"CORBET-TYPE" VOLCANOGENIC SULPHIDE DEPOSITS, AND THEIR RELATIONSHIP TO OTHER MAFIC VOLCANIC-HOSTED MASSIVE SULPHIDE ORES

BY

J.S. FOX

Teck Explorations Limited
Toronto, Canada

Paper presented at the 86th Annual General Meeting
of the Canadian Institute of Mining and Metallurgy,
Ottawa, April 1984.

ABSTRACT

A number of deposits have been identified in Canada and Scandinavia which share many of the features of the Corbet mine, in Quebec. They are all hosted by basalt or andesite of island arc affinity, and are often accompanied by minor graphitic argillite and/or ore zone carbonate. They have consistently anomalous Co and Ni contents, and are inclined to gold enrichment. The presence of stockwork-type alteration at some of these suggests that deposits of this type constitute a proximal metallogenic class that is distinct from mafic volcanic-hosted deposits of the Besshi- and Cyprus-type, and from Kuroko-type deposits.

"Corbet-type" deposits represent a new exploration opportunity. The recent discovery of the Viscaria deposit in Sweden suggests that "world class" deposits of this type remain to be found in Canada.

INTRODUCTION

Significant base metal discoveries, made recently in greenstone belts in Canada and Sweden (e.g., Corbet, Windy Craggy, Viscaria), suggest that the mafic volcanic environment may be an important, untapped source of economic sulphides in the Canadian Shield. These recent discoveries are metallogenically distinct from Besshi- and Cyprus-type deposits, which are relatively common in Proterozoic and Phanerozoic mafic volcanic terrains. Instead, they seem to belong to a previously unrecognized category, typified by the Corbet deposit in Quebec, which appears to have significant potential in the Archean rocks of the Canadian Shield.

Although the recognition of these "Corbet-type" deposits has generated a moderate amount of exploration activity in Scandinavia, little interest has been shown in them in Canada, despite their inclination to gold-enrichment. This lack of Canadian activity is probably due to an absence of documentation and, hence, to the absence of a metallogenic model. This paper describes the preliminary results of some research, which was undertaken specifically to delineate such metallogenic guidelines.

MAFIC VOLCANIC-HOSTED MASSIVE SULPHIDE DEPOSITS

Until recently, only two types of proximal, mafic volcanic-hosted volcanogenic sulphide deposits have been recognized -- Besshi- and Cyprus-types. Besshi-type mineralization is characterized by an association with continentally-derived clastic sediment, and with subordinate basalt of oceanic or intra-plate chemistry. Deposits of this type seem to form in immature, epicontinental rifting environments (Fox, 1984). Cyprus-type deposits, such as those currently forming on the East Pacific and Juan de Fuca Ridges, as well as those whioh are thought to have formed in back-arc basins, constitute a second class, are associated with basalts of oceanic character and have virtually no accompanying mechanical sediment (e.g., Normark, et al., 1982).

Corbet-type deposits constitute a third, basalt-related, metallogenic category. As will be shown, they are associated with rocks similar to those formed during the initial stages of arc development, which clearly contrasts with the petrogenetic association of Besshi- and Cyprus-type ores.

THE CORBET DEPOSIT

The Corbet deposit is found in the Abitibi greenstone belt, 7 km northwest of the town of Noranda (Figure 1). It came into production in 1980, with reserves of 2.7 M tonnes, grading 3.1% Cu, 2.8% Zn, 23 g/tonne Ag and 1 g/tonne Au.

The deposit occurs in the mafic volcanics of the Archean Blake River Group and, in particular, in the Flavrian Andesite, which lies at the base of one of the mafic to felsic erruptive cycles recognized in the central part of the Group. Most of the Kuroko-type mineralization in the Noranda camp is found at the top of the same cycle, 1,000 m stratigraphically above the Corbet ores (Knuckey and Watkins, 1982; Watkins, 1980 - Figure 2).

The Flavrian Andesite in the vicinity of Corbet consists of basalt and andesite, and is characterized by a differentiation trend that straddles the boundary between calc-alkaline and tholeiitic on an AFM plot. Dimroth et al. (1982) believe these rocks to represent primitive arc lavas, extruded during the pre-caldera phase of the Noranda stratovolcanic complex. Gelinas et al. (1984) believe them to have formed as a result of continental rifting, and deep-mantle crustal fusion.

The Flavrian Andesite is composed of massive, pillowed and local amygdaloidal flows, and minor hyaloclastite. Coarse, vesicular mafic pyroclastic rocks are important constituents of this unit in the vicinity of Corbet. Isopach maps of the andesite reveal the presence of a paleotopographic high in the vicinity of the deposit. These features suggest mafic volcanic doming which, according to Knuckey and Watkins (1982), was localized by the footwall McDougall and Despina faults (Figure 3).

The main ore zone at Corbet is a lensoid, stratiform body which is directly underlain by a small but distinct stockwork alteration pipe. The alteration is characterized mainly by Fe- and Mg-enrichment and by Si-, Ca- and Na depletion (Knuckey and Watkins, 1982), but sporadic Na-enrichment at the outer edge of the alteration envelope may also be present. This alteration has been superimposed on an earlier event of spilitization and epidotization (H. Gibson, pers. comm., 1984).

Mineralization in the main ore zone consists of massive to semi-massive pyrrhotite, pyrite, chalcopyrite, sphalerite and magnetite, and attains a thickness of up to 70 m above the alteration stockwork. The main ore lense exhibits the hanging wall to footwall Cu to Zn zoning typical of other volcanogenic deposits in the region.

OTHER "CORBET-TYPE" DEPOSITS

A number of other Corbet-type deposits can be identified from the literature with a moderate degree of certainty, e.g., Haveri (Kahkonen et al., 1981), Pahtavuoma (Inkinen, 1979), Bidjovagge (Hagen, 1982; Hollander, 1979) and Coronation (Froese, 1969 - Table 1). Other deposits which may belong in this category are New Insco and Magusi which, like Corbet, appear to be hosted by andesite occuring low in the Blake River sequence (Larson, 1983), and the large, newly discovered Windy Craggy deposit in British Columbia. However, the Maybrun and Viscaria deposits illustrate the main features of this group particularly well, and are briefly described below.

(a) Maybrun

The Maybrun Cu-Au deposit is located in the mafic volcanics of the Wabigoon greenstone belt, 70 km southwest of Dryden (Figure 4). It contains indicated reserves of 2.8 M tonnes grading 1.1% Cu and 3 g/tonne Au, and is the largest of several similar deposits in the area (Setterfield, 1980; Setterfield et al., 1983).

The deposit occurs in rocks probably equivalent to the Archean Populus Volcanics, a sequence that is dominated by mafic volcanic flows, but which also contains minor andesite, mafic pyroclastics, graphitic argillite and chert. South of Maybrun, in the vicinity of the Cameron Lake gold deposit, the Populus Volcanics may be underlain by a sequence of tholeiitic to calc-alkaline mafic to intermediate flows and pyroclastics. At Rowan Lake, these, in turn, are underlain by extensive magnesian tholeiitic volcanics of probable oceanic affinity (Davies, 1973; Trowell et al., 1980; Blackburn, pers. comm., 1984).

The Populus Volcanics in the vicinity of Maybrun exhibit a restricted, iron-rich tholeiitic magmatic trend on an AFM plot. Blackburn (1980) and Langford and Morin (1976) have emphasized the arc-like geochemical and morphological nature of possibly equivalent rocks elsewhere in the region, such as the Upper Wabigoon Volcanics.

Mineralization at Maybrun consists of pyrrhotite, chalcopyrite, minor sphalerite and, locally, carbonate in pillow interstices at the tops of three stratigraphically separate basaltic flows. In each of these, sharp contacts are observed between mineralized pillowed flows and overlying massive flows (H. Matthews, pers. comm., 1984).

Bedded sulphides have not been found, and this indicates that although the Maybrun ores are volcanogenic and stratabound, they are not exhalative. Similar inter-pillow mineralization is present locally at Corbet, and probably reflects a multi-phase evolution of the relevant hydrothermal cell (viz., subsurface mixing with cool seawater).

Three distinct flow units have been recognized on the mine property, and consist of aphyric, plagioclase-phyric and carbonatized aphyric basalt. Lenses of vesicular mafic lapilli tuff are locally intercalated with these flows. The bulk of the known Cu-Au ore occurs near the contact between the plagioclase-porphyritic and the carbonatized aphyric basaltic units (H. Matthews, pers. comm., 1984 - Figure 5). The basalts associated with the mineralization have been moderately depleted in Ca and Na, and enriched in Fe, Mg and K (Setterfield, 1980; Setterfield et al., 1983).

(b) Viscaria

The Viscaria deposit is located only 3 km west of the iron ore complex at Kiruna, Sweden. It is a "world class" deposit, having gone into production in 1983 with estimated reserves of 24 M tonnes grading 2.0% Cu to 400 m in three stratigraphically separate zones. Possible reserves exceed 50 M tonnes, and grades increase to the 4-5% Cu range with depth. Although the Zn and precious metal contents of the ore are low near surface, there is some indication that the latter increase in grade at depth (L. Godin, pers. comm., 1984; Mining Magazine, 1983).

The deposit occurs in the Kiruna Greenstone Group, a sequence of east-facing subaqueous volcanics composed of basaltic flows, mafic tuff and subordinate graphitic argillite and dolomitic limestone (Figure 6). To the east, the Kiruna greenstones are unconformably overlain by the Proterozoic andesite, rhyolite and trachyte of the Kiruna Porphyry Group, in which the Kiruna iron ores are found. The Kiruna Greenstone Group is thought to be coeval with the Archean Kittila greenstone complex of northern Norway and Finland, in which similar "Corbet-type" deposits occur (e.g., Bidjovagge, Pahtavuoma - Forsell and Godin, 1980; Hagen, 1982; Lundberg and Smellie, 1979; Gaal et al., 1978; Inkinen, 1979 - Figure 7).

The Kiruna Greenstones in the vicinity of Viscaria exhibit a restricted tholeiitic differentiation trend on an AFM diagram. Although no tectonic or petrogenetic modelling has previously been attempted for these rocks, the presence of an older granitic substratum, the abundance of distal mafic pyroclastic rocks and associated fine-grained clastic sediment, and the absence of ophiolite-equivalent intrusive rocks suggest an arc-like environment of deposition.

Mineralization at Viscaria is confined to basalt-hosted zones of graphitic argillite and limestone (Figure 8). Pyrrhotite and chalcopyrite are the most abundant sulphides, but sphalerite and magnetite are also common. No evidence of focussed hydrothermal alteration has yet been found, although scattered areas of scapolitization, and pervasive spilitization, and epidotization are known in the surrounding basalts (L. Godin, pers. comm., 1984).

BASALT GEOCHEMISTRY

Significant compositional overlap exists between island arc basalt (IAB), "normal" mid-oceanic basalt (N-MORB) and basalt from back arc basins (BABB), despite their different parentage. As a result, many conventional geochemical discriminants, such as those which use elemental ratios of high field strength cations, often give unacceptable petrogenetic separation (e.g., Perfit et al., 1980; Hawkins, 1980). Inconclusive results of this sort were obtained for analyses of relatively unaltered host basalt and basaltic andesite from Corbet, Maybrun and Viscaria, when plotted on Pierce and Cann's (1973) Ti-Zr and Zr-Y diagrams (Figure 9).

A somewhat better magma-type categorization was obtained with Pierce's (1976) major element discriminant, which showed these rocks to have IAB affinity. The categorization achieved is remarkably consistent, particularly in view of the susceptibility of the heavily weighted discriminating variables (K_2O, MgO, SiO_2, Al_2O_3) to hydrothermal alteration and weathering.

Geologically younger IAB are consistently depleted in some transition metals, and notably enriched in some alkali metals with respect to basalts formed at constructive plate margins (Hawkins, 1980; Garcia, 1980). This reflects the contrasting clinopyroxene-olivine- and plagioclase-olivine-dominant controls on fractionation shown by IAB and N-MORB, respectively (Saunders, 1984; Perfit et al., 1980; Taylor et al., 1980; Rhodes and Bence, 1980). In this regard, Ni, Cr and Ba appear to be particularly useful petrogenetic indicators, since they are moderately inert. These discriminants have been used to confirm the IAB affinity for the Corbet, Maybrun and Viscaria rocks that was suggested by the major element data (Figure 10).

The rare earth elements (REE) are also sensitive to magmatic processes, and can be used to constrain petrogenetic models (Haskin, 1984; Hanson, 1980). Chondrite-normalized plots of the Corbet, Maybrun and Viscaria basalt analyses show the flat to moderately light REE-enriched abundance patterns common to geologically young IAB (e.g., Philpotts et al., 1971; Dixon and Batiza, 1979; Perfit et al., 1980 - Figure 11). The Maybrun and Viscaria basalts have REE abundance patterns which are similar in shape to that shown by Taylor et al.'s (1980) IAB reference suite, but they are richer in total REE. The REE pattern for the Flavrian Andesite shows that it is somewhat more evolved than the rocks of the reference suite. Significant Eu anomalies are absent in all of the basalts analyzed, as is the case for most aphyric IAB (Condie and Baragar, 1974; Taylor et al, 1980), and this can also be attributed to the absence of liquidus phase plagioclase in primitive IAB fractionation (Hanson, 1980; Rhodes and Bence, 1980). The absence of an Eu anomaly is in contrast with recent observations made for ore-associated felsic volcanic rocks (Campbell et al., 1982).

These IAB-like REE patterns can be compared with those characterizing N-type MORB. About 75% of the oceanic crust is "normal" (Kay and Hubbard, 1978), and basalts of this type appear to host most of the active Cyprus-type metalliferous systems that have recently been reported on, for example, the East Pacific Rise (Scheidigger and Corliss, 1981). In contrast to the IAB-like basalts that host Corbet-type deposits, N-MORB shows consistent LREE depletion (La/Sm are usually <1.0) and, when moderately evolved, exhibit negative Eu anomalies (Rhodes and Bence, 1980).

The ophiolite suites in which many older Cyprus-type deposits are found are now thought to represent material from back-arc spreading centres, rather than from mature, mid-oceanic rifts (e.g., Smewing et al., 1975; Pierce, 1975). However, from the point of view of basalt geochemistry, and particularly REE, Cyprus-type BABB and N-MORB are indistinguishable (Hawkins, 1980). Both are significantly different geochemically from the IAB-type rocks with which "Corbet-type" deposits are found (Figure 12a,b). It should be noted that many back arc-type ophiolite suites contain IAB high in their stratigraphic succession (e.g., Luzon-Hawkins, 1980; Pindos, Greece - Capedri et al., 1980), and some of these IAB host massive sulphide deposits which are in many ways similar to Corbet (e.g., Skouriotissa, Cyprus - Constantinou, 1980).

The flat REE patterns for basalts hosting the Besshi-type Goldstream and Ore Knob deposits (Fox, 1984) are similar to those of the three Corbet-type deposits, although they can easily be differentiated on the basis of other geological and geochemical criterion. For example, Slack (1983) and Gair and Slack (1983) have discussed the high Cr, Ni, V and Ti contents of the MORB-like basalts hosting the Besshi-type Elizabeth deposit, and the deposits of the Great Gossan Lead. The REE patterns shown in Figure 12c are also similar to those exhibited by the "transitional" (T-MORB) basalts of some slow spreading rate oceanic ridge segments (e.g., Galapagos, Gulf of Aden - e.g., Rhodes and Bence, 1980; Schilling, 1971) to which they may be more closely related, genetically.

ORE GEOCHEMISTRY

The Co, Ni, Au contents of seven "Corbet-type" deposits are compared with those of other volcanogenic sulphide ores in Table 2. Although the data are incomplete, there is a clear indication that the Corbet-type ores have an inclination to gold enrichment. Two of these deposits, Maybrun and Haveri, appear to be near economic at current prices on the basis of their gold content alone. All known "Corbet-type" deposits are lead-poor.

Corbet-type deposits are also relatively rich in Ni and Co, and this clearly distinguishes them from Kuroko-type ores, with which they have been compared in the past. The mean Co contents of all three mafic-hosted metallogenic types appear to be similar, but Corbet-type ores seem to have Ni contents which are an order of magnitude greater than those of Besshi- and Cyprus-type deposits.

DISCUSSION

Moderately evolved basalt and basaltic andesite, similar to those hosting Corbet, Maybrun and Viscaria, and richer in total REE than Taylor et al.'s (1980) IAB reference suite, are found in a number of island arcs in the southwestern Pacific, including Fiji (Figure 13). The Fijian IAB, which are contained in the Wainamala Group and which are overlain by calc-alkaline and shoshonitic rocks, were formed as a result of the subduction of the Pacific plate under the Indo-Australian plate in the late Miocene (Lawrence and Savage, 1976; Eguchi, 1984 - Figure 14).

A number of small volcanogenic massive sulphide deposits are found in the Wainamala mafic volcanics (e.g., Tholo-i-Sava, Wainaleka - Lawrence and Wood, 1980). These deposits are lead-poor, locally gold-enriched, are associated with chloritic and silicic alteration (Colley and

Greenbaum, 1980), and contrast metallogenically with the lead-rich massive sulphide and vein-type gold deposits found in the overlying volcanic suites. Although detailed descriptions are lacking, these deposits may prove to be geologically young analogues of the Precambrian "Corbet-type" ores.

Debate still exists regarding the nature of plate tectonics in the Precambrian, specifically in terms of the presence or absence of subduction-related phenomena in early crustal history, and this prevents a direct comparison of the Fijian and other geologically younger IAB environments with those hosting Corbet, Maybrun and Viscaria. Whatever the tectonic process involved, however, the distinctive chemistry of the Precambrian IAB-like basalts which host the three "Corbet-type" deposits is indicative of source magmas which must have been different from those responsible for the ancient analogues of constructive marginal basalts (e.g., Naldrett and Smith, 1980; Condie, 1982). Ancient IAB chemistry is consistent with hydrous melting of mantle material, and with amphibole-and/or garnet-controlled fractionation, as is the case for younger IAB.

Carbonate is an important ore-horizon constituent in many Corbet-type deposits (e.g., Viscaria, Pahtavuoma, Bidgovagge, Maybrun). This is a feature which is also typical of Besshi-type deposits, but which is rare in Cyprus- and Kuroko-type ores. The latter two, in contrast, often contain ore-horizon sulphate (Rona, 1984, Constantinou, 1980).

It is tempting to appeal to the differing chemical characteristics of orogenic and anorogenic basalt to explain this phenomenon, as well as the inclination to gold- and nickel-enrichment apparent for "Corbet-type" ores. For example, geologically young IAB are known to have significantly higher contents of CO_2 (up to 0.44 wt.%) and Cl (up to 0.24 wt.%), as well as higher H_2O and F than N-MORB (Perfit et al., 1980; Haggerty, 1980). These volatile species are known to enhance the mobility of Au, as well as Ni, during metasomatism (e.g., Haggerty, 1973; Kerrich and Fyfe, 1981).

Fluid history may have also had an influence on the different ore horizon lithologies. For example, rock-dominated hydrothermal systems, involving basalt-seawater interaction, are known to be characterized by significant Ca-mobilization and by relatively complete SO_4^{2-} reduction (Mottle and Holland, 1978; Hajash and Archer, 1980). Research may show that "Corbet type" deposits form from mineralizing fluids having lower water-rock ratios than is the case for Cyprus-type deposits.

IAB-like rocks are common in the Precambrian (e.g., Jahn, 1974; Condie and Baragar, 1974), and this suggests that Corbet-type deposits may also be relatively abundant. However, ancient magnesian and Fe-rich tholeiites in some ways analogous to oceanic basalt are also known (e.g., Ludden and Gelinas, 1982) and, by analogy with their younger equivalents, should also contain volcanogenic sulphide deposits.

The Potter mine near Timmins, from which 500,000 tons of Cu-Zn ore were extracted between 1967 and 1972, may be one such example of an Archean Cyprus-type deposit (Coad, 1976). The mine occurs in a sequence of low-K tholeiitic basalts and komatiites which make up Naldrett and Smith's (1980) "picrite-tholeiite" series, and which are underlain by a body of differentiated gabbro-peridotite (Figure 15). The host tholeiites fall in the field of oceanic basalt on Pierce's (1976) major element discriminant diagram, and are also similar to N-MORB in terms of their high Ni and Cr contents (Figure 16). In contrast with the Cyprus Lower Lavas, however, these tholeiites show moderate LREE enrichment (Naldrett and Smith, 1980), and in this respect, as well as in terms of their tectonic setting, they seem to be closer to intraplate basalts.

The distinctiveness of "Corbet-type" deposits, and the petrogenetic environment in which they occur, has been emphasized. However, it may also be possible to think of these in terms of a metallogenic link between back-arc Cyprus-type deposits and Kuroko-type ores. The close temporal and spatial relationship that exists between Skouriotissa and the Lower Lava-hosted ores on Cyprus may be instructive in this regard, as may be the petrogenetic convergence of some geologically young IAB and BABB (e.g., Lau basin - Gill, 1976; Japan - Masuda and Aoki, 1978), and the possibility that many Kuroko-type deposits may have formed in failed back-arc rifts (e.g., Cathles et al., 1983). A linkage may also exist with basalt-hosted, volcanogenic gold deposits such as Agassiz and Detour Lake.

CONCLUSIONS

It has been shown that "Corbet-type" deposits constitute a class of proximal, volcanogenic ores which, by virtue of their arc-like host rock geochemistry, are distinct from other mafic volcanic-hosted ores, such as Cyprus- and Besshi-type deposits. Their frequent association with mafic pyroclastic rocks, vesicular basalt, and with subordinate fine clastic sediment, all of which are rare in the oceanic environment (Garcia, 1980), provides further discrimination, as does their commonly observed stratigraphic location at the base of arc-like mafic to felsic volcanic sequences. "Corbet-type" deposits are distinguished from other volcanogenic massive base metal sulphide deposits by their apparent inclination to gold enrichment (Table 3).

The abundance of IAB-like rocks in the Shield suggests that deposits of this type could also be relatively abundant in Canada. Moreover, the recent discovery of the large Viscaria deposit suggests that additional "world-class" deposits of this type remain to be found. The 350 M ton Windy Craggy deposit, with its arc-like host basalts, ore-zone calcareous and graphitic argillite, high Co content and local Au enrichment (J. Gammon, pers. comm., 1984) may be another case in point. From all of this, it must be concluded that "Corbet-type" deposits represent an important new exploration opportunity for the Canadian mining industry.

Q JSF-119/ef
Apr 13/84

REFERENCES

Assad, R., and Favini, G., 1980. Previsions de minerai cupro-zincifere dans le nord-ouest Quebecois. Que. Dept. Energy and Resources, DPV-670.

Bischoff, J.L., Rosenbauer, R.J., Aruscavage, P.J., Bardecher, P.A. and Crock, J.G., 1983. Geochemistry and economic potential of massive sulphide deposits from the eastern Pacific Ocean. U.S.G.S. OF-83-224.

Blackburn, C.E., 1980. Towards a mobilist tectonic model for part of the Archean of northwestern Ontario. Geoscience Canada, V. 7, pp. 64-72.

Campbell, I.H., Coad, P., Franklin, J.M., Gorton, M.P., Scott, S.D., Sawa, J. and Thurston, P.C., 1982. Rare earth elements in volcanic rocks associated with Cu-Zn massive sulphide mineralization: A preliminary report. Can. J. Earth Sci., V. 19, pp. 619-623.

Capedri, S., Venturelli, G., Bocchi, G., Dostal, J., Garuti, G. and Rossi, 1980. The geochemistry and petrogenesis of an ophiolitic sequence from Pindos, Greece. Contrib. Mineral Petrol; 74, pp. 189-200.

Cathles, L.M., Guber, A.L., Lenagh, T.C. and Dudas, F.O. (1983). Kuroko-type massive sulphide deposits of Japan: products of an aborted island arc rift. Econ. Geol, Monograph 3, pp. 96-114.

Coad, P.R., 1976. The Potter Mine. M.Sc. thesis, U. of Toronto.

Colley, H., and Greenbaum, D., 1980. The mineral deposits and metallogenesis of the Fiji platform. Econ. Geol. 75, pp. 807-829.

Condie, K.C. and Baragar, W.R.A., 1974. Rare-earth element distributions in volcanic rocks from Archean greenstone belts. Contr. Mineral. and Petrol. 45, pp. 237-246.

Condie, K.C., 1982 Archean andesites. In: Thorpe, R.S. (ed.). Andesites: orogenic andesites and related rocks. J. Wiley and Sons, pp. 505-590.

Constantinou, G. and Govett, G.J.S., 1973. Geology geochemistry and genesis of Cyprus sulphide deposits. Econ. Geol 68, pp. 843-858.

Constantinou, G., 1980. Metallogenesis associated with the Troodos ophiolite.
In: Panayiotou, A. (ed.). Ophiolites: proceedings, International Ophiolite Symposium, Cyprus, 1979. Cyprus Geol. Survey., pp. 663-673.

Davies, J.C., 1973. Geology of the Atikwa Lake area, District of Kenora. O.D.M. GR. 111.

Dimroth, E., Imreh, L, Rocheleau, M. and Goulet, N., 1982. Evolution of the south-central part of the Archean Abitibi Belt, Quebec. I - Stratigraphy and paleogeographic model. Can. J. Earth Sci., V. 19, pp. 1729-1758.

Dixon, T.H. and Batiza, 1979. Petrology and chemistry of recent lavas in the northern Marianas: Implications for the origin of island arc basalts. Contrib. Mineral. Petrol. V. 70, pp. 167,181.

Eguchi, T., 1984. Seismotectonics of the Fiji Plateau and Lau basin. Tectonophysics, pp. 17-32.

Forsell, P., and Godin, L., 1980. Geology of the Kiruna area. 26th I.G.C., Guidebook for Excursion, 78 A+C, pp. 13-20.

Fox, J.S., 1984. Besshi-type volcanogenic sulphide deposits - a review. C.I.M.M. bull., (in press).

Froese, E., 1969. General geology of the Coronation mine area.
In: Byers, A.R. (ed.), Symposium on the geology of the Coronation mine, Saskatchewan. Geol. Surv. Canada, pap. 68-5, pp. 7-35.

Gaal, G., Mikkola, A., and Soderholm, B., 1978. Evolution of the Archean crust in Finland. Precam. Res., V.6, pp. 199-215.

Gair, J.E. and Slack, J.F., 1983. Deformation, geochemistry and origin of massive sulphide deposits, Gossan lead district, Virginia.
In: Programs and abstracts, symposium on stratabound sulphides of the Appalachian-Caledonian orogenic, Ottawa, Sept. 1983, Project 60, p. 15.

Garcia, M.O., 1979. Criteria for the identification of ancient volcanic arcs. Earth-Sci. Rev., V. 14, pp. 147-165.

Gelinas, L., Trudel, P. and Hebert, C., 1984. Chemostratigraphic division of the Blake River Group, Rouyn-Noranda area, Abitibi, Quebec. Can. J. Earth Sci., V. 21, pp. 220-231.

Gill, J.B., 1970. Geochemistry of Viti Levu, Fiji and its evolution as an island arc. Contr. Mineral and Petrol, V. 27, pp. 179-203.

Gill, J.B., 1976. Composition and age of Lau basin and ridge volcanic rocks: Implications for evolution of an interarc basin and remnant arc. Geol. Soc. Am. bull., V. 87, pp. 1384-1895.

Hagen, L., 1982. The Bidjovagge copper-gold deposits of western Finnmark, Norway. Geol. Rundsch. 71, pp. 94-103.

Haggerty, S.E., 1980. Volatiles in planetary basalts: Hydrogen, carbon and sulphur gas species.
In: Basalt volcanism study project. Pergamon Press, pp. 385-398.

Hajash, A. and Archer, P., 1980. Experimental seawater/basalt interactions: Effects of cooling. Contrib. Mineral. Petrol., V. 75, pp. 1-13.

Hanson, G.N., 1980. Rare earth elements in petrogenetic studies of igneous systems. Ann. Rev. Earth Planet. Sci., V. 8, pp. 371-406.

Haskin, L.A., 1979. On rare-earth element behaviour in igneous rocks.
In: Ahrens, L.H. (ed.). Origin and distribution of the elements. Pergamon Press, pp. 175-189.

Hawkins, J.W., 1980. Petrology of back-arc basins and island arcs: Their possible role in the origin of ophiolites.
In: Panayiotou, A. (ed.). Ophiolites: Proceedings, International Ophiolite Symposium, Cyprus, 1979. Cyprus Geol. Surv., pp. 244-254.

Hollander, N.B., 1979. The geology of the Bidjovagge mining field, western Finnmark, Norway. Geol. Tidsskrift, V. sa., pp. 327-336.

Inkinen, O., 1979. Copper, zinc and uranium occurrences at Pahtavuoma in the Kittila Greenstone Complex, northern Finland. Econ. Geol. 74, pp. 1153-1165.

Jahn, B., Shih, C. and Murthy, V.R., 1974. Trace element geochemistry of Archean volcanic rocks. Geochem. Cosmochem Acta. V. 38, pp. 611-627.

Kahkonen, Y., Makela, K., and Rosenberg, R.J., 1981. Rare earth elements in Proterozoic metabasalts and associated volcanic sulphide ore from Haveri, south-western Finland. Bull. Geol. Soc. Finland, V. 53, pp. 11-16.

Kay, R.W. and Hubbard, W.J., 1978. Trace elements in ocean ridge basalts. Earth and Planet. Sci. Lett., V. 38, pp. 95-116.

Kay, R.W. and Senechal, R.G., 1976. The rare earth geochemistry of the Troodos ophiolite complex. J. Geophys. Res., V. 81, pp. 964-970.

Kerrich, R. and Fyfe, W.S., 1981. The gold-carbonate association: The source of CO_2 and CO_2 fixation reactions in Archean lode deposits. Chem. Geol,, V. 33, pp. 27-65.

Knuckey, M.J., and Watkins, J.V., 1982. The geology of the Corbet massive sulphide deposit, Noranda district, Quebec, Canada.
In: Hutchinson, R.W. (ed.) et al., Precambrian Sulphide deposits. Geol. Assoc. Canada Spec. Paper 25, pp. 297-317.

Langford, F.F. and Morin, J.A., 1976. The development of the Superior Province of northwestern Ontario by merging island arcs. Am. J. Sci., V. 276, pp. 1023-1034.

Larson, J.E., 1983. Geology, geochemistry and wall-rock alteration at the Magusi and New Insco massive sulphide deposits, Hebecourt Township, Northwestern Quebec, M.Sc. thesis, Univ. of Western Ontario, 171 p.

Lawrence, L.J., and Savage, E.N., 1976. Ore genesis in the Wainivesi area, Fiji and some exploration implications. Proc. Australas, I.M.M., no. 260, pp. 59-70.

Lawrence, L.J., and Wood, B.L., 1980. Mineralization, petrogenesis and tectonic evolution of Fiji.
In: Ridge, J.D. (ed.). Proc. 5th IAGOD symp., Stuttgart, pp. 377-387.

Ludden, J. and Gelinas, L., 1982. Archean metavolcanics from the Rouyn-Noranda district, Abitibi greenstone belt, Quebec, II - Mobility of trace elements and petrogenetic constraints. Can. J. Earth Sci., V. 19, pp. 2276-2287.

Lundberg, B., and Smellie, J.A.T., 1979. Painirova and Mertainen iron ores: Two deposits of the Kirura iron ore type in northern Sweden. Econ. Geol. 74, pp. 1131-1152.

Makela, K., 1980. Geochemistry and origin of Haveri and Kiipu, Proterozoic stratabound volcanogenic gold-copper and zinc mineralizations from southwestern Finland. Geol. Surv. Finland, Bull. 310.

Masuda, Y. and Aoki, K., 1978. Two types of island arc tholeiite in Japan. Earth and Plan. Sci. Lett., V. 39, pp. 298-302.

Mining Magazine, 1983. Viscaria - a new copper mine in northern Sweden. Mining Mag., October, pp. 225-233.

Mottl, M.J. and Holland, H.D., 1978. Chemical exchange during hydrothermal alteration of basalt by seawater: I. Experimental results for major and minor components of seawater. Geochem. Cosmochem. Acta V. 42, pp. 1103-1115.

Naldrett, A.J. and Smith, I.E.M., 1980. Mafic and ultramafic volcanism during the Archean. In: Basaltic volcanism study project. Pergamon Press, pp. 5-29.

Normark, W.R., Morton, J.L. and Delaney, J.R., 1982. Geological setting of massive sulphide deposits and hydrothermal vents along the southern Juan de Fuca ridge. U.S.G.S. OF-82-200A.

Perfit, M.R., Gust, D.A., Bence, A.E., Arculus, R.J. and Taylor, S.R.., 1980. Chemical characteristics of island arc basalts; implications for mantle sources. Chem. Geol. 30, pp. 227-256.

Philpotts, J.A., Martin, W. and Schnetzler, C.C., 1971. Geochemical aspects of some Japanese lavas. Earth and Planet. Sci. Lett., V. 12, pp. 89-96.

Pierce, J.A., 1975. Basalt geochemistry used to investigate past tectonic environments on Cyprus. Tectonophysics, V. 25, pp. 41-67.

Pierce, J.A., 1976. Statistical analysis of major element patterns in basalt. J. Petrol, 17, pp. 15-43.

Pierce, J.A., and Cann, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analysis. Earth and Plan. Sci. Lett. V. 19, pp. 290-300.

Rhodes, J.M. and Bence, A.E., 1980. Ocean-floor basaltic volcanism.
In: Basaltic volcanism study project. Pergamon Press, pp. 132-160.

Rona, P.A., 1984. Hydrothermal mineralization at seafloor spreading centres. Earth-Sci. Rev., V. 20, pp 1-104.

Saunders, A.D., 1984. The rare earth element characteristics of igneous rocks from the ocean basins.
In: Henderson, P. (ed.). Rare earth element geochemistry. Elsevier, pp. 205-236.

Scheidigger, K.F. and Corliss, J.B., 1981. Petrogenesis and secondary alteration of upper layer 2 and basalts of the Nazca plate.
In: Kuhn et al. (eds.) Nazca Plate: Crustal formation and Andean Convergence. Geol. Soc. Am., mem. 154, pp. 77-107.

Schilling, J.G., 1971. Sea-floor evolution: rare-earth evidence. Phil. Trans. Roy. Soc. Lond., A268, pp. 663-706.

Setterfield, T., Watkinson, D.H., and Thurston, P.C., 1983. Quench-textured pillowed metabasalts and copper mineralization, Maybrun mine, northwestern Ontario. Bull. C.I.M.M., V. 76, no. 859, pp. 69-74.

Setterfield, T.N., 1980. Petrology and chemistry of pillowed metabasalts and their copper mineralization, Maybrun mine, Ontario. B.Sc. Thesis, Carleton Univ. 52 p.

Shimazake, Y., 1974. Ore minerals of the Kuroko deposits.
In: Soc. Mining Geol. Japan, Spec. Issue 6, pp. 311-322.

Slack, J.F., 1983. Lithogeochemical setting of the massive sulphide deposits of the Elizabeth mine, Vermont.
In: Programs and abstracts, Symposium on stratabound sulphides in the Appalachain-Caledonian orogen. Ottawa, Sept. 1983. IGCP Project 60, p. 25.

Smewing, J.C., Cimonian, K.O. and Gass, I.G., 1975. Metabasalts from the Troodos massif, Cyprus: Genetic implications deduced from petrography and trace elements geochemistry. Contrib. Mineral. Petrol., V. 51, pp. 49-64.

Spence, C.D., and de Rosen-Spence, A.F., 1975. The place of sulphide mineralization in the volcanic sequence at Noranda, Quebec. Econ. Geol. 70, pp.90-101.

Taylor, S.R., Arculus, R. and Perfit, M.R., 1980. Island arc basalts.
In: Basaltic volcanism study project. Pergamon Press, pp. 193-213.

Trowell, N.F., Blackburn, C.E., and Edwards, G.R., 1980. Preliminary geological synthesis of the Savant Lake-Crow Lake metavolcanic-metasedimentary belt. O.D.M. MP. 89.

Watkins, J.J., 1980. The geology of the Corbet Cu-Zn deposit and the environment of ore deposition in the central Noranda area. M.Sc. Thesis, Queen's Univ.

Whitmore, D.R.E., 1969. Geology of the Coronation Copper Deposit.
In: Byers, A.R. (ed.). Symposium on the geology of the Coronation mine, Saskatchewan, G.S.C. pap. 68-5, pp. 37-54.

Yamaoka, K., 1962. Studies on the bedded cupriferous iron sulphide deposits occuring in the Sanbagawa metomorphic zone. Sec. Rept. Tohoku, Univ., V. 8, pp. 1-68.

Q JSF-119

FIGURES

1. Geology of the Noranda region, after Spence and de Rosen-Spence (1975).

2. Schematic cross section through the Blake River Group in the Noranda area, showing the stratigraphic location of the Corbet deposit with respect to the other volcanogenic sulphide deposits in the region (from Knuckey and Watkins, 1982).

3. Schematic cross section through the Corbet deposit (from Knuckey and Watkins, 1982).

4. Geology of the Atikwa Lake region, northwestern Ontario (simplified from Trowell et al., 1980).

5. Geological plan of the Maybrun deposit (from H. Matthews, pers. comm. 1984).

6. Geology of the Kiruna-Viscaria region (from L. Godin, pers. comm., 1983).

7. Geology of northern Scandinavia, showing the location of the Kiruna and Kittila greenstone belts (from Hagen (1982).

8. Schematic cross section through the Viscaria deposit (from L. Godin, pers. comm., 1983).

9. Geochemical variation diagrams for the Corbet, Maybrun and Viscaria host basalts and basaltic andesites.

   a), b) Pierce's (1976) major element discriminant diagrams, where:

   $F_1 = +0.088\ SiO_2 - 0.0774\ TiO_2 + 0.0102\ Al_2O_3 + 0.0066\ FeO - 0.0017\ MgO - 0.0143\ CaO - 0.0155\ Na_2O - 0.007\ K_2O$;

   $F_2 = -0.0130\ SiO_2 - 0.185\ TiO_2 - 0.0129\ Al_2O_3 - 0.0134\ FeO - 0.0300\ MgO - 0.0204\ CaO - 0.0481\ Na_2O + 0.0715\ K_2O$; and

   $F_3 = -0.0221\ SiO_2 - 0.0532\ TiO_2 - 0.0362\ Al_2O_3 - 0.0016\ FeO - 0.0310\ MgO - 0.0237\ CaO - 0.0614\ Na_2O - 0.0289\ K_2O$

   OFB = ocean floor basalt, LKT = low-K tholeiite,
   CAB = calc-alkali basalt, SHO - shoshonite,
   WPB = within plate basalt

   c), d) Pierce and Cann's 1973) Zr-Y and Ti-Zr discriminant diagrams.

10. Ti-Cr, Ni-Y and Ti-$(Ba/La)_{CH}$ geochemical variation diagrams (Pierce, 1975; Perfit et al., 1980), for the host basalts from Corbet, Maybrun and Viscaria.

11. Chondrite normalized rare earth element abundance diagrams for the Corbet, Maybrun and Viscaria basalts. The shaded area corresponds to Taylor et al.'s (1980) island arc basalt reference suite.

12. Chondrite-normalized rare earth element abundance diagrams for "normal" oceanic basalt, in which most of the active mineralizing systems on the East Pacific rise are found, for the Lower Lavas on Cyprus and for basalts hosting two Besshi-type ores.

13. Geology of Viti Levu, Fiji (after Gill, 1970).

14. Geochemical variation diagrams for the island arc basalts of the Wainimala Group, Fiji (data from Gill, 1970).

15. Surface plan of the Potter Mine near Timmins, Ontario (from Coad, 1976).

16. Geochemical variation diagrams for the basalts hosting the Potter ores. The rare earth element data is from Naldrett and Smith (1980).

Q JSF-119

TABLE 1

CORBET-TYPE DEPOSITS

Deposit	Age	Tonnage x 10^6	Cu %	Zn %	Oz/t Ag	Oz/t Au
CANADA						
Corbet	Archean	2.7	3.1	2.8	0.68	0.03
New Hosco (?)	Archean	2.2	1.4	1.1	0.11	0.001
Maybrun	Archean	2.8	1.1			0.08
Coronation	Proterozoic	1.5	4.2			0.05
Cuprus	Proterozoic	0.5	3.3	6.4	0.5	0.02
Windy Craggy (?)	Triassic	350 (approx)	1.5			
SCANDINAVIA						
Viscaria	Archean	50	1.6-5.0	0.3		0.01
Haveri	Proterozoic	1.5	0.4			0.10
Bidjovagge	Archean	3	1.8	0.1	0.5	0.04-0.13
Pahtavuoma	Archean	4.4	1.0	0.1	0.63	0.02
AUSTRALIA						
Cadia (?)	Ordovician	43	0.7		0.20	0.02

Q JSF-119

TABLE 2

METAL CONTENTS OF VOLCANOGENIC MASSIVE SULPHIDE ORES

Deposit Type	Au	Ni	Co
"Corbet"[1]	1.8 ± 1.0	393 ± 300	445 ± 300
Besshi[2]	0.5 ± .3	27 ± ?	530 ± ?
Cyprus (oceanic)[3]	0.09 ± .04	11 ± 10	500 ± 25
Cyprus (back-arc)[4]	-	53 ± 25	57 ± 25
Kuroko (Canada)[5]	0.5 ± .5	-	-
Kuroko (Japan)[6]	1.1 ± 0.5	20 ± 10	25 ± 10

(1) Corbet, Viscaria, Maybrun, Pahtayuoma, Bidjovagge, Coronation, Haveri (Fox, unpubl.; Makela, 1980; Inkenen, 1979; Whitmore, 1969)

(2) Fifteen Sanbagawa belt mines, including Besshi (Yamaoka, 1962)

(3) EPR, Atlantis II Deep, Red Sea (Rona, 1984; Bischoff et al., 1983; Scott, per comm 1983)

(4) Mathiati, Agokipian, Kokkinoyia (Constantinou and Govett, 1973)

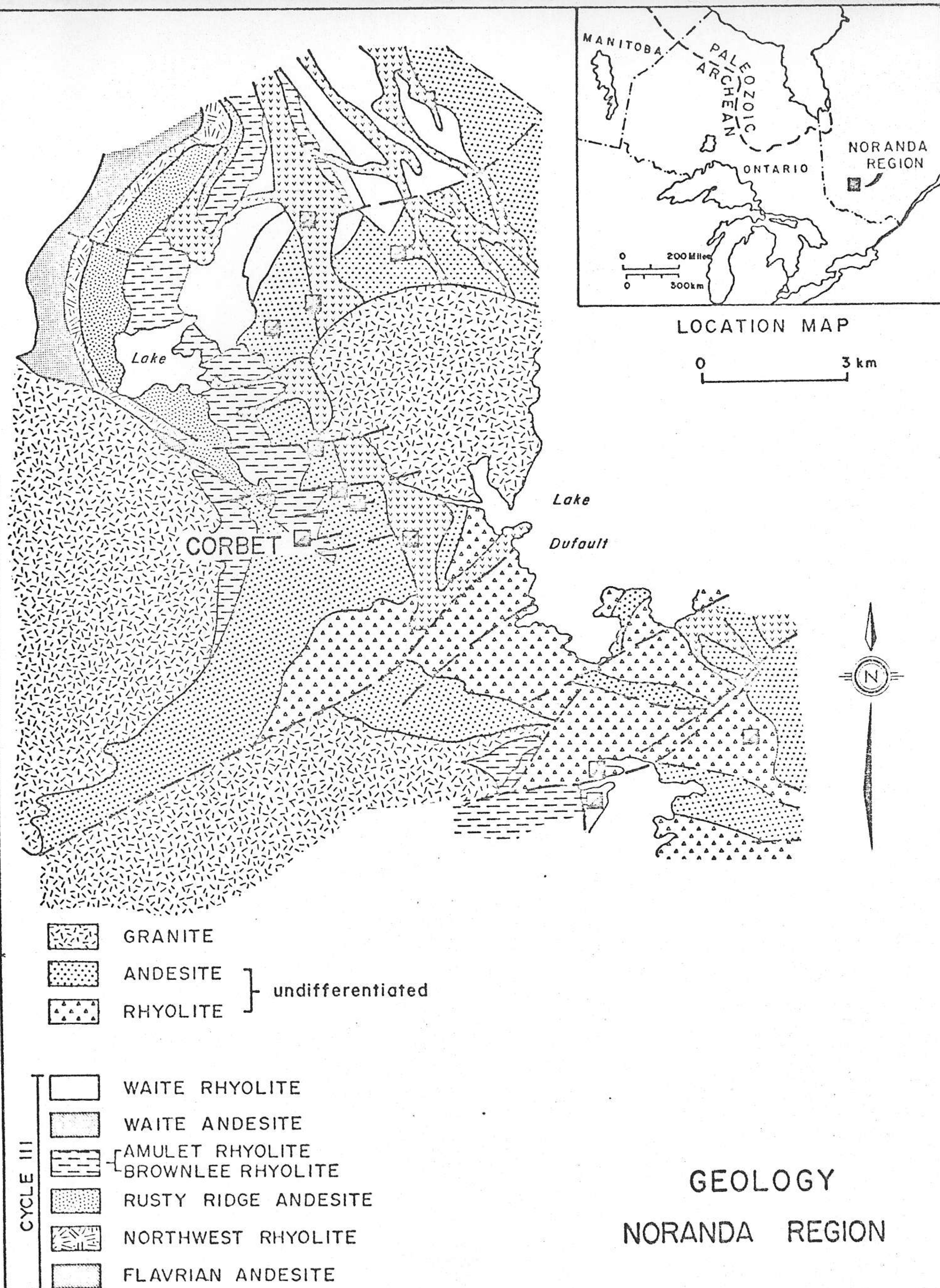
(5) 72 deposits (Assad and Favini, 1980)

(6) Kosaka, Hanoka, Kano (Shimazaki, 1974)

TABLE 3

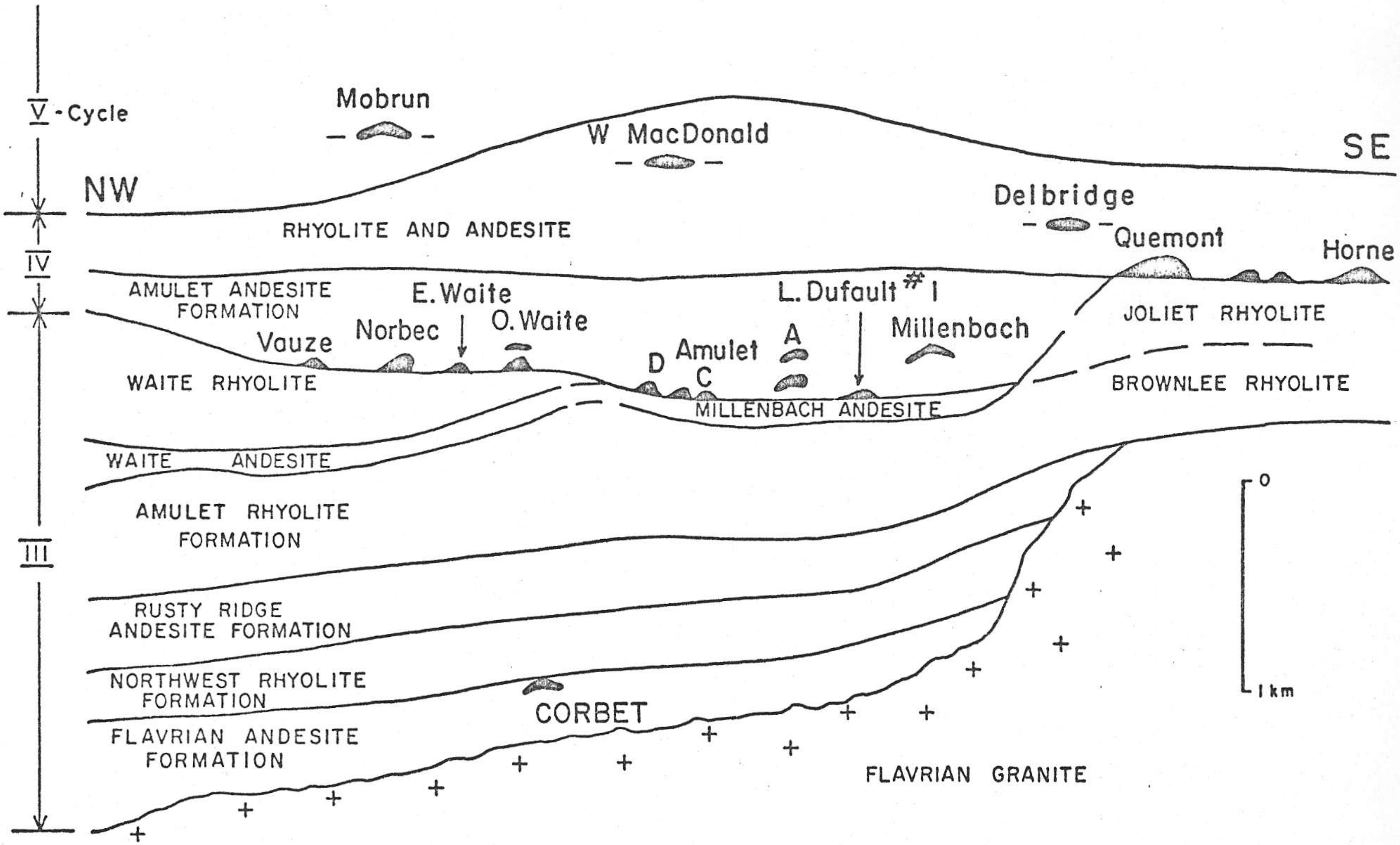
CHARACTERISTICS OF BASALT-HOSTED VOLCANOGENIC DEPOSITS

	Besshi-type	"Corbet-type"	Cyprus-type
Possible environment	Epicontinental rift	Early arc	Oceanic, back-arc rifts
Host rocks	T-MORB, IPB(?) continent-derived sed.	IAB volcanogenic sed.	N-MORB, T-MORB(?)
Tenor	Cu-Zn (±Co)	Cu-Zn-Au (±Co, Ni)	Cu-Zn (±Co)
Accessory ore horizon lithologies	Iron fmn., limestone, argillite	Limestone, argillite	Sulphate
Age range	Proterozoic-recent	Archean-Eocene (?)	Archean?-recent
Recent examples	Guaymas basin	Tholo-i-Suva (?)	EPR-21°N, -20°S, Juan de Fuca, etc.
Ancient examples	Besshi Ducktown Trondheim	Corbet Viscaria Maybrun	Cyprus Betts Cove Potter



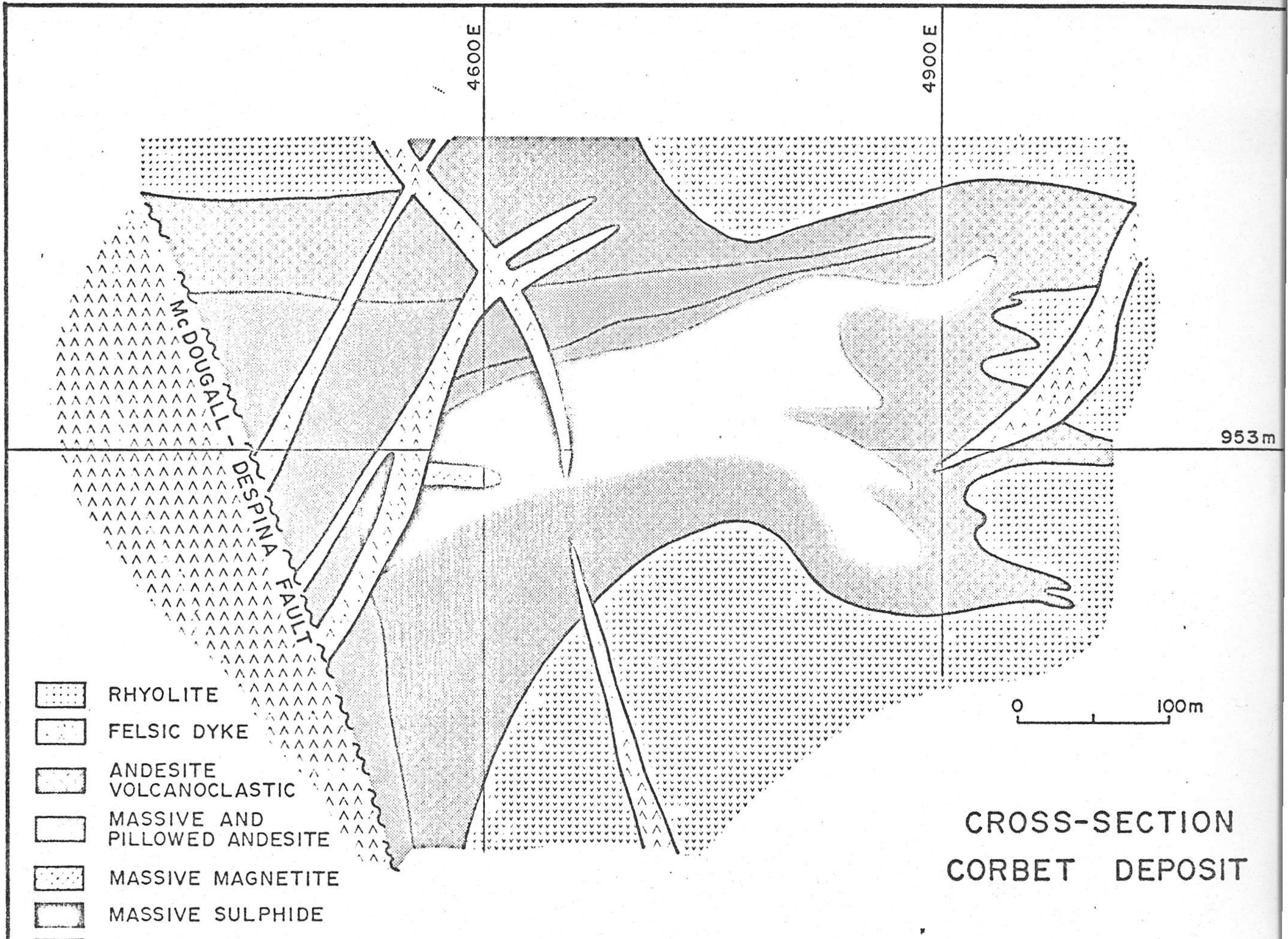
GEOLOGY
NORANDA REGION

(Simplified from Spence and Rosen-Spence, 1975)



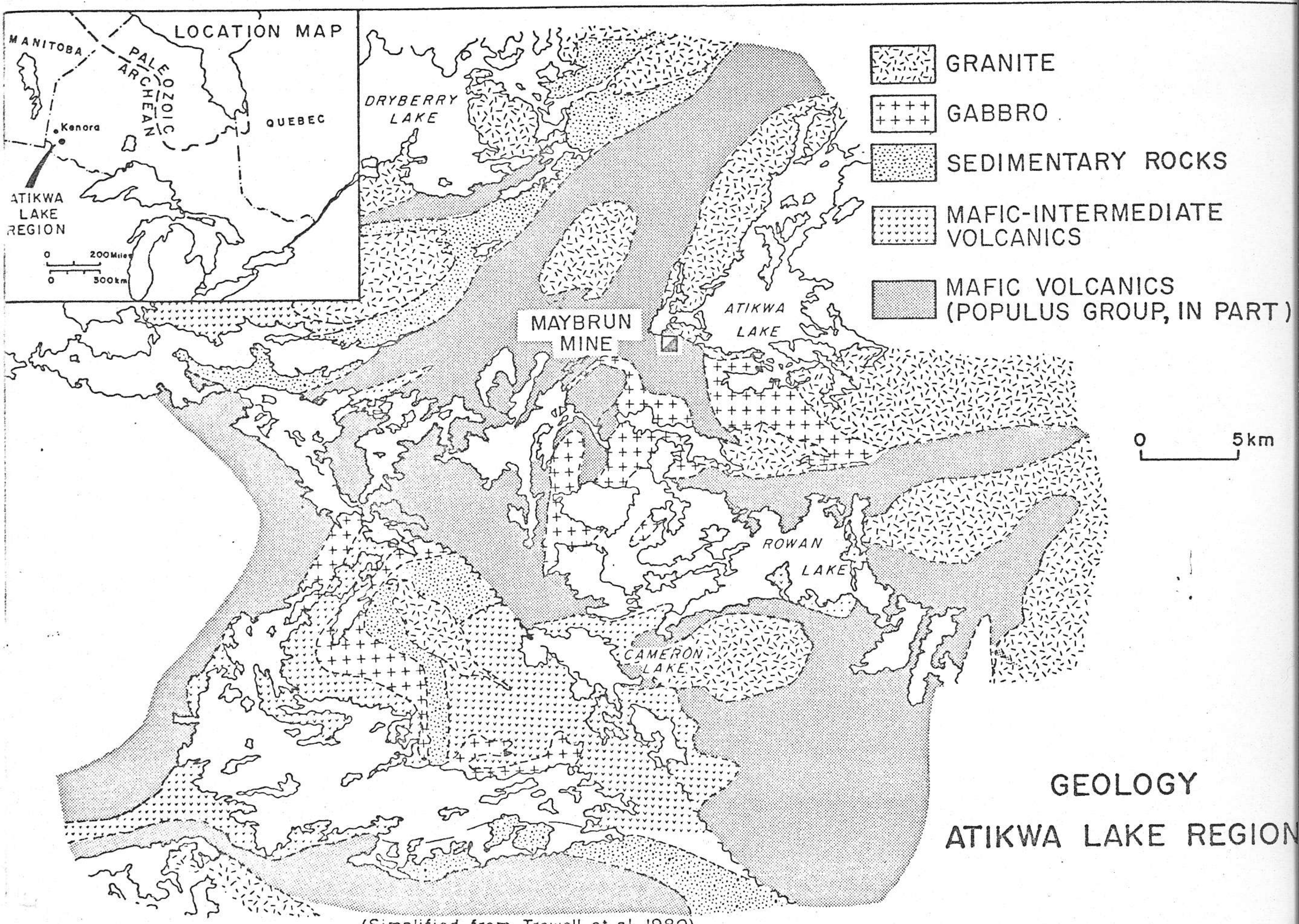
Cross-section, Noranda District, Quebec

(from Knuckey and Watkins, 1982)

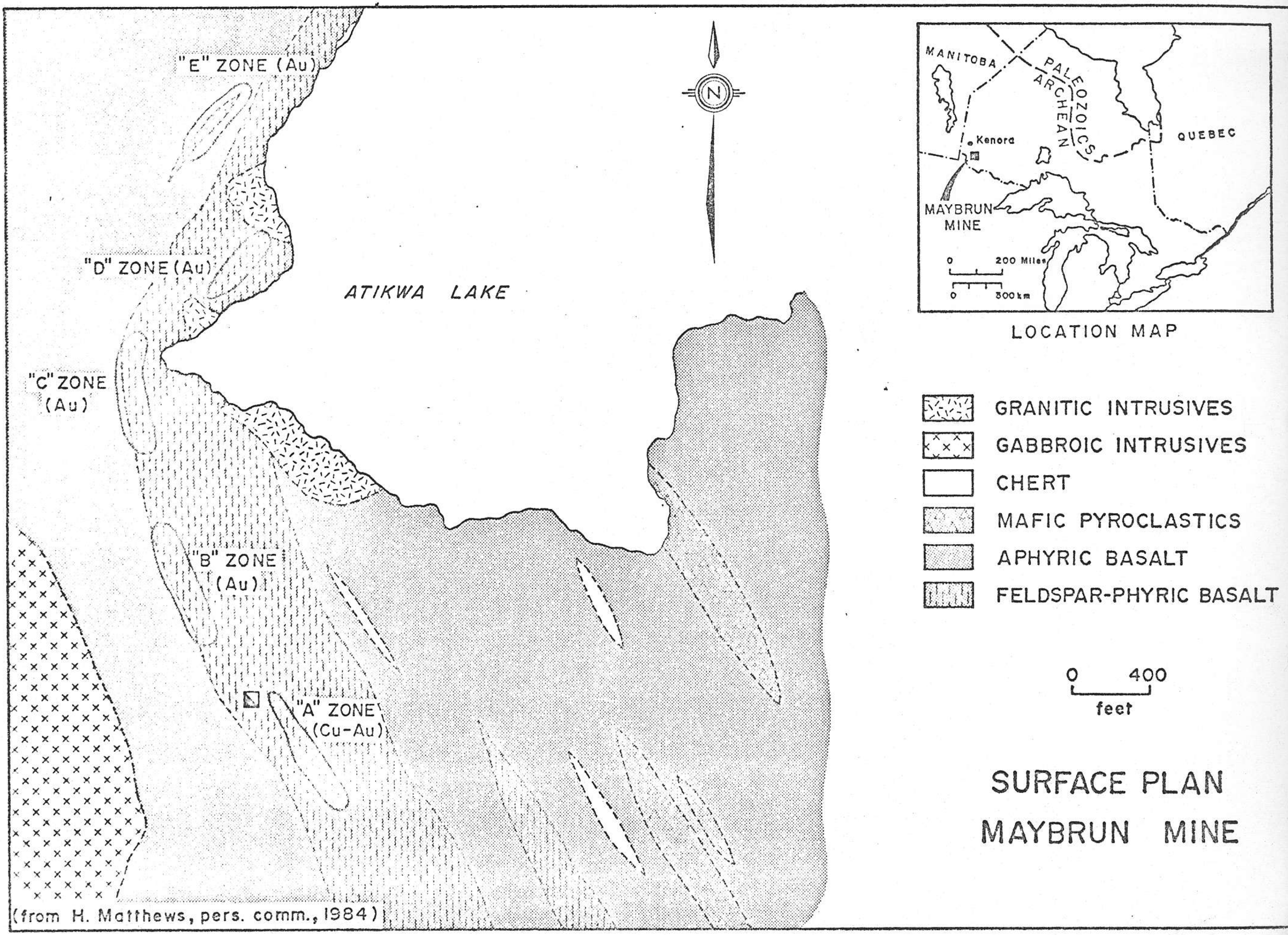


CROSS-SECTION CORBET DEPOSIT

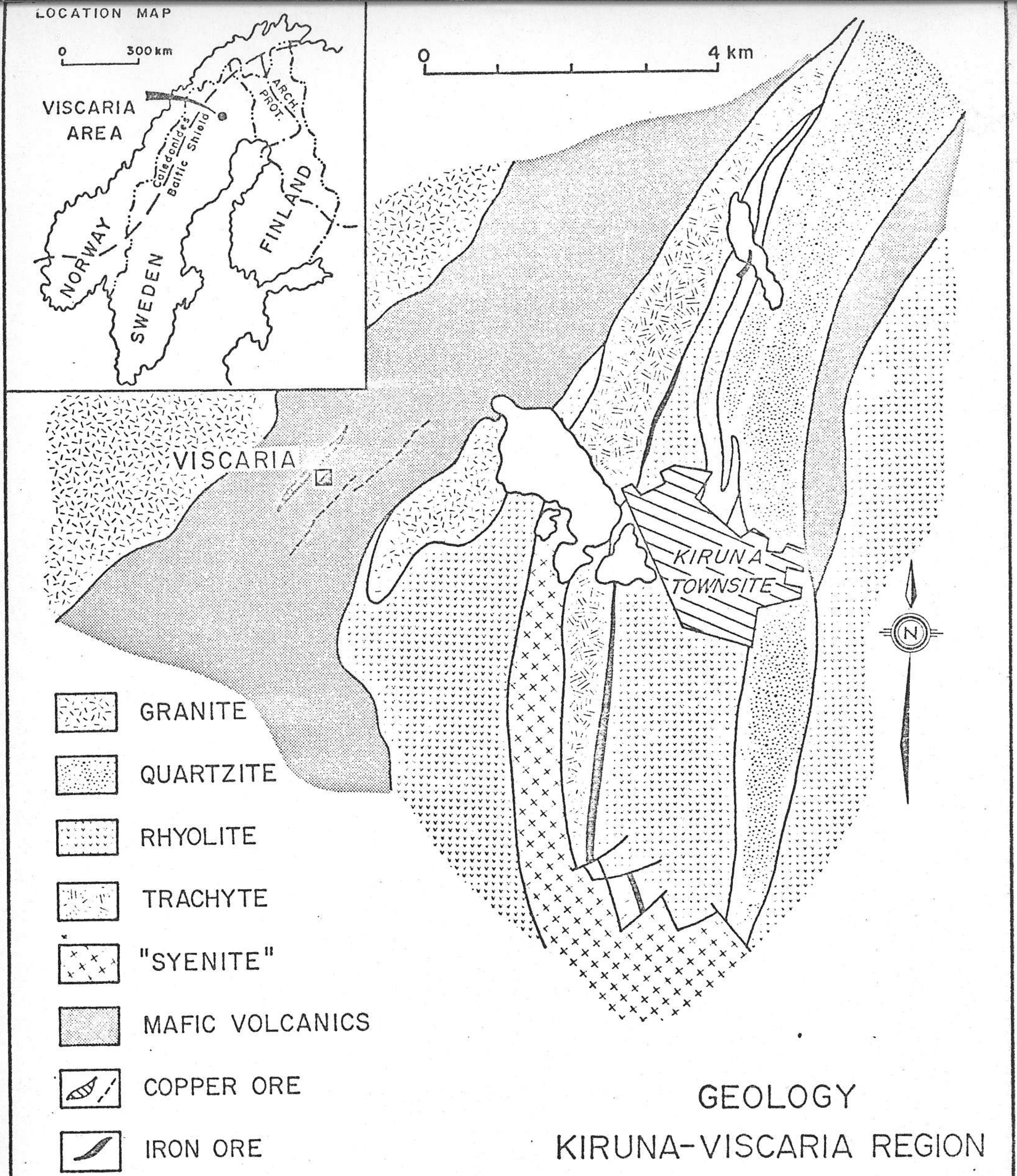
(from Gibson and Watkins, 1982



(Simplified from Trowell, et al, 1980)

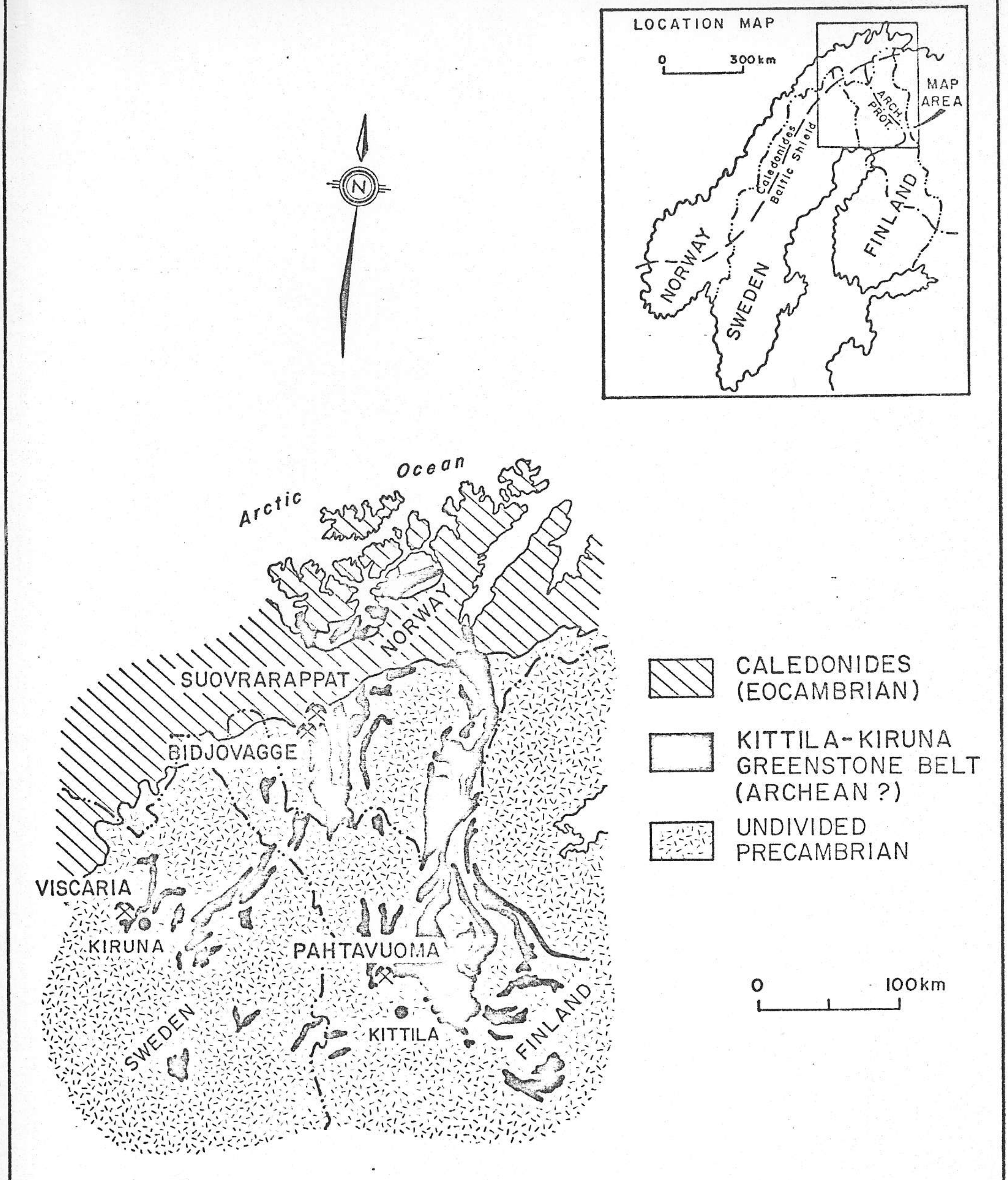


SURFACE PLAN
MAYBRUN MINE

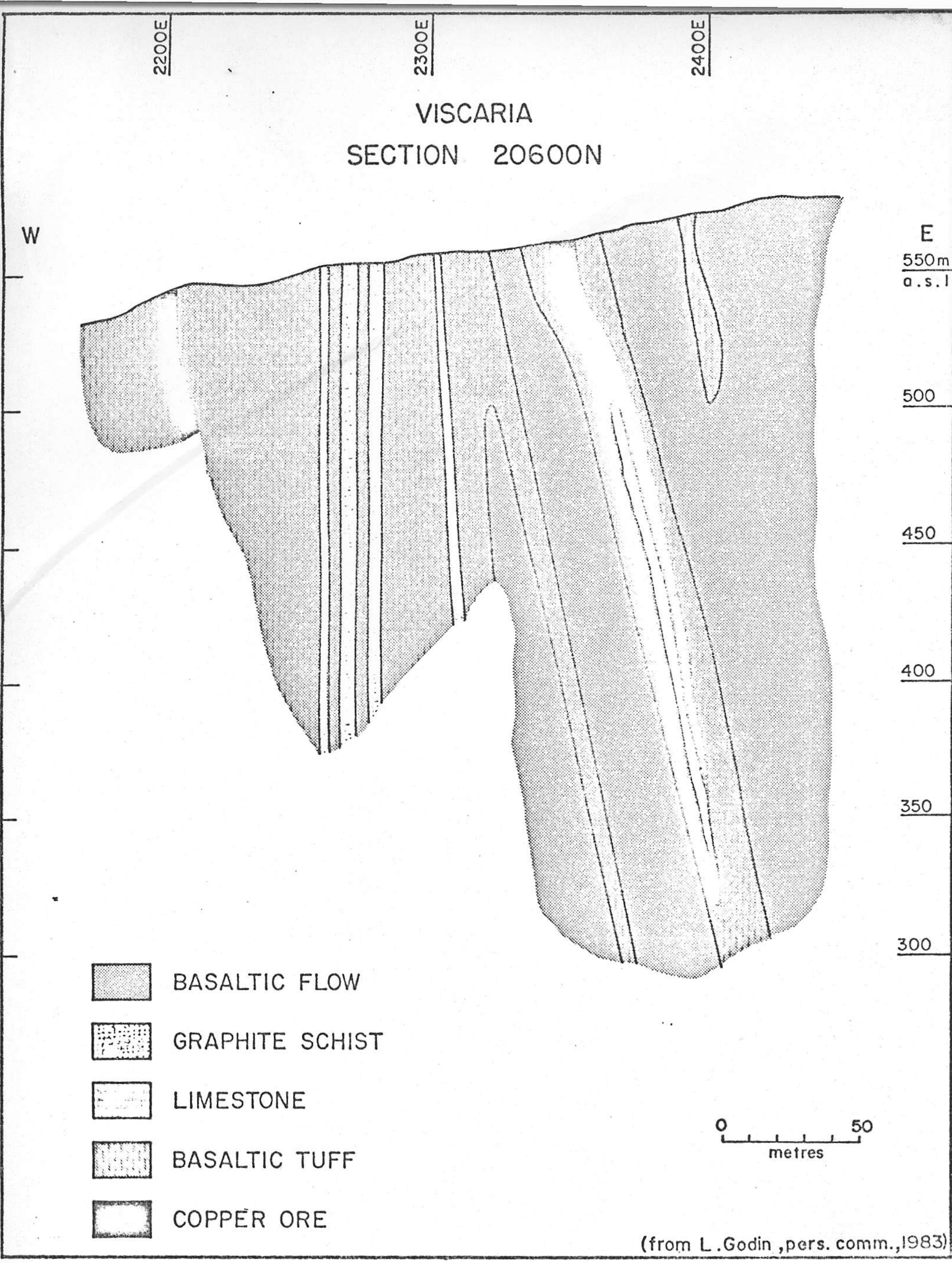


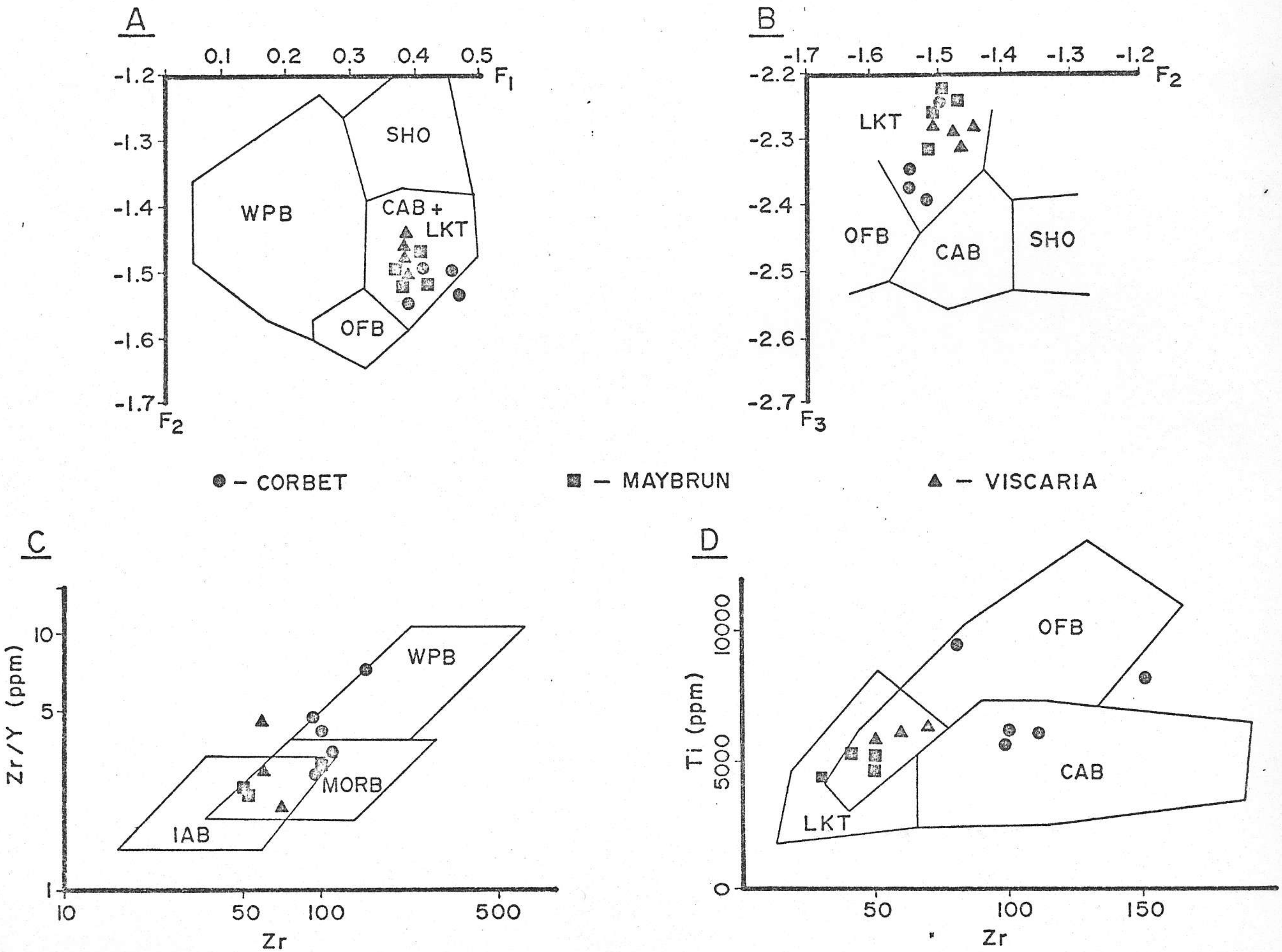
GEOLOGY
KIRUNA-VISCARIA REGION

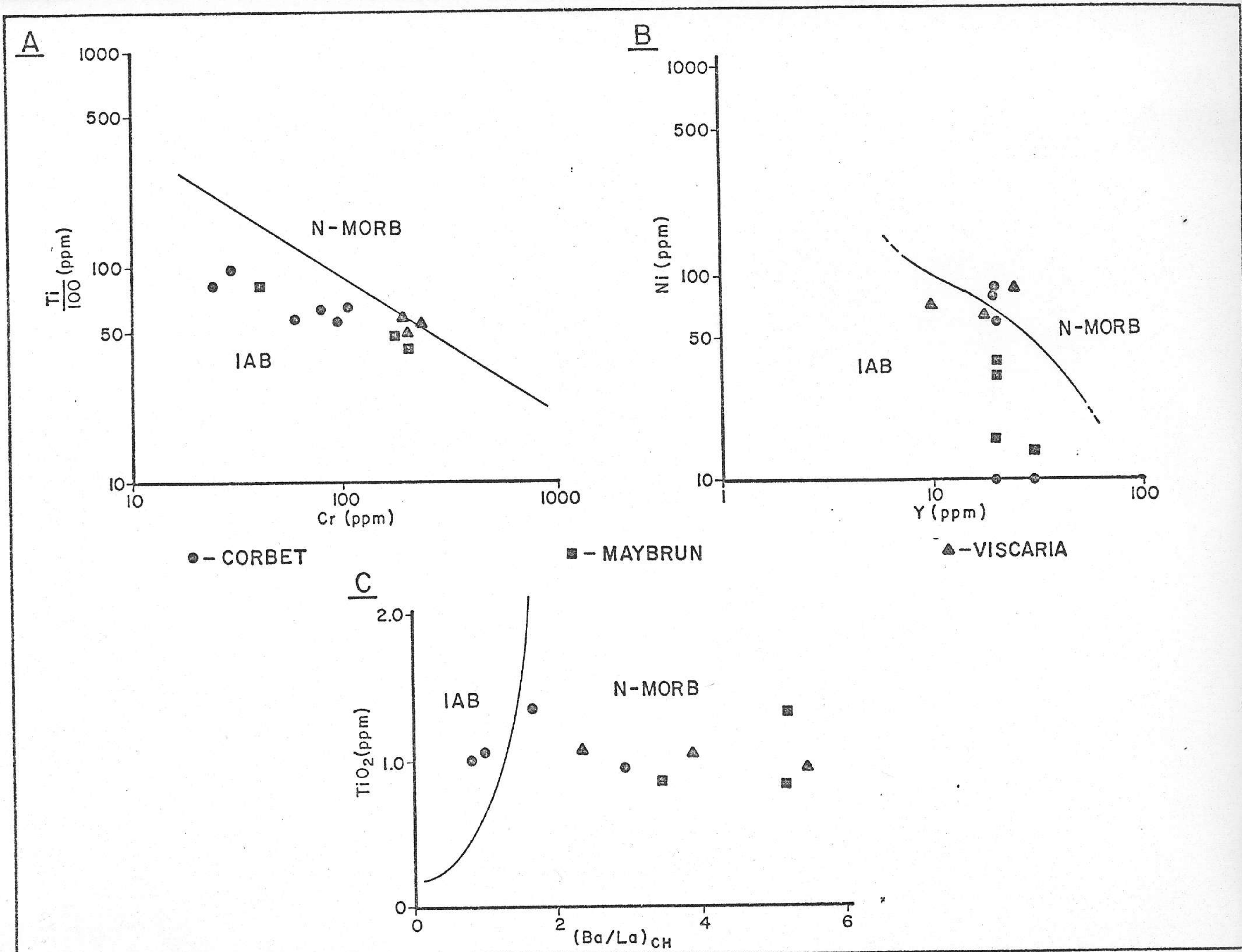
(from L.Godin, pers. comm., 1983)



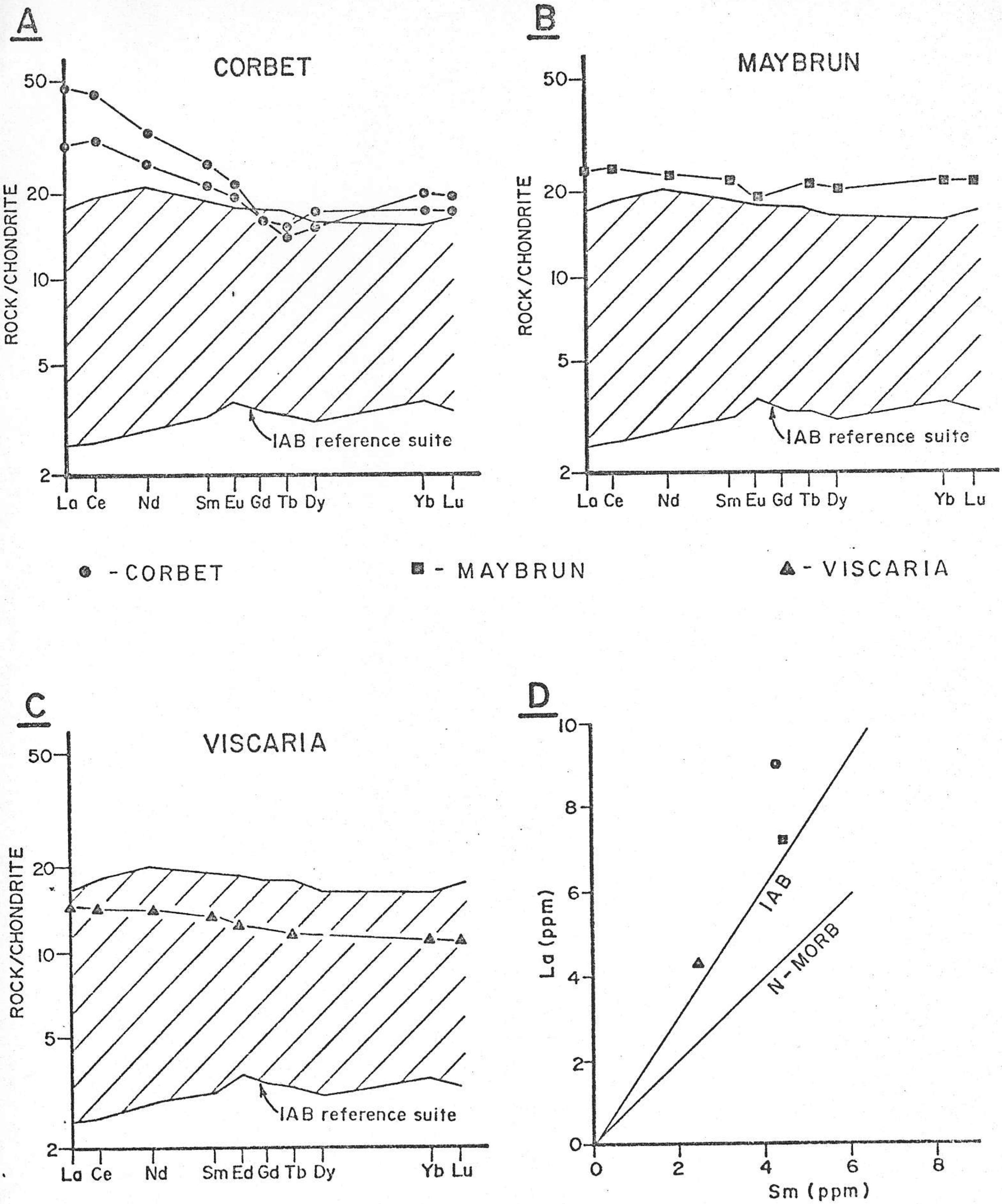
KITTILA-KIRUNA GREENSTONE BELT

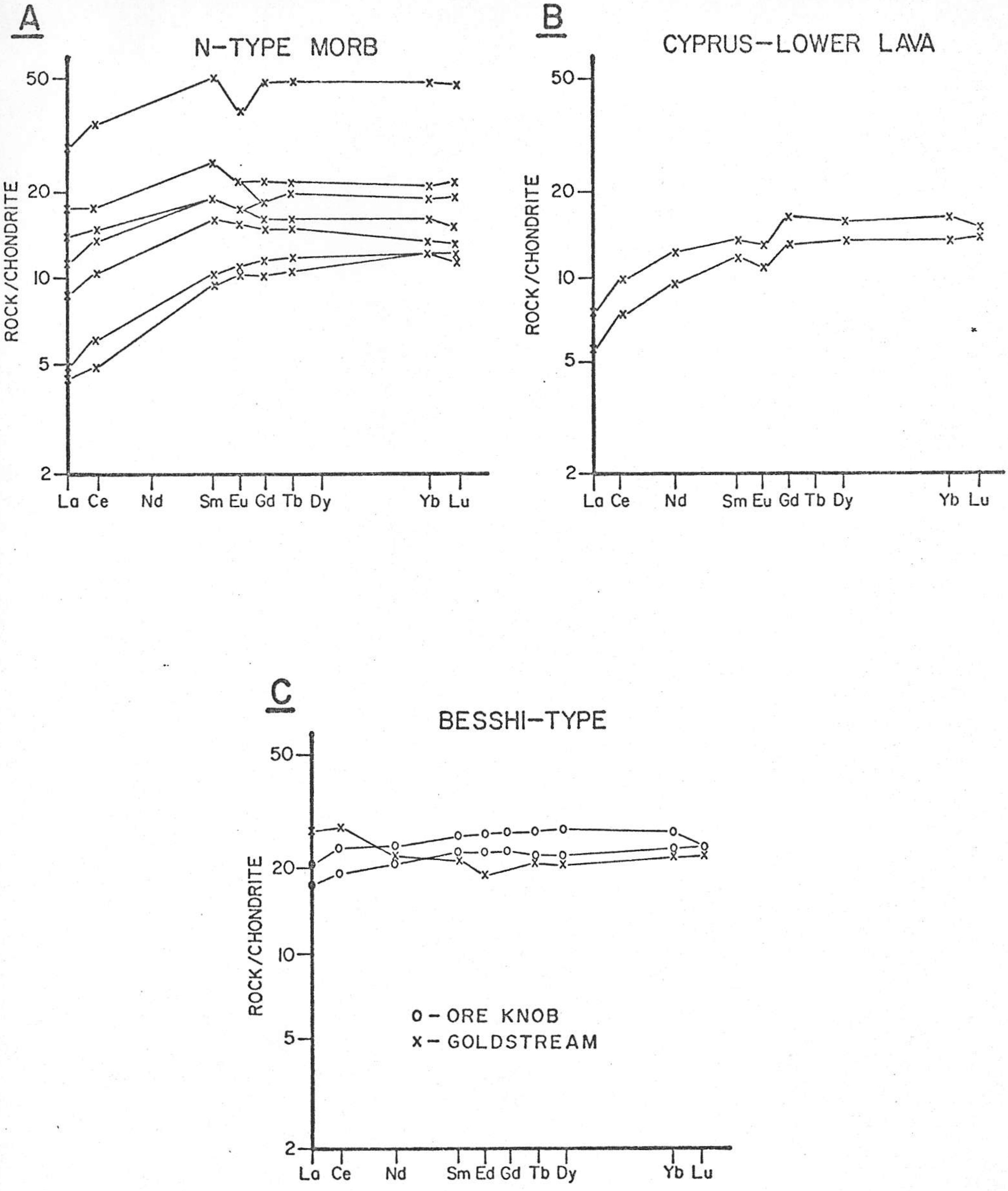

2200E
2300E
2400E
VISCARIA
SECTION 20600N
W
E
550m
a.s.l
500
450
400
350
300
BASALTIC FLOW
GRAPHITE SCHIST
LIMESTONE
BASALTIC TUFF
COPPER ORE
0
50
metres
(from L.Godin, pers. comm., 1983)


A
0.1
0.2
0.3
0.4
0.5
F1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
F2
SHO
WPB
CAB +
LKT
OFB
B
-1.7
-1.6
-1.5
-1.4
-1.3
-1.2
F2
-2.2
-2.3
-2.4
-2.5
-2.6
-2.7
F3
LKT
OFB
CAB
SHO
- CORBET
- MAYBRUN
- VISCARIA
C
Zr/Y (ppm)
10
5
1
10
50
100
500
Zr
WPB
MORB
IAB
D
Ti (ppm)
10000
5000
0
50
100
150
Zr
OFB
CAB
LKT

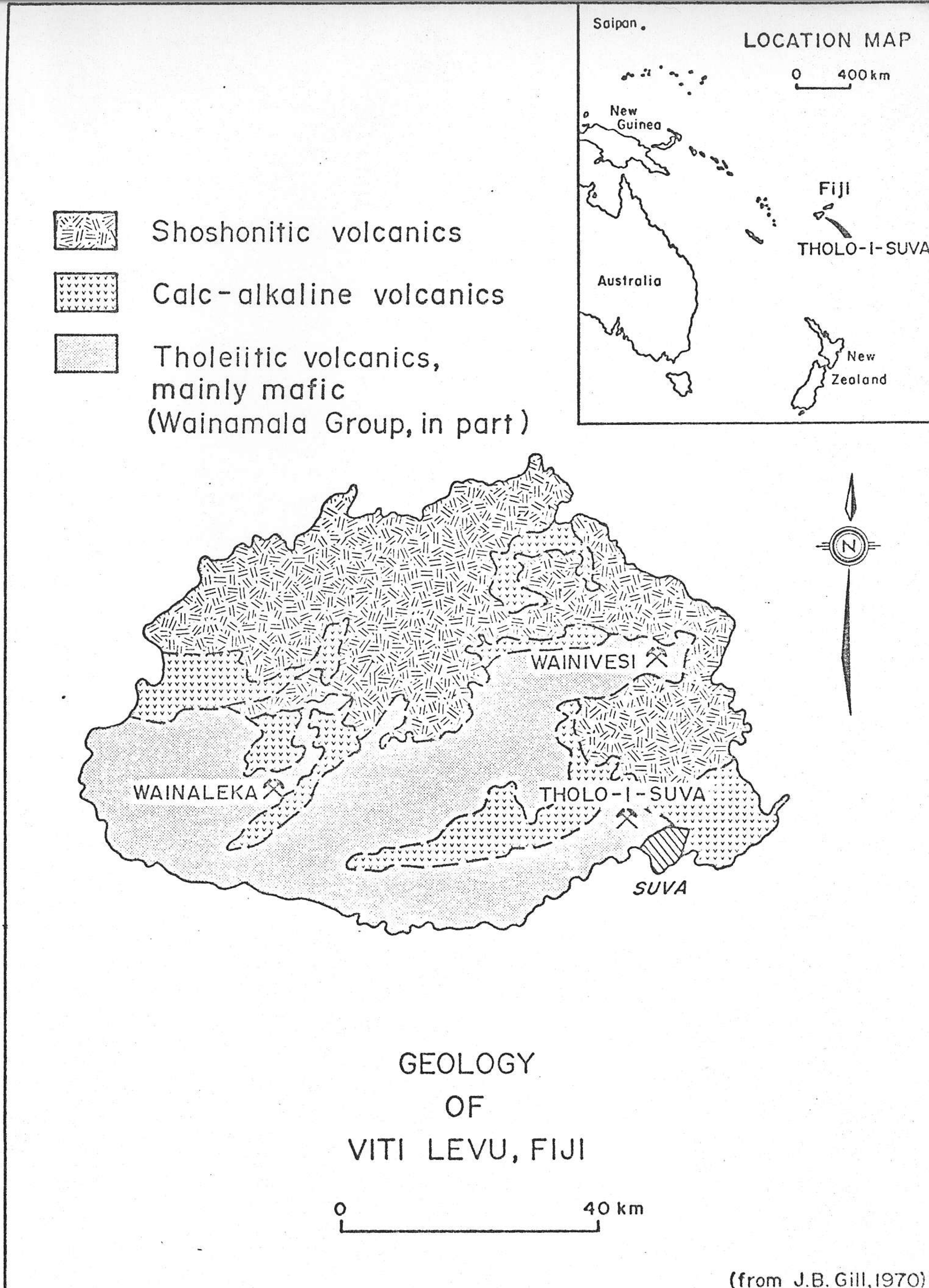


A
1000
500
100
50
10
Ti/100 (ppm)
10
100
1000
Cr (ppm)
N-MORB
IAB
B
1000
500
100
50
10
Ni (ppm)
1
10
100
Y (ppm)
IAB
N-MORB
● - CORBET
■ - MAYBRUN
▲ - VISCARIA
C
2.0
1.0
0
TiO2 (ppm)
0
2
4
6
(Ba/La)CH
IAB
N-MORB

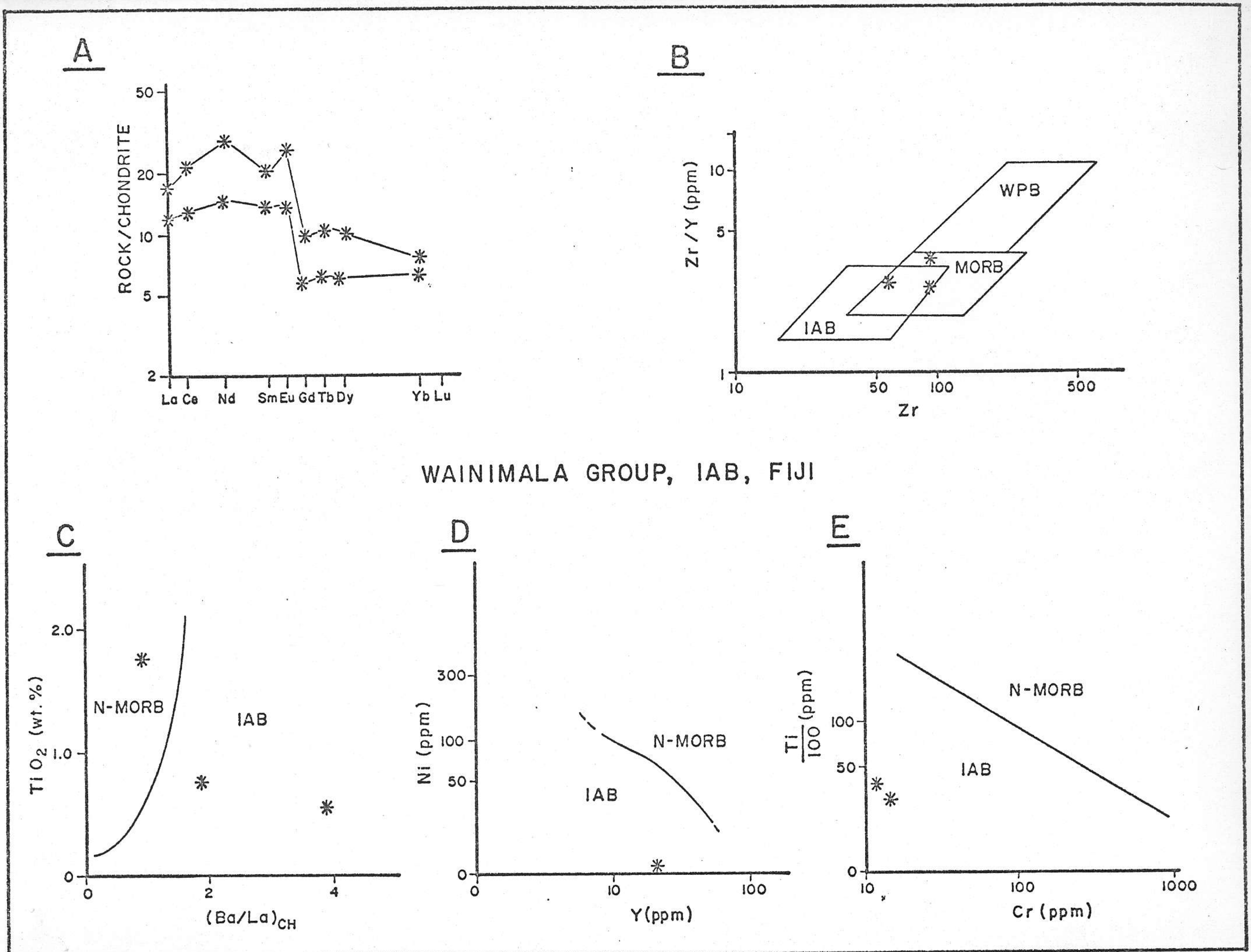

A
CORBET
ROCK/CHONDRITE
50
20
10
5
2
La Ce Nd Sm Eu Gd Tb Dy Yb Lu
IAB reference suite
B
MAYBRUN
ROCK/CHONDRITE
50
20
10
5
2
La Ce Nd Sm Eu Gd Tb Dy Yb Lu
IAB reference suite
- CORBET
- MAYBRUN
- VISCARIA
C
VISCARIA
ROCK/CHONDRITE
50
20
10
5
2
La Ce Nd Sm Ed Gd Tb Dy Yb Lu
IAB reference suite
D
La (ppm)
10
8
6
4
2
0
IAB
N-MORB
0 2 4 6 8
Sm (ppm)



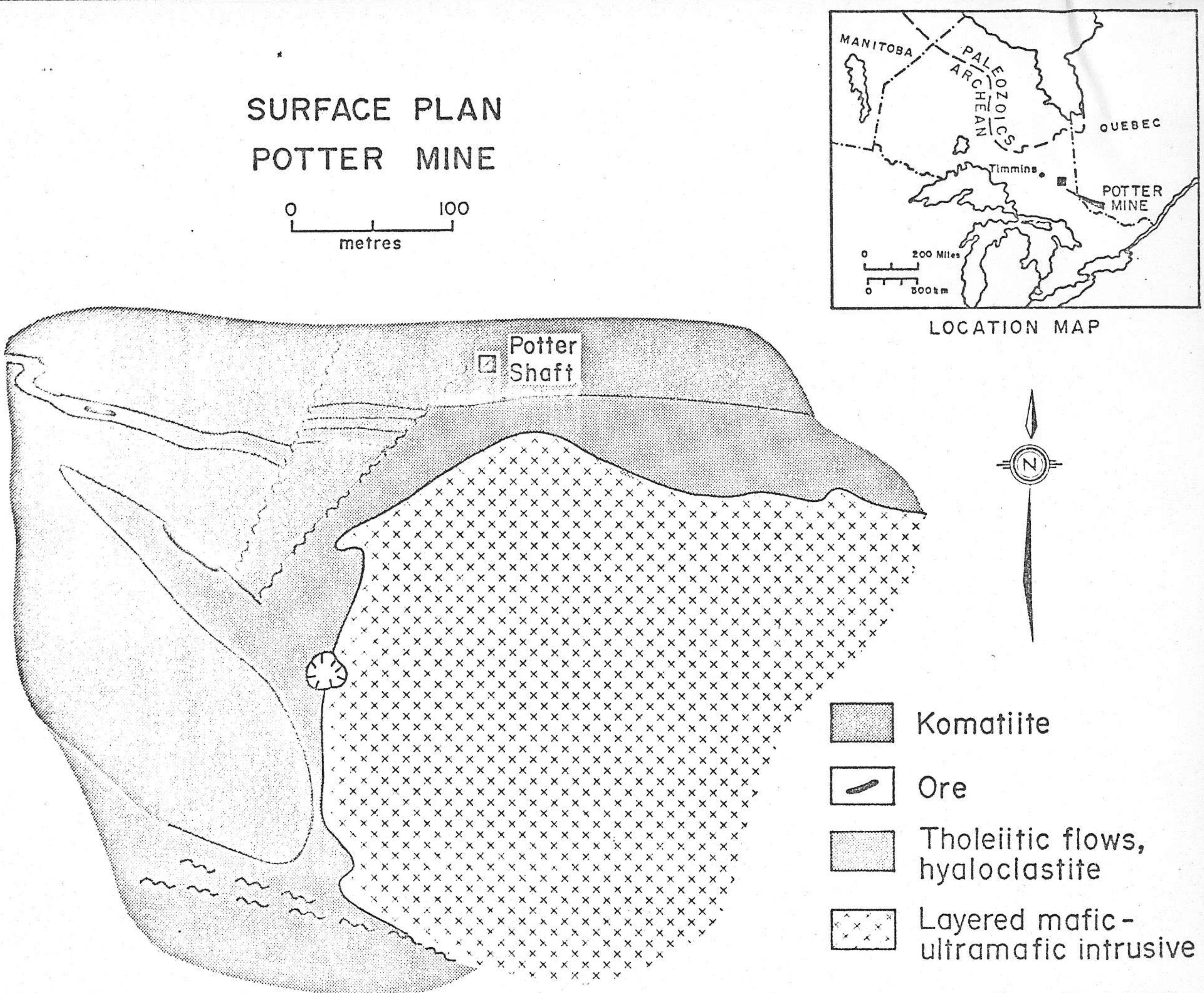
A
N-TYPE MORB
50
20
10
5
2
ROCK/CHONDRITE
La Ce Nd Sm Eu Gd Tb Dy Yb Lu
B
CYPRUS-LOWER LAVA
50
20
10
5
2
ROCK/CHONDRITE
La Ce Nd Sm Eu Gd Tb Dy Yb Lu
C
BESSHI-TYPE
50
20
10
5
2
ROCK/CHONDRITE
o - ORE KNOB
x - GOLDSTREAM
La Ce Nd Sm Ed Gd Tb Dy Yb Lu



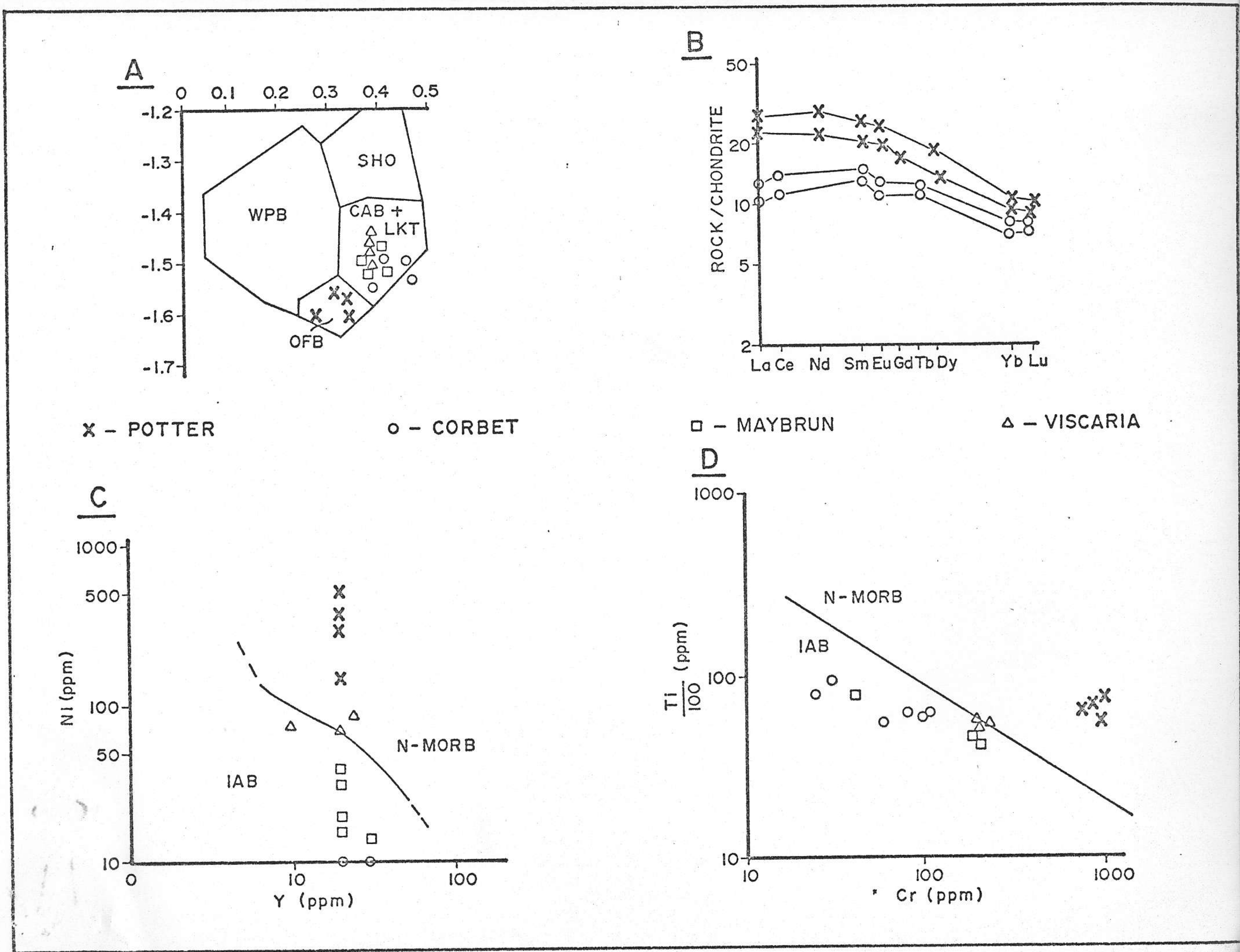
GEOLOGY
OF
VITI LEVU, FIJI


A
50
20
10
5
2
ROCK/CHONDRITE
La Ce Nd Sm Eu Gd Tb Dy Yb Lu
B
10
5
1
Zr / Y (ppm)
WPB
MORB
IAB
10 50 100 500
Zr
WAINIMALA GROUP, IAB, FIJI
C
2.0
1.0
0
Ti O2 (wt. %)
N-MORB
IAB
0 2 4
(Ba/La)CH
D
300
100
50
0
Ni (ppm)
N-MORB
IAB
0 10 100
Y(ppm)
E
100
50
0
Ti/100 (ppm)
N-MORB
IAB
10 100 1000
Cr (ppm)

SURFACE PLAN
POTTER MINE



(from Coad, 1976)


A
0 0.1 0.2 0.3 0.4 0.5
-1.2 -1.3 -1.4 -1.5 -1.6 -1.7
SHO
WPB
CAB + LKT
OFB
B
50 20 10 5 2
ROCK / CHONDRITE
La Ce Nd Sm Eu Gd Tb Dy Yb Lu
X - POTTER
o - CORBET
□ - MAYBRUN
△ - VISCARIA
C
1000 500 100 50 10
Ni (ppm)
IAB
N-MORB
0 10 100
Y (ppm)
D
1000 100 10
Ti/100 (ppm)
N-MORB
IAB
10 100 1000
Cr (ppm)