore 2.

He called this deposit Radiore "East" to distinguish it from Radiore "A", the present Norita Mine, and interpreted the volcanic rocks as being enclosed within the Bell River complex. At the base of the volcanic succession he recognized an andesitic lava unit which passed upwards into siliceous breccia, chloritic and biotitic schists, and laminated and brecciated siliceous rocks. Above, those units the sequence continued into another andesitic flow which terminated against gabbro that formed the north wall to the volcanic rocks (Fig. 5).

Sharpe (1968, p. 81) described the ore as follows:

> "The metallic minerals are distinctively zoned across the thickness of the deposit; the south part is enriched with pyrrhotite, the medial part with pyrite, and magnetite is concentrated along the north flank of the lens. No pronounced zonation of copper and zinc was noted although the copper is usually associated with pyrrhotitic zones and the sphalerite is always in pyrite-rich zones.
>
> The sulfides are massive, regularly layered, or have foliate textures. Most of the pyrite is in medium grained subhedral aggregates. Irregular streaks and fragments of microcrystalline pyrite are present in some sectors, particularly in the layered types of sulfides. The pyrrhotite is variable in habit; disposed as structureless masses; intergrowths with pyrite and chalcopyrite; and as veinlets and networks in gangue. A distinctive "porphyritic pyrite" texture was noted in places. This is due to subhedral (pyritohedral) crystals of pyrite up to 2 cm wide, scattered through a pyrrhotite base.

Table 1. Exploration and development expenditures incurred during the initial period of investigation — 1961-1963 (from Woakes 1964).

Diamond drilling	
10,631 feet x $3.00	$31,893
Geophysical surveys	
An electromagnetic survey conducted by Radiore crew in 1961	
43 miles x $100	$4,300
Staking of Claims	
37 claims x $30	$1,110
Cost of holding claims	$4,500
Assaying	$1,200
Wages and salaries	$5,000
Transportation, freight, supplies, miscellaneous	$5,000
Total	$53,003

The pyrite crystals have mutual interference boundaries and occur within both massive and disseminated pyrrhotite. These are probably porphyroblasts. The chalcopyrite forms intricate networks in fractures and is disseminated in the interstitial material of the siliceous breccias. Chloritic zones within the massive sulfides are commonly enriched in chalcopyrite. The sphalerite is invariably mixed with pyrite."

On the alteration of the deposit he (1968, p. 82) states:

"The predominant alteration products are chlorite, silica and brown mica. Chlorite is an ubiquitous component of all the volcanic rocks and occurs in concentrated form as bands and irregular clots in the host rocks. Considerable silica has been introduced into the volcanic breccias which contains veins of porcellaneous and cherty silica. Silica also impregnates and accentuates the margins of lithic fragments. It is notable that some of the silicified rocks are intricately brecciated and thus the silicification predates a time of deformation. The brown mica is probably biotite and has developed from a pre-existing alteration product — the chlorite. The mafic lavas are slightly amphibolitized."

As to genesis, Sharpe (1968) refers to the deposits in the Matagami district as belonging to the "massive replacement-type".

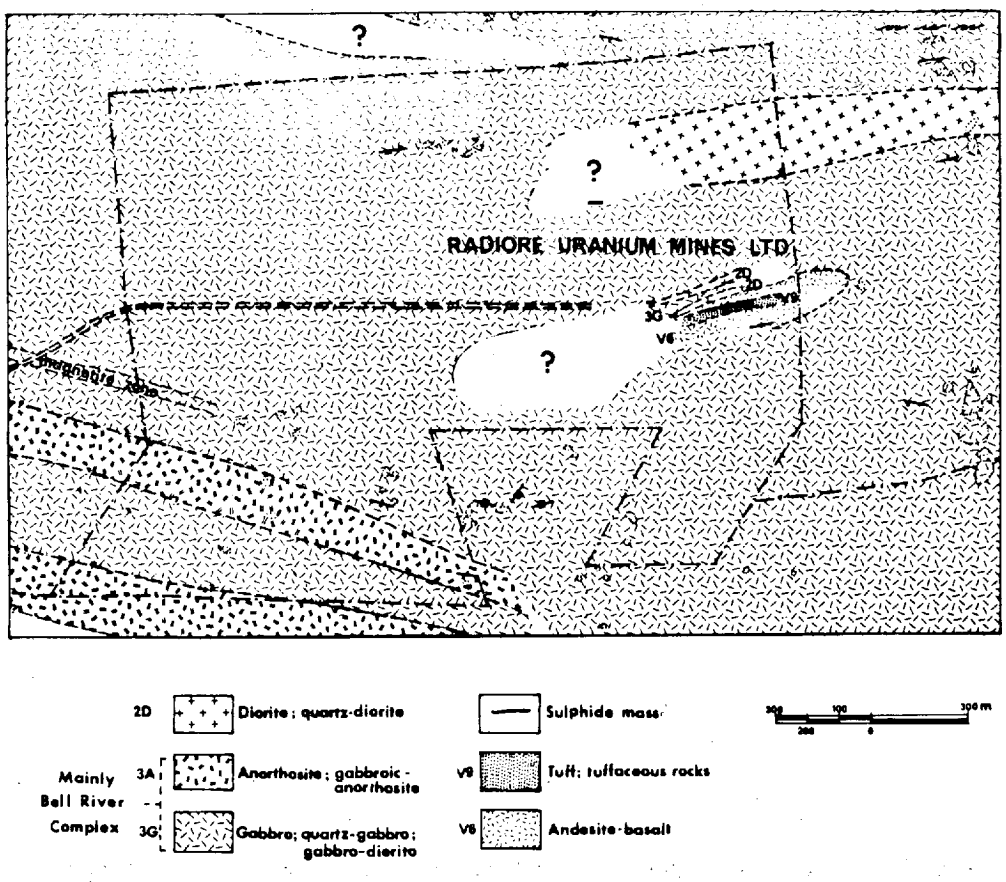


Fig. 5. Geologic map of the area around Radiore 2. From Sharpe (1968).

Mapping by P.J. MacGeehan (1974-1979)

As part of the ABITIBI Project and his Ph.D. research at McGill University, P.J. MacGeehan (1979) mapped the surface outcrop in detail (summarized at a reduced scale in Fig. 6). He found that the volcanic rocks do not lie as an enclave within the Bell River complex but are continuous throughout the area and are cut by numerous sills and dykes formed as subsidiary intrusions of the complex. He mapped part of the mine ramp (Fig. 7) and revised the stratigraphy, recognizing a rhyolitic unit (Norita rhyolite) as the base of the volcanic succession. This unit was overlain, in turn, by a spilitized and silicified pillowed basalt (B1), and then the massive and chloritized spherulitic Bell Channel rhyolite which was laid down just before the emplacement of the Radiore 2 massive sulphide deposit. He found the Bell Channel rhyolite to be overlain by more altered pillow basalt, which he interpreted to be the B3 basalt, and then the volcanic stratigraphy to be truncated against the southern border of a thick quartz-diorite sill (Figs. 6 and 7).

Describing the alteration MacGeehan (1979, p. 189) states:

> "The alteration of footwall rocks at Radiore is petrographically identical to that developed underlying the Bell Channel No. 1 and Norita deposits. However, unlike these deposits, the overlying volcanic rocks are also altered (Table 6.7), and there is evidence for a later stage alteration event. A degraded hornfels assemblage represented by relict pintized cordierite grains is developed in volcanic rocks underlying the 600 m thick diorite intrusion, and biotite is a common constituent in the alteration products underlying the massive sulphide deposit. This latter fact was established by Sharpe (1968, p. 80), who also noted that the biotite was at "an incipient stage of development from chlorite in most samples". There is good petrographic evidence that the biotitization was a late event which occurred after emplacement of the sulphide lens and alteration of the underlying rocks."

Considering the volcanic nature of the host-rocks, the clustering distribution of the Zn-Cu massive sulphide deposits at Matagami, conformability, internal metal zoning and associated wall-rock alteration, he (1979) genetically associated the deposit to a volcanogenic exhalative origin, which had earlier been proposed for other deposits in the district by Roberts (1975), MacLean and MacGeehan (1976), and MacGeehan (1978).

Mining Activity

Mine development work by Mine Noranda Limitée, the present owner of Radiore 2, started in 1975 by driving a decline ramp (Fig. 8a) to provide access to the orebody. Because of a fall in copper price, operations were postponed and only resumed in December 1979. Mining of the deposit was contracted to Mining Corporation of Canada, which completed the ramp to the bottom lense and developed two mining levels (Fig. 8c and 8d) with the object of dividing the ore into two zones. Due to the shallow depth of the ore the overlying glacial till was removed. Long-hole drilling for blasting purposes was expedited from surface and from level No. 1. The ore was then blasted in large slabs towards a generally vertical face of the stope (Fig. 8b). The broken ore was recovered through draw points and trucked to the Orcham mill at Mattagami Lake Mine for further processing.

Ore in the mine was exhausted in August 1980 but the workings were kept open for further exploration drilling.

The total amount of ore treated at the mill was 153,862 tons containing 1.34% Zn, 1.57% Cu, 0.25 troy oz/ton Ag and 0.009 troy oz/ton Au.

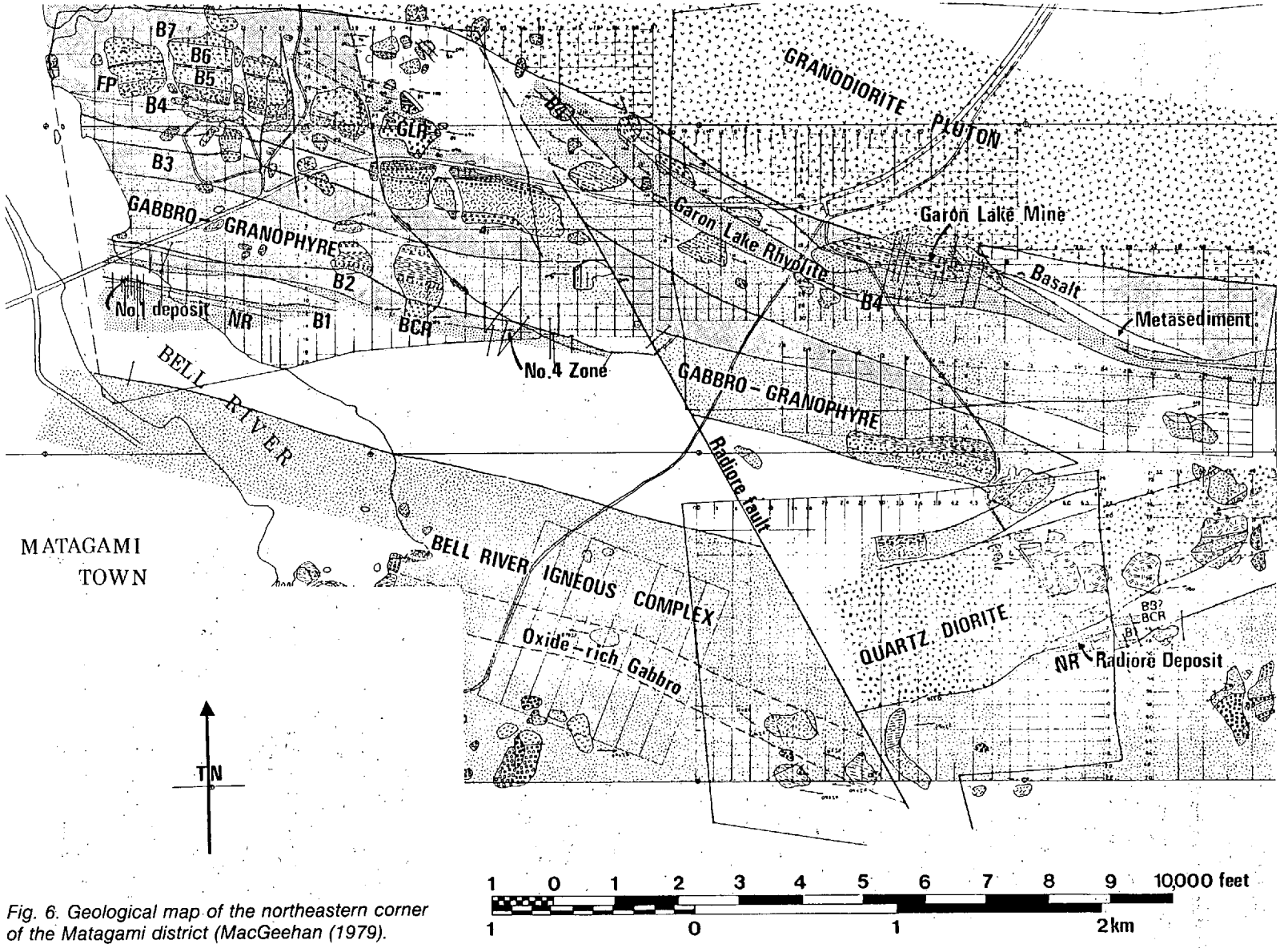


Fig. 6. Geological map of the northeastern corner of the Matagami district (MacGeehan (1979).

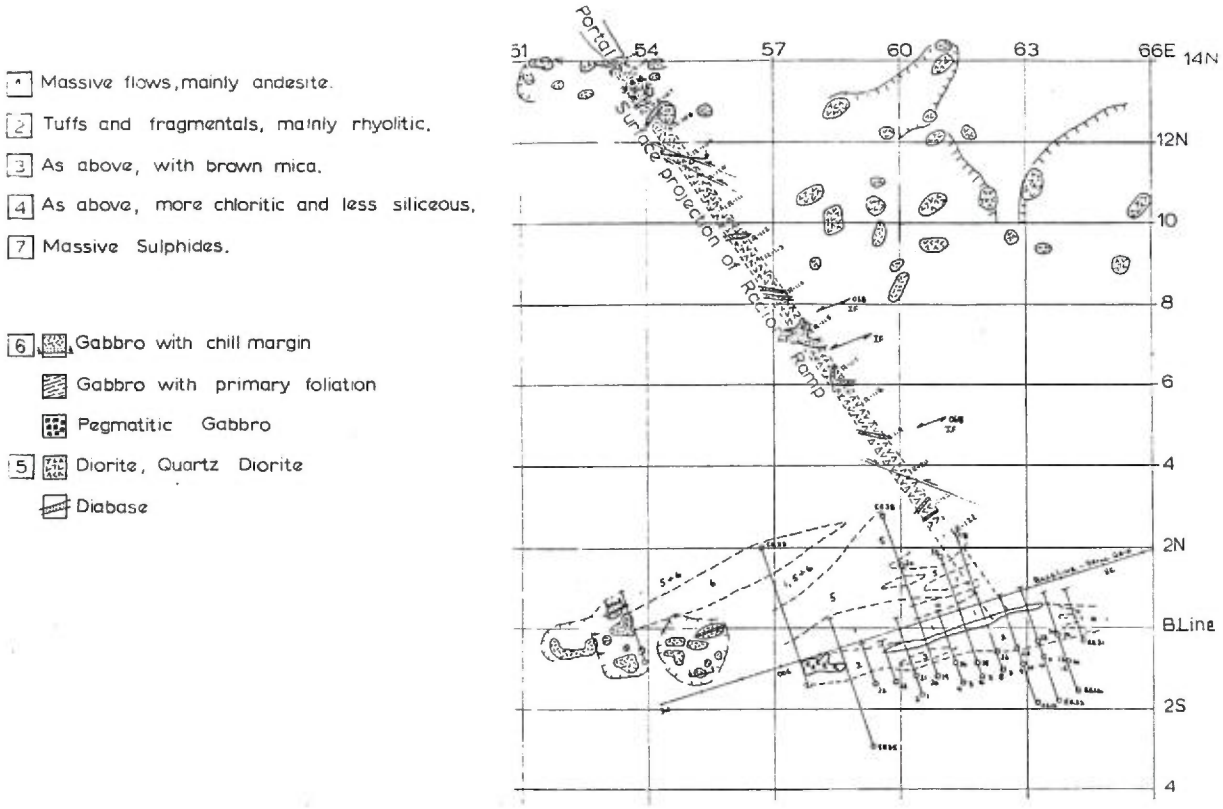


Fig. 7. Map showing the geology of the ramp and orebody at Radiore 2. (from MacGeehan, 1979).

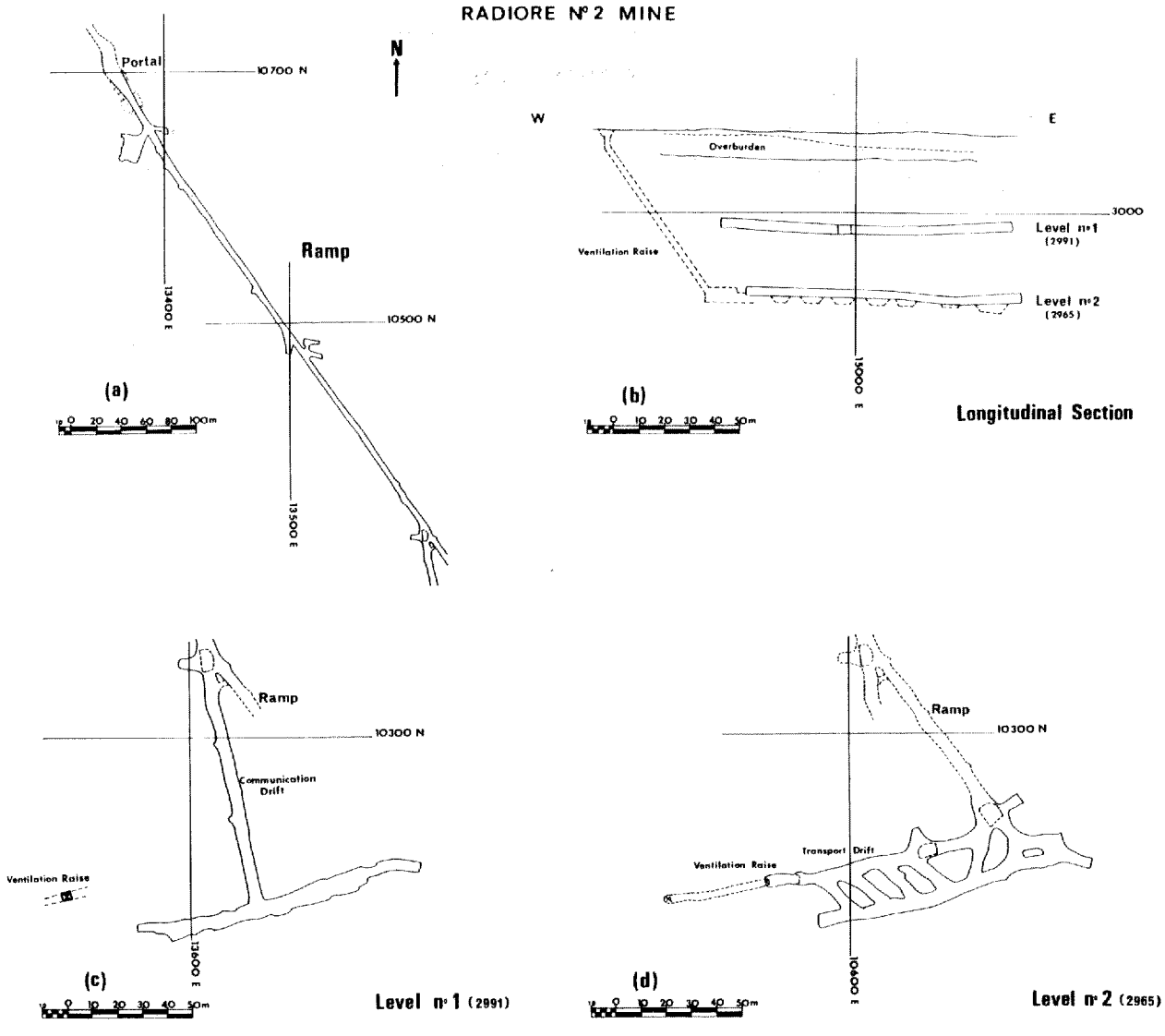


Fig. 8. Layout of mine workings at Radiore 2. (Bonavia 1981).

Geology at the Radiore 2 Mine

Introduction

The Abitibi project was set up at McGill University in 1974 with the intention to study in detail a part of the Archean Abitibi greenstone belt and related ore deposits occurring at Matagami, Quebec. The present study is part of this research and was initiated in January 1980.

The main purpose was to conduct a geological and geochemical investigation of Radiore 2 Mine, for at that time the mining operation was in full activity to exploit the orebody. Hence the opportunity was used to obtain access to some part of the massive ore and expedite underground geological mapping and sampling, as part of the scope of the Abitibi Project is to collect and retrieve basic data from the mines in the area which otherwise would have been lost.

The research was entirely devoted to the orebody and to the volcanic rocks stratigraphically 100 metres above and 250 metres below, because of constraints imposed by the lack of outcrops and the limited extent of stratigraphy investigated by drilling. A detailed surface geology map (1 inch = 100 feet) was available from the previous regional study by McGeehan (1979); re-mapping around the mine was not considered as it would have added little information for the present geological interpretation.

Regional Geology

Radiore 2, located at Matagami, is in one of the largest volcanic centres in the Abitibi greenstone belt of the Superior Province (Goodwin and Ridler, 1970). Unfortunately, for geological mapping and mineral exploration, the area is largely covered by glacial deposits which obscure most of the Archean volcanic rocks. These rocks range in composition from basalt to rhyolite have been intruded by the Bell River igneous complex, a layered basic intrusion, and by many subsidiary sills and dykes. The entire area was metamorphosed largely to the greenschist facies and then folded into what has been interpreted as a westward plunging anticlinal structure. On the northern limb the volcanic rocks strike approximately east-west, face north and dip vertically, while a more gentle southerly dip is observed on the south limb which has a northwest trend (Sharpe, 1968).

A total of twelve Zn-Cu massive sulphide deposits, ranging in size from 100,000 tons (Bell Channel No. 1) to 25 million tons (Mattagami Lake), have been discovered in volcanic rocks on the sides of the anticline. All the deposits are broadly found along rhyolite-basalt contacts. The "Key Tuffite", a cherty tuffaceous layer, is the marker bed in which all the massive sulphide deposits on the southern limb occur (Sharpe, 1968). The "Key Tuffite" has not been recognized in the northern limb and, with the exception of the Garon Lake deposits which lie stratigraphically higher in the sequence, all the other deposits are associated with a continuous rhyolitic horizon at the base of the exposed volcanic succession (MacGeehan, 1979).

Stratigraphy

Given the poor preservation of the rocks it is difficult to classify them correctly. This study proposes that three rhyolites (Norita rhyolite, NR; Radiore rhyolite, RR; and Bell Channel rhyolite, BCR) are intercalated with two mafic flows (B1a metavolcanic, and B1b metavolcanic) which, along with mafic sills and dykes, form the stratigraphic succession at Radiore (Fig. 9).

Schematic Correlation of Horizontally Projected Boreholes

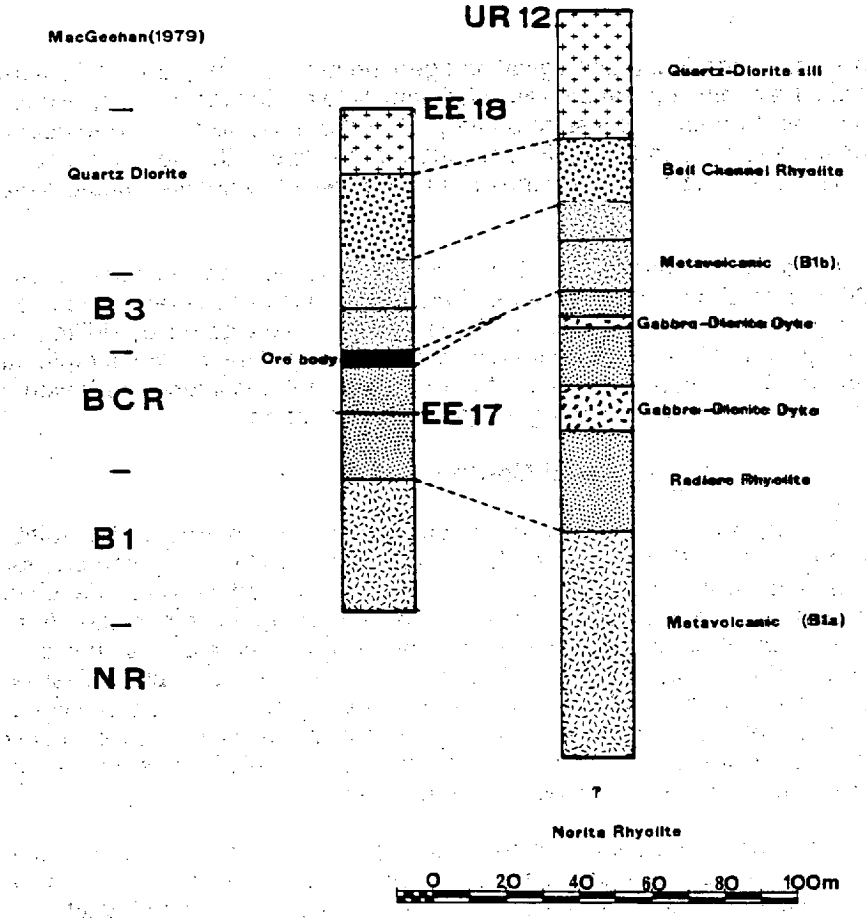


Fig. 9. Proposed stratigraphic succession at Radiore 2 derived from diamond drill cores. Positions of holes are shown on Fig. 11. The interpretation by MacGeehan (1979) is at the left. (from Bonavia 1981).

On the basis of their stratigraphic position (Fig. 10) five major mappable units were defined. Minor units occur but do not persist laterally and probably represent continuous emplacement of discrete cooling flows over newly formed lava and metasediments. The lateral and vertical extensions of the units and the ore are illustrated on a plan map (Fig. 11) and vertical cross-sections (Fig. 12) of the mine. The base of the volcanic succession is interpreted by MacGeehan (1979) to be formed by the Norita rhyolite and in this study it was recognized in one of the older diamond drill-holes (EE-35). It was not intersected in UR-12, logged as far as 632 metres. However, as the UR-12 drill-hole was deepened beyond this point, a rhyolite was intersected at greater depth (A. Bonenfant, personal communication). If our interpretation is correct this latter unit should be the Norita rhyolite.

The Norita rhyolite is overlain by 30 to 50 metres of metavolcanic (B1a). MacGeehan described this unit as a massive pillowed basalt. The present interpretation agrees with the massive appearance of these rocks but no pillows were identified in the unit. The rocks are highly altered and textureless and exhibit gradational changes into the overlying Radiore rhyolite. From the reconstruction of drill-hole data they appear to have been deposited on the eastern flank of a topographic high (Fig. 11).

The Radiore rhyolite was originally interpreted by MacGeehan (1979) to be the equivalent of the Bell Channel rhyolite which he first described at the Norita mine. They are indeed very similar, both often amygdaloidal with a massive devitrified texture, but with the basic difference that tridymite crystals are distinctly displayed in the Bell Channel rhyolite (Fig. 13a), a diagnostic characteristic elsewhere for this unit (MacGeehan, 1979). The Radiore rhyolite is often chloritized and transected by microcrystalline quartz veinlets; it also contains layers with fragmented and perlitic textures intercalated with tuffs or metasediments (Figs. 13b,c), but none of the characteristic tridymite crystals of the Bell Channel rhyolite.

The Radiore rhyolite is overlain by B1b metavolcanic interpreted by MacGeehan as resembling B3 basalt and being pillowed. In an inspection of the mine drift from which the ramp gives access to level No. 1 (Fig. 8c) no pillows were recognized. The rocks look similar to B1a. They have a cleaved appearance above the ore zone suggesting that this part is formed by metasediments while the rest may have indeed been basic flows.

Lying on top of this basalt-like unit is the Bell Channel rhyolite. It displays quartz phenocrysts (Fig. 13d) and tridymite crystals and also appears to be the least altered of all extrusive rocks. Much of this unit is a massive devitrified amygdaloidal rhyolite in excess of 40 metres in thickness and is cut to the north by a large quartz-diorite sill. To the south, it grades into metavolcanic rocks. The BCR-B1b contact is arbitrarily drawn on the basis of colour and texture changes. A poorly developed lateral unit termed 'blue' quartz-eye rhyolite occurs towards the base of BCR (Fig. 10). It proved difficult to relate it as part of a rhyolite flow or a rhyolitic intrusion.

Intrusive Rocks

A thick quartz-diorite sill transects the upper stratigraphic sequence at a low angle (Fig. 11). From the core logging, two distinct mappable units, one coarse grained and one fine grained, were identified. Although chilled margins were not always clearly observed the two rocks are interpreted to have formed as multiple intrusions.

The quartz-diorite sill has in turn been intruded by thin, mostly aphanitic, diabase dykes which have been deflected into fractures giving rise to an anastomosing pattern observable in the ramp.

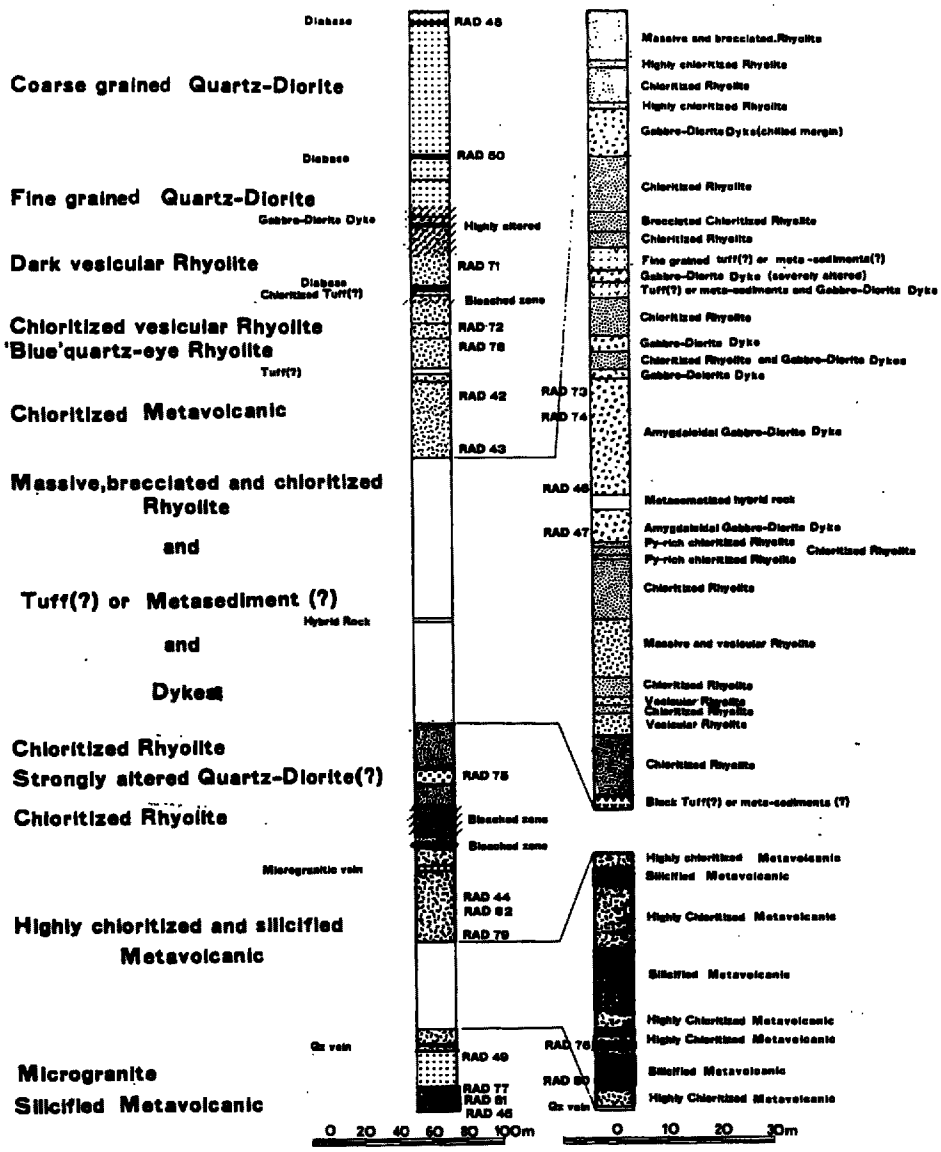


Fig. 10. Detailed geological description of UR-12 drill hole. UR-12 cut through the entire stratigraphy at Radiore 2. (from Bonavia 1981).

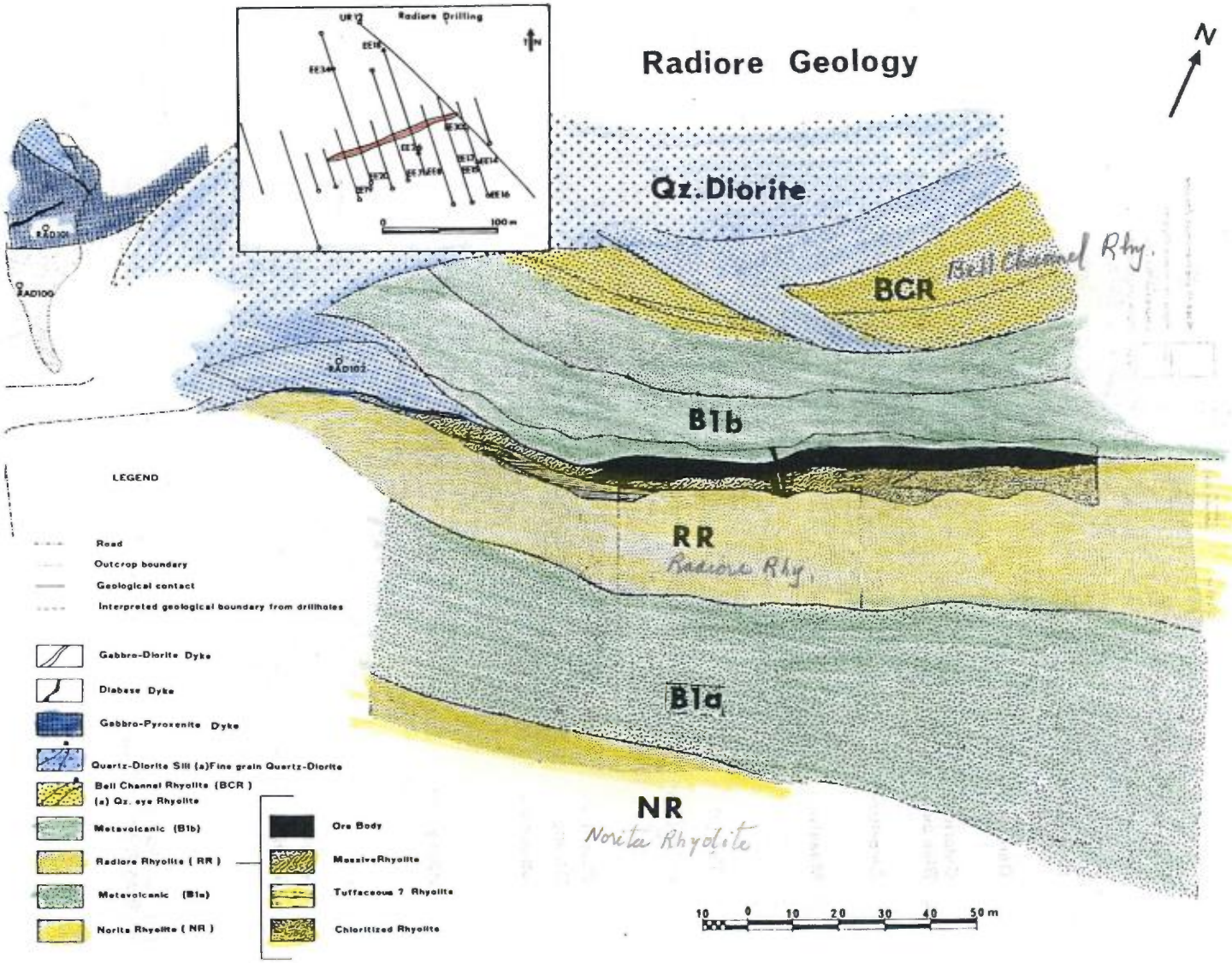


Fig. 11. Geological map (surface) of the Radiore 2 mine (from Bonavia 1981).

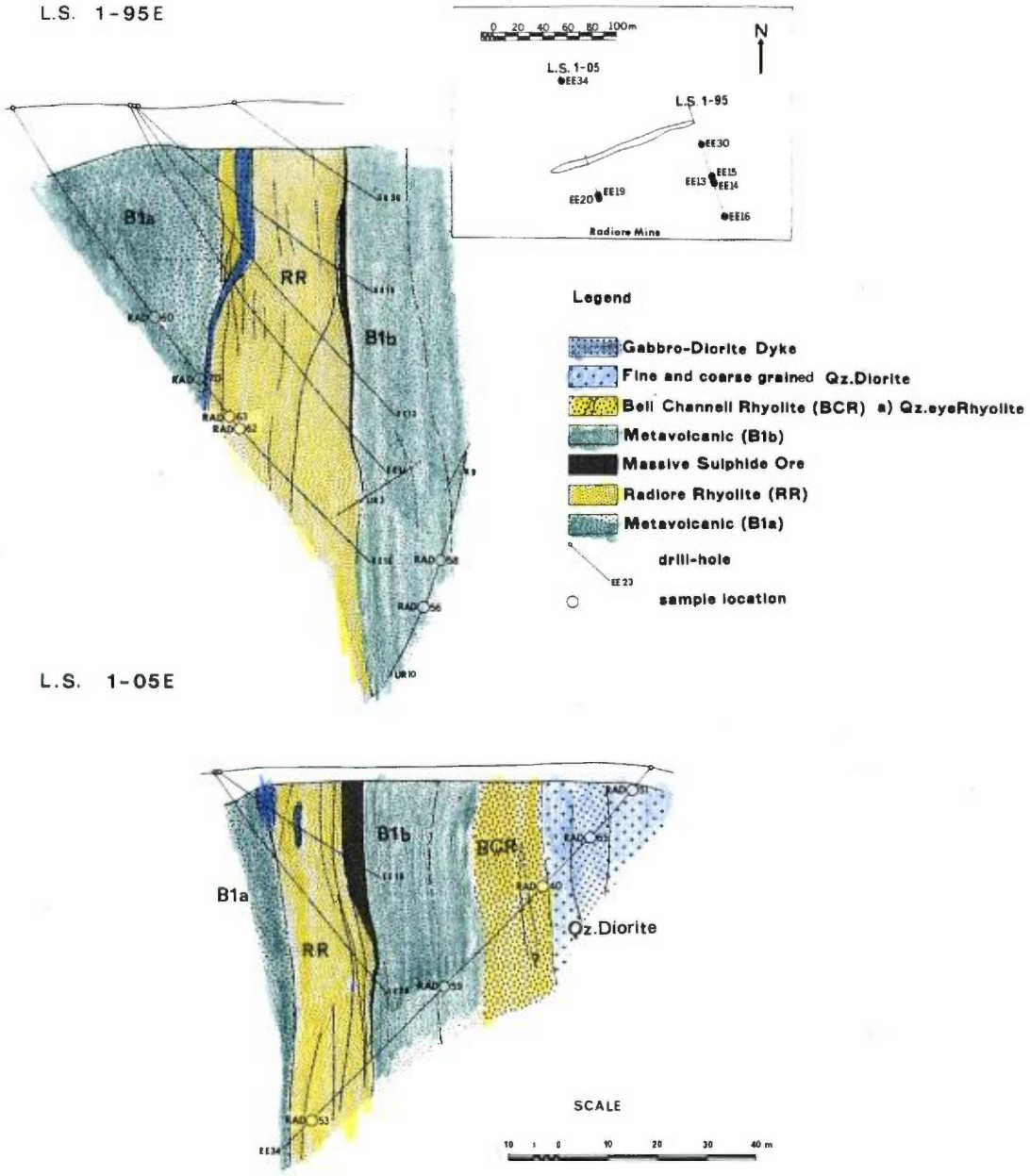


Fig. 12. Geological cross-sections through the Radiore 2 mine (after Bonavia 1981).

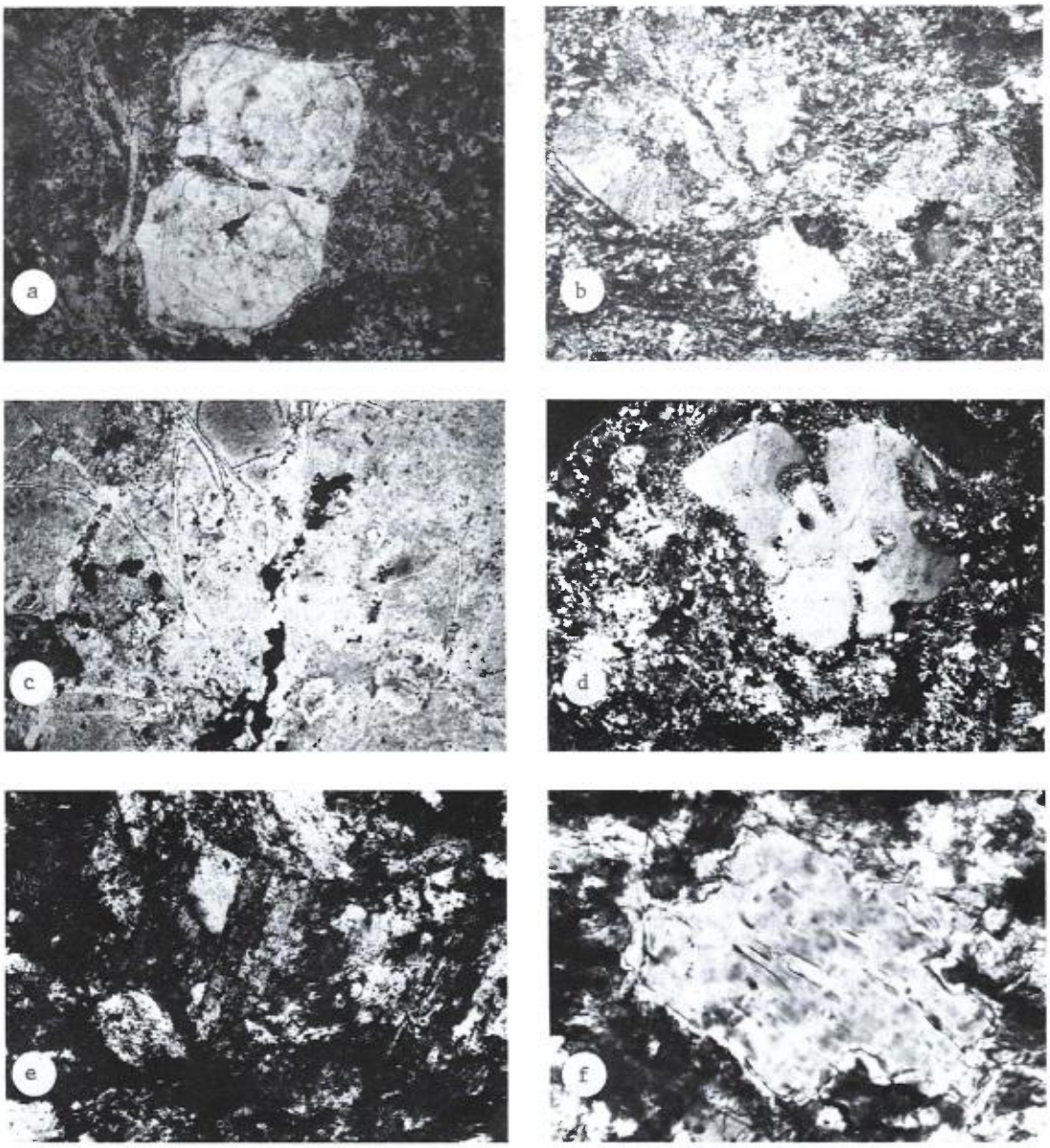


Fig. 13(a) Bell Channel rhyolite: alpha-quartz paramorph of beta-quartz, flanked by a dense cluster of quartz microlites. Elongate optically continuous crystals are alpha paramorphs after tridymite. Plane light, view 2.6 mm across.
(b) Radiore rhyolite: isolated spherules showing original radiating structures preserved by a series of optically continuous sectors of inclusions of quartz-albite and probably sericite. Crossed nicols, view 2.6 mm across.
(c) Radiore rhyolite: cracks forming small spheroidal parting due to contraction during cooling — perlitic texture. Plane light, view 2.6 mm across.
(d) Bell Channel rhyolite with embayed quartz phenocryst and sodic plagioclase microphenocrysts. Plane light, view 2.6 mm across.
(e) B1a metavolcanic (basalt): well-preserved sodic plagioclase phenocryst in a quartz-albite matrix surrounded by a network of chlorite grains. Crossed nicols, view O.9 mm across.
(f) B1a metavolcanic (basalt): green-brown biotite grain showing a reaction rim of alteration to chlorite. Crossed nicols, view 0.2 mm across.

To the west of the mine an ENE striking gabbro-pyroxenite dyke outcrops and cuts the B1b metavolcanic. It is interpreted to be part of the gabbro dyke intruding the quartz-diorite mapped previously in the Radiore ramp (Fig. 7).

The extrusive rocks, the earlier intrusives, and the orebody have been injected by a series of amygdaloidal dykes, found in places to be formed of at least two successive intrusions, as the same rock type was observed chilled against an earlier intrusive phase.

Structure

The stratigraphic top direction of the volcanic rocks is inferred by the position of the orebody which generally lies above felsic volcanic rocks. At Radiore this indicates a northerly direction. Furthermore, underground mapping of the massive sulphide ore revealed the orebody has an undulate profile, with topographic lows and highs at the rhyolite-massive ore contact which indicates this contact was the depositional surface; the contact of the ore with the overlaying rocks is linear and thus moreso interpretable as the top of a filled depression (Fig. 11). The same conclusion has been arrived at by observing the mesoscopic structures within the massive ore in which the convexity of the ore beds is constantly facing north.

Tops north

The strike and dip of the volcanic rocks are respectively E-W and subvertical. Variations in the dip range within 15 degrees from vertical, and are interpreted to be due mainly to original irregularities in the rhyolite paleosurface which were further inflated by the emplacement of sills and dykes and by folding.

A fault is interpreted to have formed soon after deposition of the ore at the west end of the lens. It cuts across the orebody at a low angle displacing the upper block a short distance to the east (Fig. 11).

Small subvertical faults and shear zones trending roughly NW-SE have been mapped throughout the mine ramp by MacGeehan (personal communication). An extensional fault with similar trend, but cutting the orebody and subsequently intruded by a gabbroic dyke, was mapped on level No. 1 (Fig. 11). The magnitude of the strike-slip is in the order of one-half metre and can probably be related to the same phase of faulting that produced the Radiore fault inferred further east by MacGeehan (1979).

Alteration and Metamorphism

The metamorphic evolution of the volcanic rocks can be divided into three major stages: seafloor weathering or halmyrolysis (high to low temperature alteration), high temperature hydrothermal alteration, and local and regional metamorphism. No reliable criteria were found to distinguish the first two events as they both presumably attained greenschist facies. However, it is interpreted that hydrothermal alteration, active during fluid circulation in the geothermal system, is by and large responsible for the mineral assemblages observed, and further reference to alteration is to this type.

Massive sulphide deposits are invariably described in the literature as being associated with rock alteration, and this alteration has generally been found to be restricted to rocks beneath the massive sulphides.

In the Noranda district a typical hydrothermal alteration assemblage is chlorite-sericite-quartz, with chlorite closely associated with ore (Kelly, 1975). At Matagami, Roberts and Reardon (1978), in a study of the Mattagami Lake mine, found that talc, chlorite and to

some degree sericite were formed by alteration processes, while actinolite, biotite and stilpnomelane were metamorphic products. Also at Matagami, MacGeehan et al. (1981) reported that hydrothermal alteration at the Norita mine has produced variable but intense chloritization in the rhyolites. Furthermore, MacGeehan and MacLean (1980a) have proposed that convective circulation of seawater-derived brine below the Garon Lake rhyolite produced an intense spilitization with mineral assemblages in the greenschist facies. At Radiore similar mineral assemblages occur in the metavolcanics and support the interpretation that the rocks have been hydrothermally altered before being affected by contact and regional metamorphism.

To coherently develop the discussion it is important to remember that contact and regional metamorphism may have re-equilibrated the alteration mineral assemblages. Therefore, minerals observed today have not necessarily been formed under hydrothermal conditions.

Assuming that the chemical character of the basic rocks discussed earlier is not disputed, the presence of different mineral assemblages implies that these changes resulted from modified fluid circulation.

On the basis of the colour and textures associated with specific mineral assemblages, it is possible to distinguish the alteration effects and group those of:

1) spilitization
2) potassium metasomatism
3) chloritization

1) The spilitized rocks are usually light in colour ranging from grey-green to light-green (they would be commonly termed "andesite" or "dacite" in the field). Two equilibrium assemblages are petrographically observed:

a) tremolite(actinolite)-plagioclase-chlorite-quartz-sericite
b) actinolite(hornblende)-plagioclase-quartz-epidote-chlorite-biotite

The plagioclase generally varies from oligoclase to andesine and occasionally unaltered phenocrysts and remnants of the igneous fabric are observed (Fig. 13e). Samples often show cross-cutting veinlets of quartz, chlorite, or actinolite-epidote-pyrite, obviously related to later phases of fluid circulation.

The spilitization assemblage has minor biotite which occasionally shows incipient chloritization (pseudomorphism, Fig. 13f). It is suggested that this biotite (or similar precursor) formed during K-metasomatism. The reasoning to equate such a relationship with a subsequent fluid phase lies on the petrographic evidence that K-metasomatized rocks display a similar biotite-chlorite transformation in more heavily chloritized rocks.

2) The potassium metasomatized metavolcanics are light in colour and have been mapped as silicified rocks. They have a recrystallized texture and are defined by the assemblage biotite-plagioclase(albite/oligoclase)-dolomite-chlorite-quartz-pyrite. This alteration was intersected towards the base of B1a metavolcanic by drill hole UR-12 and some samples show relict domains of chlorite-dolomite-quartz.

The metasediments or tuffs are much darker in colour and exhibit a variable mineralogy. The observed biotite-rich assemblage is unlikely to have been derived isochemically from low-potassium tholeiites; it is probably related to the potassic alteration event.

3) The chloritized rocks are dark green and could easily be mistaken for altered "basalt" or "andesite". Chloritization is a pervasive alteration mainly below the orebody but it is not possible to distinguish between chlorite formed during spilitization and that formed during

this later process. Qualitatively the sharp increase of chlorite is observed in hand specimen and thin-section, and cannot be accounted for by the breakdown of the ferromagnesian minerals. It can instead be explained by an addition of magnesium to the rock; in this respect the chemistry is indicative: altered samples show values well above 10% MgO, while in spilitized rocks it rarely exceeds 5%.

The existence of different mineral assemblages points to a paragenetic order of alteration events. Relict phenocrysts are occasionally and only observed in the spilitized rocks, indicating that this alteration is associated with the least altered rocks. The widespread occurrence of the spilitized assemblages implies that it represents the major alteration event in the area. The clear petrographic evidence of spilitized relict domains in K-metasomatized and chloritized rocks indicates its earlier formation.

The restricted areas in which intense K-metasomatism and chloritization are observed suggest that fluids were moving preferentially along channelways with a small part of the fluids penetrating microfractures in the metavolcanics and the highly porous metasediments or tuffs. The consistent textural evidence that chlorite pseudomorphs biotite allows the interpretation that progressive chemical changes occurred in the circulating fluids.

Two major alteration events have thus produced a greenschist facies assemblage (spilitization) followed by a prograded alteration from K-metasomatism to chloritization. A generalized sequence of alteration events is summarized in Table 2. Contact metamorphism associated with the intrusion of the quartz-diorite sill has produced grains of pinitized cordierite mainly in rocks below the massive sulphide ore and close to the intrusion. The volcanic rocks below the orebody have distinctly higher normative corundum contents than rocks above suggesting they are more strongly altered and consequently favour the formation of cordierite.

In this study a poorly developed regional metamorphic assemblage was recognized. It is related to the oligoclase-actinolite (hornblende)-chlorite zone (Winkler, 1979), typical of metabasaltic greenstones and diagnostic of the lower amphibolite facies.

Wall-rock Geochemistry

MacGeehan and MacLean (1980a) proposed a tholeiitic affinity for the volcanic rocks on the northern side of the Matagami district and interpreted the calc-alkaline trend of the "intermediate" volcanic rocks originally put forward by Descarreaux (1973) as being the result of widespread hydrothermal seawater circulation through an original basalt-rhyolite bimodal suite. This interpretation was based on the geochemistry of the least altered volcanic rocks extruded above the Bell Channel rhyolite, the B2 to B7 basalts and the Garon Lake rhyolite. It is unfortunate that due to the extensive glacial cover the B1 basalt has only been sampled from drilling holes adjacent to mineralization where it is invariably hydrothermally altered, and consequently the basaltic nature was primarily inferred by analogy with the adjacent basic flows.

Metavolcanics

The least altered metavolcanics at Radiore 2 (Table 3) are the spilitized rocks which were only locally affected by subsequent chloritization and K-metasomatism. The addition of silica is a consequence of spilitization: silica is dissolved in fluids in some parts of the geothermal system and precipitated in others, increasing the SiO_2 content of the original basalt and generating a pseudo-calc-alkaline trend (MacGeehan, 1979; MacGeehan and MacLean, 1980a). This feature is observed in almost all the spilitized rocks. In fact, the in-

Table 2. Sequence of alteration events.

Alteration Type	Field Relationships	Mineral Assemblages (in the metavolcanics)	Hydrothermal Event	Texture
Spilitization	Widespread	Tr-Chl-Plag-Q-Ser Act(Hb)-Plag-Q-Ep-Ser-Chl-Bi	Hydrolitic alteration of mafic minerals plus silicification	Remnants of igneous fabric. Silica veinlets or dissolution and replacement by quartz.
K-metasomatism	Localized at the base of B1a or in meta-sediments and tuffs (Radiore rhyolite or slightly above)	Bi-Q-Chl-Dol	K+ and CO_2	Relicts of spilitization
Chloritization	Mainly below B1a; Very intense at base, otherwise more restricted or in veins in spilitized rocks.	Chl-Dol-Q Act-Ep	Mg^{+2}	Relicts of spilitization and chlorite pseudomorphs biotite.

Tr — tremolite Chl — chlorite Plag — plagioclase Q — quartz Ser — sericite
Hb — hornblende Ep - epidote Bi — biotite Dol — dolomite — Act — actinolite

Table 3. Chemical analyses of volcanic rocks at the Radiore 2 Mine.

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	62.43	58.53	62.43	52.71	73.15	73.57
TiO_2	1.24	1.63	1.33	1.49	0.74	0.44
Al_2O_3	13.05	12.73	10.30	14.93	11.01	8.63
Fe_2O_3*	2.76	3.15	2.85	3.02	2.25	1.95
FeO	9.14	11.55	9.43	13.71	3.03	6.69
MgO	6.36	3.24	6.46	12.38	6.39	2.06
CaO	2.00	4.28	0.73	0.55	0.39	3.39
Na_2O	1.81	3.86	2.39	0.83	0.44	1.82
K_2O	1.10	0.82	3.85	0.37	2.63	1.10
P_2O_5	0.10	0.20	0.23	0.03	—	0.34
Rb ppm	27	21	318	17	54	28
Sr	65	118	65	11	11	124
Y	59	78	100	42	68	57
Zr	218	240	327	89	368	318
Nb	13	11	19	7	20	12
Zn	72*	68	95	90 *	41	43
Cu	89*	25	125	18 *	18	55
Ni	23*	11	39	15 *	64	9
Mn	1117*	1612	1445	1929 *	280	385
Cr	20*	3	68	264 *	—	—
S	278*	160	162	66 *	284	728
Norm. An %	33	31	10	27	32	44
Norm. Cor. %	5	0	1	12	7	0
Color Index	35	34	36	58	23	20

Fe_2O_3* calculated as wt.% TiO_2 + 1.5
* average of 2 analyses

(1) spilitized B1a metavolcanic. RAD 60.
(2) spilitized B1b metavolcanic. RAD 43.
(3) K-metasomatized B1a metavolcanic. RAD 80.
(4) chloritized B1a metavolcanic. RAD 44.
(5) slightly altered Radiore rhyolite. RAD 62.
(6) Bell Channel rhyolite. RAD 40.

tensely spilitized samples at Radiore display regular changes in elements with increasing silicification that mimic the calc-alkali trend.

K-metasomatism produced drastic changes (Table 3). In addition to potassium, the relatively immobile elements, P, Ti, Y, Zr and Nb have been added. The presence of dolomite and minor calcite are evidence that CO_2-rich fluids were part of the alteration. CO_2-rich fluids are reported by Hynes (1980) to be extremely effective in mobilizing Ti, Zr and Y and thus may account for the abrupt changes in the other elements accompanying K-metasomatism.

Chloritization is the last pervasive alteration in the mine area. Mg was the main metasomatising element, and Ca, Na and K were stongly depleted during this phase of alteration (Table 3).

Rhyolite

Definite mineralogical imprints of all three alteration phases are not seen in the rhyolites. Many elements (e.g., Na and Ca) have been depleted, but it is impossible to attribute these changes to a specific alteration. K-metasomatism has, however, pervasively affected the Radiore rhyolite, in particular the clastic parts (tuffs or metasediments). It was not always possible to distinguish between rocks derived from massive rhyolite or from metasediments and tuffs; however, samples with low silica and high Al_2O_3 are likely to be metasediments.

Intrusive Rocks

Sharpe (1964, 1968) interpreted the numerous sills to be high level subsidiary intrusions of the Bell River Complex, and MacGeehan (1979) showed that they are co-magmatic with the basalts and were derived from iron-rich tholeiitic magma. Geochemical plots confirm the tholeiitic trend of these intrusives (Fig. 14).

The gabbro-diorite dyke is, however, different and was probably one of the last intrusives emplaced at Radiore. Although rocks bordering the dykes are hydrothermally altered, there is no evidence of direct involvement of the dykes in any major alteration events. There is evidence in the dykes of a weak spilitization and, locally, of quartz-epidote veinlets and patches (bleached zones) similar to the ones described by Harrigan and MacLean (1976) for a large gabbro dyke; otherwise the chilled margins and the cores of the dykes retain their primary texture. There is no suitable interpretation to explain the calc-alkaline nature of these intrusives as shown on Figure 14 and other plots (not shown) of wt% Al_2O_3 vs An normative composition (after Irvine and Baragar, 1971), Ti/100 x Zr x Y/3 and Ti vs Zr (after Pearce and Cann, 1973) except by suggesting a separate magmatic event. No other calc-alkalic rocks are known in the area.

The Orebody

The structure of the orebody was studied by mapping the backs of the drift in mine level No. 1. Observation of the ore was difficult because of the high backs and the thick crust that had formed from diesel fumes. The massive ore can be divided into two zones:

Basal Zone. This zone is underlain by massive Radiore rhyolite and locally by sediments or tuff, but no clear contact between these units was observed. At the base the ore is very siliceous (about 50% quartz and 20% silicates) with sulfides becoming concentrated towards the top (80% combined pyrrhotite, pyrite and chalcopyrite). It reaches a maximum of 2 m thick in the centre and gradually thins laterally. At the eastern end of the lens, the basal zone is missing and a vesicular massive phase of the rhyolite is directly in contact with the Upper Zone. Fragments of chert, metasediment (or tuff) and chloritized rock up to 50 cm across are intermixed with the

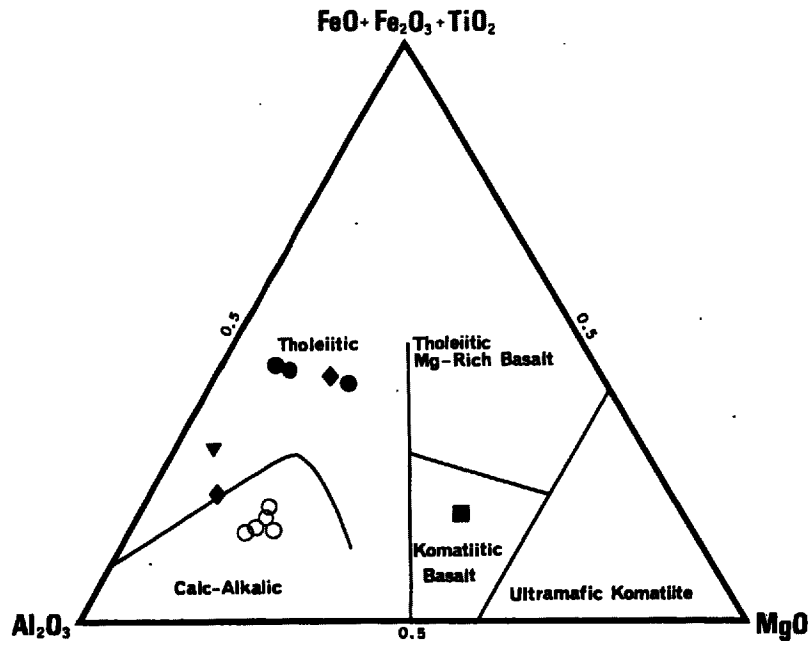


Fig. 14. Plot to discriminate various intrusive rock types at Radiore. Symbols: square — gabbro-pyroxenite, diamond — diabase, inverted triangle — granodiorite, filled circle — quartz diorite, open circle — gabbro-diorite (from Bonavia 1981).

sulphides (Fig. 15a). Such large exotic fragments and the lack of banding are clear evidence of sedimentary re-working of the sulphides.

Upper Zone. This is banded massive ore that forms the top and major part of the orebody (Figs. 15b,c). It attains a thickness of 5 m, and thins laterally to a few centimetres and interdigitates with the host rock. The contact with the Basal Zone is sharp. Banding of pyrite-rich layers up to 50 cm thick characterizes this unit, but individual bands are traceable only for a few metres. Chalcopyrite and sphalerite form monomineralic layers 1 to 10 cm thick. At the far eastern end of the lens a very distinctive layer of large pyrite crystals overlies the massive vesicular rhyolite and grades into chloritized metasediments.

Ore and Gangue Mineralogy

The ore and gangue minerals show a strong zonation with pyrrhotite, pyrite, chalcopyrite and silicates in the Basal Zone, and pyrite, sphalerite, chalcopyrite, pyrrhotite, magnetite and silicates predominating in the Upper Zone. Sphene, Fe-Ti oxides, rutile, apatite, dolomite, ankerite and calcite are occasionally found in both zones. The abundances of minerals in each zone is as follows:

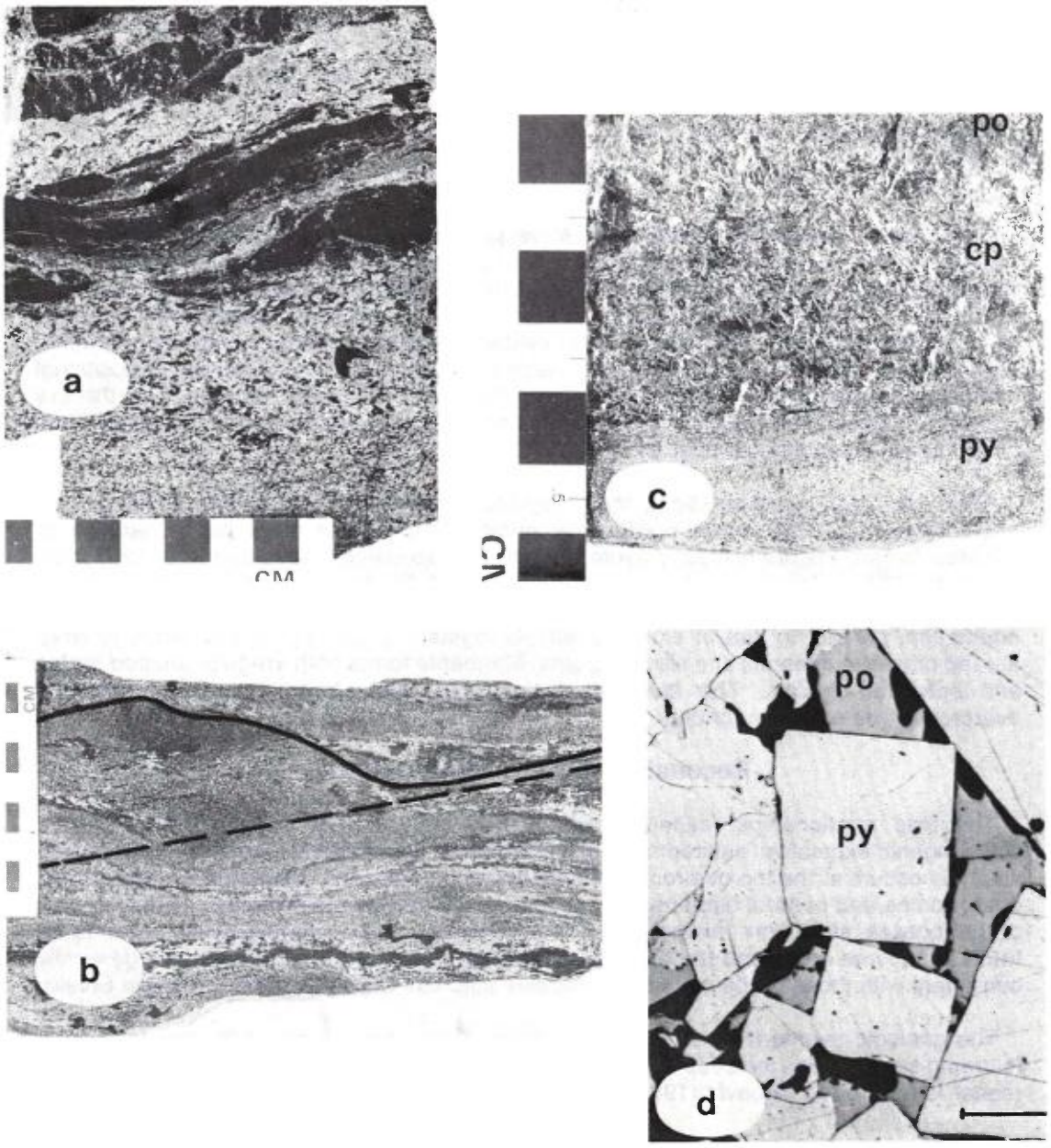


Fig. 15 (a) Massive pyrite-chalcopyrite ore showing bedding cross-cutting relationships (unconformity — solid line), and a small fault (solid line). The dark material is silicate.
(b) Massive pyrite-sphalerite-calcopyrite ore with chloritized rock fragments.
(c) Essentially monomineralic layers of pyrite (py), chalcopyrite (cp) and pyrrhotite (po) occasionally observed in the ore.
(d) Porphyroblastic pyrite in a matrix of pyrrhotite: massive sulphide ore recrystallized during metamorphism.

	Basal Zone	Upper Zone
Pyrrhotite	30 - 70 %	0 - 5 %
Pyrite	20 - 30	50 - 70
Chalcopyrite	1 - 20	1 - 20
Sphalerite	trace	1 - 20
Magnetite	—	1
Silicates	5 - 70	5 - 20

This mineral zonation is typical of massive sulphides, and also indicates that the pyrrhotite is primary and not a metamorphic product. MacDonald (1967) and Vokes (1969) have suggested that pyrite can be converted to pyrrhotite plus sulphur during metamorphism, but at Radiore the rapid change in the amount of pyrrhotite between the two zones rules out this possibility. Nor is there other evidence of replacement of pyrite by pyrrhotite. The simplest interpretation is that the variation is the result of different depositional chemistry caused by an increase in sulphur fugacity. The major difference in the ore minerals between the zones is that sphalerite and magnetite are present in the Upper Zone where pyrite predominates over pyrrhotite.

The ores have, however, been metamorphosed. Pyrite usually occurs as large porphyroblasts (Fig. 15d), often poikilitically enclosing grains of other ore minerals and silicates. Where the ore is mainly pyrite the grains have curved faces and form 120° triple junctions. Pyrrhotite, sphalerite and chalcopyrite individually form matrices to other ore minerals. Some grains of pyrrhotite and chalcopyrite are elongated and have a preferred orientation, parallel to that of elongate silicate crystals. Chalcopyrite also tends to wrap around other ore minerals and silicate grains. Magnetite forms both irregular shaped grains and euhedral crystals. The euhedral grains are mainly formed as porphyroblastic overgrowths on earlier magnetite.

Reconstruction and Genetic Model

The field relationships, mineral assemblages and textures are consistent with a volcanogenic-exhalative environment of formation of the Radiore deposit. The massive sulphide occurs at the top of strongly altered volcanic rocks and is overlain by less altered ones; zoning and mineral banding is developed in the ore; metasediments or tuff form part of the footwall; stockwork mineralization is absent; and weakly altered dykes and sills intrude the altered rocks and the massive sulphides. All these characteristics are generally consistent with those of the majority of massive sulphide deposits in the Canadian Shield.

The geologic events that led to the formation of the deposit are reconstructed in the following section. This includes a geothermal model for the genesis of the ore (Fig. 16). The reader is referred to Bonavia (1981) for a more detailed presentation of the data.

1) The Radiore rhyolite was extruded on top of the B1a metavolcanic (probably a basalt).
2) Seawater solutions reacted with B1a producing a greenschist facies mineral assemblage (spilitization) (MacGeehan, 1978, 1979; MacGeehan and MacLean, 1980b). Heavy metals (Cu, Zn, Ni, Fe, Mn, etc.) were solubilized and transported. It is evident from the thinness of the resevoir that the heat was supplied at depth, probably by one of the numerous sills found there or the Bell River Complex..
3) As the local geothermal gradient rose, new influxes of fluid changed the water/rock ratio of the system in which a greenschist facies mineral assemblage was being formed. At the same time the fluids moved upwards causing K-fixation (potassium metasomatism) and precipitation of carbonates at the low temperature end of the system. As the fluids reached some maximum of temperature and pressure, Mg-fixation (chloritization) prevailed.

4) At the discharge point of the system, Fe-Cu-Zn-Au-S material was deposited.

5) After deposition of the overlying metavolcanic and metasediment (B1b), the lenticular-shaped body was slightly deformed (Fig. 17). The thickening and thinning of the orebody is interpreted to be due to small irregularities in the original basin. At the western end of the deposit a fault offset the contact between the hangingwall rock and the massive sulphide ore. The stratigraphy at this time was tilted to a vertical position.

6) Sills and dykes were intruded at various stages through the volcanic sequence, locally producing contact metamorphism.

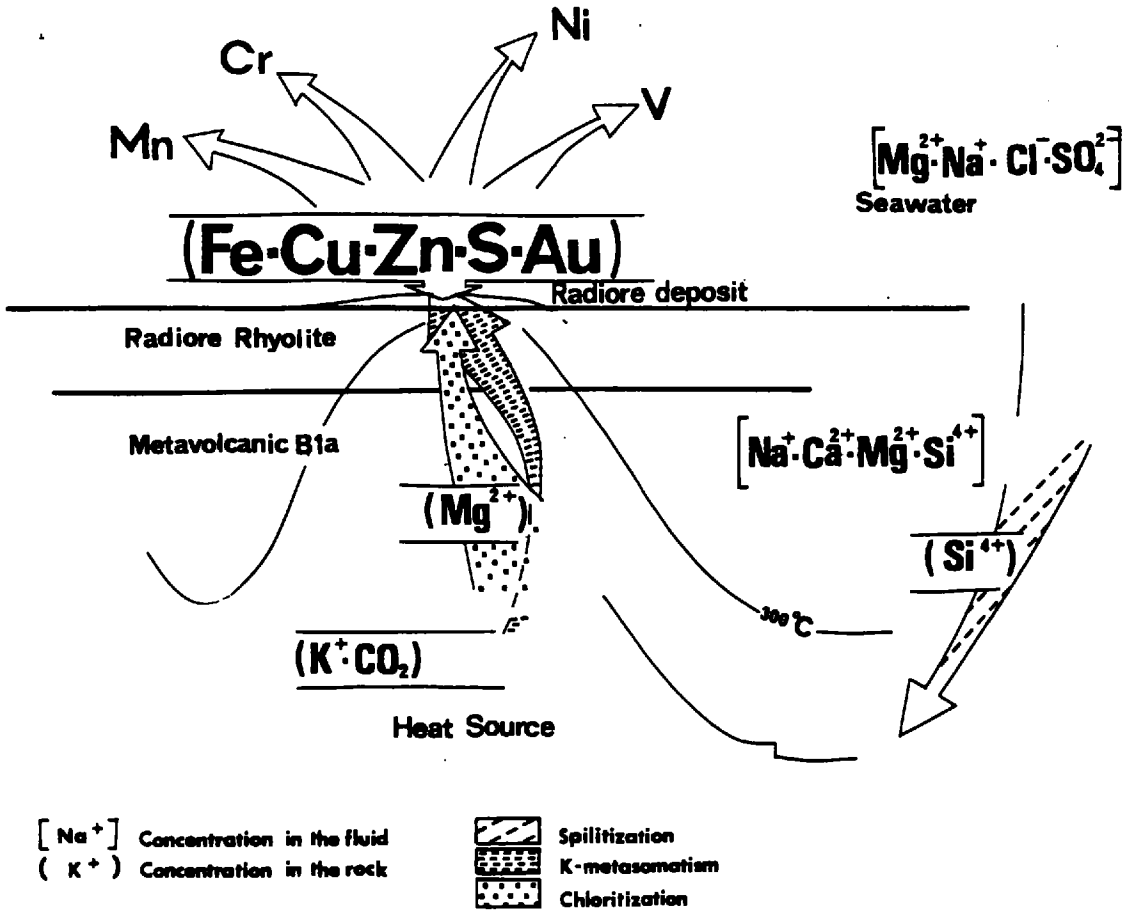


Fig. 16. Schematic illustration of the geothermal system developed below Radiore 2 deposit.

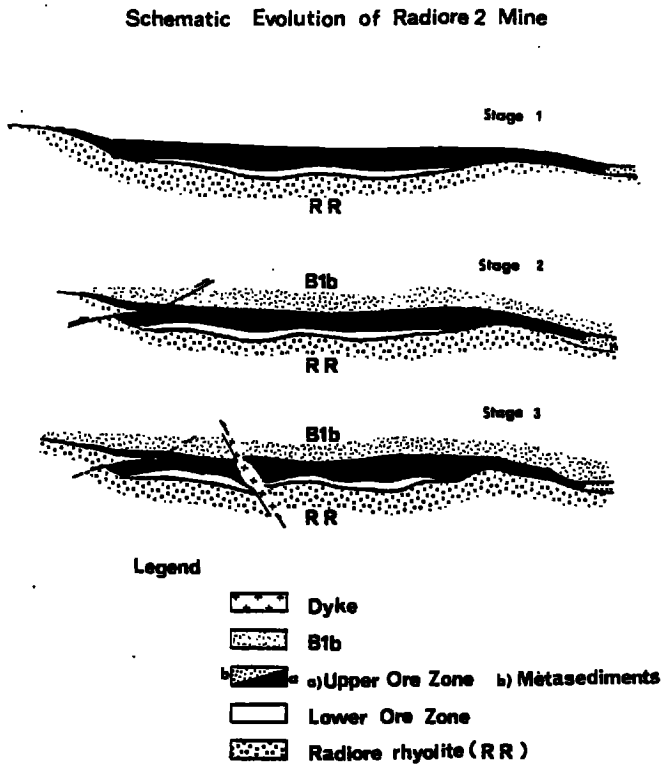


Fig. 17. A schematic reconstruction of Radiore 2 soon after ore deposition.

Acknowledgements

We wish to thank the Matagami Division of Noranda Mines Limited for allowing us to use their data on Radiore 2. Partial financial support at McGill University was provided to F.F. Bonavia by a Carl Reinhardt Summer Award, and to W.H. MacLean through NSERC grant A7719 and FCAC grant 649.

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