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Dykes, Sulphide Deposits, and Regional Metamorphism: Criteria for Determining their Time Relationship

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Relation of orebodies to adjacent dykes, often obscured by their mutual interpenetration along the contact, may be further masked due to the effects of intervening or subsequent regional metamorphism. The actual chronological sequence of the three episodes (Viz. mineralization intrusion, and dregional metamorphism) – an information often crucial from stratigraphic an oregenetic viewpoints – can be deciphered only through analyses of changes in the fabric, mineralogy, and chemistry of the contact zone and through consideration of heat and mass transfer phenomena across the interface. An attempt is made to establish objective criteria for recognition of the actual sequence of events, after examining numerous cases representing almost all possible time-sequence combinations.

Die Wechselbeziehungen zwischen Ganggefolgen und Erzkörpern sind oft verborgen durch die widersprechenden Beweise für die gegenseitigen Durchdringungen; sie können weiter kompliziert werden durch die dazwischenkommenden oder späteren Regionalmetamorphosen. Die eigentliche Zeitfolge der drei Vorgänge, nämlich Mineralisation, Eindringen des Ganges und die Regionalmetamorphose — eine aus stratigraphischen und erzgenetischen Gesichtspunkten oft sehr wichtige Angabe — kann nur entziffert werden durch eine sorgfältige Analyse der Gefügenänderungen, der Mineralogie und die chemische Zusammensetzung und Vorgänge in der Kontaktzone, sowie durch eine Betrachtung der Wärme- und Massenübertragungserscheinungen. Die vorliegende Arbeit versucht, Kriterien zur Bestimmung der eigentlichen Altersfolge aufzustellen. Dabei werden mehrere Fälle zitiert, die fast alle möglichen Zeitfolgekombinationen aufweisen.

Introduction

The general relationship of orebodies to dikes and sills has been discussed in an excellent review paper by Lewis (1955). The purpose of this paper is to examine critically some cases where the dykes apparently transect orebodies, but are also modified by them, so that their relative age becomes problematic. Such instances include, among many others, the Broken Hill area, Australia (Stillwell and Edwards 1956), the Coeur D'Alene district, Idaho (Sorensen 1951), the Horne (Price 1934; Suffel 1935) and the Normetal (Brown 1948) mines, Quebec, and the Zawar mine (Mookherjee 1964b), India. Members of the so-called 'Keweenawan dyke swarm' exhibit a similar controversial relationship with the strata-bound massive sulphide orebodies in many mines in Ontario and N. W. Quebec.

Pre-ore age of such intrusives, if proven, would automatically rule out a syngenetic mode of origin (favored by many geologists) for some of these deposits; it is therefore imperative that the relative ages of such intrusives and orebodies be known in unequivocal terms. Further, post-ore intrusives provide rare opportunities for studying high-temperature phase relations of sulphides in nature, with materials of known initial bulk composition and under known temperature conditions.

The relationship is, however, sometimes obscured by an overprint of regional metamorphism. Criteria, therefore, have to be found for recognizing pre-ore and post-ore intrusives with or without a preceding, intervening, or succeeding period of regional metamorphism. The present paper summarizes the results of investigations on several Canadian and Indian occurrences and attempts to establish such criteria. Regional polymetamorphism, which had undoubtedly affected some of the older Precambrian orebodies, is not considered.

Review of Relevant Literature

The problem of relative ages of orebodies and cross-cutting dykes has figured rather prominently in geological literature. The controversy over the Late Diabase-massive sulphide age relationship at the Horne mine, Noranda, P. Q., is longstanding and well-known. Price (1934, 1948, 1949), Suffel (1935), and others (Bruce 1933; Cooke, James, and Mawdsley 1931) hold that although the Late Diabase dyke apparently transects the country rock and the orebodies alike, penetration and replacement of the dyke borders by ore minerals are indicative of a younger age of mineralization. A similar conclusion has been drawn by Stillwell and Edwards (1956) for the uralite dolerite dikes at Broken Hill, Australia, on similar reasoning. On the other hand Brown (1948), following Hawley's (1941) experimental findings, suggested that ore veins in the dyke at the Normetal mine (and also at the Horne) owe their origin to thermal mobilization of chalcopyrite; Brett and Kullerud (1964, 1967) and Craig and Kullerud (1967), from studies on Fe-Pb-S and Fe-Pb-Cu-S systems respectively, suggested that such ore 'veins' in dolorites at Broken Hill could be of rheomorphic origin; Mookherjee and Suffel (1967, 1968) demonstrated that the sulphide bodies were thermally metamorphosed at the Horne mine along the Late Diabase contact.

It becomes apparent from the foregoing discussion that injection of ore veins and marginal modification of dykes are not incontrovertible evidence of pre-ore age of intrusives, just as the apparently transgressive nature of dykes is no proof of their younger age: for such 'pseudotransgressive' character could also be acquired if the country rock on both sides is preferentially replaced at a later date.

Similar controversial relationships, though not always particularly emphasized, have been reported from the Magma mine, Arizona (Peterson 1962; Sell 1960; Short 1943), from Pachuca-Real del Monte, Mexico (Geyne 1956; Wisser 1942), and from the Rhodesian copper belt (Jordaan 1961). Diabase dykes cross-cutting the gold-bearing sulphides at the Espirito Santo and the Raposos mines, Brazil, are believed to be younger than the sulfides (Matheson 1956). In the Witwatersrand gold field, the value of gold remains unchanged in the reefs near the dykes "though small amounts of gold have been reworked in the igneous metamorphic aureole leaving mineralization along cross-cutting dykes and gash veins" (Park and Macdiarmid 1964, p. 402). Dunham (1952), while studying the age relationships of the epigenetic mineral deposits of Britain, reported some confusing cases (p. 419) where the ores lie alongside the margin of the dykes and slightly penetrate them (cf. Lamplough 1903).

Definite evidence of thermal metamorphism of adjacent sulphides (thus conclusively demonstrating the younger age of the intrusive) have been cited by several workers. Sales and Meyer (1951) described dissociation of pyrite to iron-oxide, and transformation of pyrite-chalcocite assemblage to chalcopyrite-bornite (with concomitant release of silver from chacocite) in ores adjacent to a rhyolite dyke at Butte. Stevenson (1937) reported pyrrhotite and cubanite in the contact aureole of chalcopyrite ore against a comptonite dyke from the Eustis mine, Quebec. Watson (1954) described thermal metamorphic effects on sulphide ores from the Mindamar mine, Nova Scotia. Mookherjee (1964b) noted dissociation and recrystallization of pyrite, increase in iron content of sphalerite and several other textural and mineralogical changes in the orebody against a dolerite dyke from the Zawar mine, India. Ames (1962), Wanless *et al.* (1960) and Jensen (1962) recorded measurable depletion in the lighter S^{32} isotope in sulphides adjacent to post-ore dykes. Yarosh *et al.* (1957) found that sphalerites suffer a loss of photoluminescence near dyke contacts. Orthorohombic $\rightarrow$ cubic transformation of cubanite in ores from the Noril'sk deposit has been ascribed to local thermal activity by Genkin *et al.* (1965). Mookherjee and Suffel (1968) gave a detailed account of the textural and mineralogical reconstitutions of the sulphide wall against the N-S Late Diabase dyke at the Horne mine and also noted the reciprocal effects on the intrusive. Graham (1967) described the thermal metamorphism of the No. 2 ore body along a diabase contact from the Willroy mine, Manitouwadge. Lockerman (1962) and Shatagin (1968) reported partial to complete destruction of fluid inclusions in sulfide minerals in response to thermal metamorphism. Antun (1967) described the metamorphism of sedimentary pyrite to homogeneous monoclinic pyrrhotite from the contact aureole of the Oslo region (Permian Drammen granite aureole) for a distance up to 3 km. Macdonald (1967), and recently Vokes (1969), in two comprehensive surveys of the effect of metamorphism on sulphide assemblages, reviewed some of the well-documented instances of thermal metamorphism of sulfides.

Sulfide xenoliths in diabase porphyry dykes have been described by Starostin (1964) from Gay, southern Urals, where lattice-like intergrowth of chalcopyrite-sphalerite along the borders of the inclusions is believed to be the result of thermal metamorphism. Mookherjee and Suffel (1968) described sulphide xenoliths from the Horne mine with magnetite coronas and relatively low S^{32} values. Jordaan (1961) recorded xenoliths of Ore Shale within a kersantite dyke from Mindola 1 shaft at Nkana deposit, Rhodesia. He also noted interfingering of dyke and ore material, and a slight decrease in copper values in the ore body near the dyke.

Experimental investigations having direct or indirect bearing on this problem include practically all the sulphide phase equilibria studies made so far (e. g. Yund and Kulierud 1966). Of particular significance are the works of Brett and Kullerud (1964, 1967) and Craig and Kullerud (1967) who demonstrated the possibilities of partial fusion of materials of specific composition in the systems Fe-Pb-S and Cu-Fe-Pb-S at geologically reasonable temperatures. Davies (1965) studied the annealing and plastic deformation of chalcocite at high temperature. Filimonova (1964) recorded the changes in the forms of intergrowth of natural chalcopyrite-sphalerite on heating and her results are strikingly similar to the pattern produced by Roberts (1965) with synthetic mixtures. Significant contributions in this line have also been made by the McGill group (Gill 1965, MacDougall *et al.* 1961), who are actively engaged in research on solid diffusion and volatilization of metallic sulphides. Mention must also be made of Hawley's (1941) simple and elegant experiment on heat effects on sulphides.

Post-Ore Dykes

General Considerations

When an orebody along with the enclosing country rocks is transected by a dyke, the rate of heat conduction across the intrusive-sulphide interface and the intrusive-rock interface would be different, due to appreciable difference in the thermal constants of the metallic and the non-metallic 'conductors'. Also, the temperature at the interface immediately after intrusion — the maximum temperature ever attained by any part of the country rock — would be significantly different for silicate and sulphide walls. Calculations (Lovering 1935, 1936, 1955; Mookherjee and Suffel 1968xx) show that the maximum temperature at the sulphide wall could be as low as nearly 50 per cent of that in a rock-wall. Consequently, a dyke-sulphide interface would remain isothermal for a relatively longer time, till the thermal gradients on either side are equilibrated.

Several significant conclusions emerge from these findings: firstly, the *intensity* of thermal metamorphism in sulphide and silicate walls along their respective interfaces would not be isofacial, even though these were initially isothermal and were affected by the same dyke. Therefore, lack of high temperature reconstitution in the sulphide wall, to the extent indicated by the mineralogy of the silicate contact aureole, should not be construed as evidence of post-intrusive mineralization. Secondly, the relatively lower temperature along the sulphide-dyke interface would necessarily imply a steeper thermal gradient within the intrusive there: chilling of the dyke border should therefore be more pronounced along such contacts, and a comparison of the glass: crystal ratio of the chilled edges against rock and ore walls would be a fair measure of the relative degrees of chilling. Thirdly, the relatively prolonged isothermal condition of the sulphide-dyke contact would tend to ensure more complete reconstitution.

Incontrovertible evidence of post-ore emplacement of dykes would, then, consist of (a) thermal metamorphism of the sulphide wall along the interface, though this might not register as high a temperature as that in the non-sulphide wall, and (b) a higher glass: crystal ratio of the chilled edge against the sulphide wall.

These relationships, however, are likely to be modified if regional metamorphism takes place before or even after the intrusion. Pre-intrusive regional metamorphism might equilibrate the entire orebody to a high P. T. condition so that renewed heating along the dyke contact would fail to bring about any further reconstitutions. On the other hand, if regional metamorphism

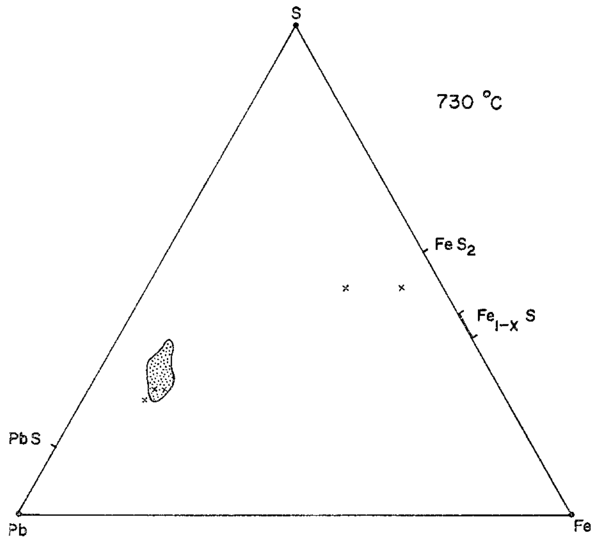

Fig. 1. 730 °C isothermal section of the system Fe-Pb-S, showing the ternary liquid field (Brett and Kullerud 1964) and the compositions of rheomorphic ore veins from Zawar mines, Rajasthan (indicated by cross marks)

postdates intrusion, the effects of prior thermal metamorphism could be masked, if not completely obliterated, and the chilled border might also lose its identity due to recrystallization. (Figs. 17a + b).

Practical experience (Mookherjee 1964 b; Mookherjee and Suffel 1968) and theoretical considerations (Ehrenburg 1932; Lovering 1934, 1935, 1955) show that for dykes of few tens of feet thickness, no heat effect of any consequence is 'felt' by the country rock beyond a couple of feet from the contact. The aureole, specially in cases of sulphides, could therefore be easily overlooked.

Examples of ore-dyke relationships of such types are discussed below:

Type I — Orebody and Dyke Both Unmetamorphosed/Post-Metamorphic

Zawar Mine, Rajasthan, India

The Pb-Zn orebody in the Machia Magra Hill is traversed by a 40 foot thick dolerite intrusive which is partly a sill, and partly a dyke. Regional metamorphism in this area is demonstrably pre-ore (Mookherjee 1964a) and, as such, has no modifying influence on the dyke-ore relationship.

A preliminary report on the thermal metamorphism of sulphides along the contact of the dyke has been published (Mookherjee 1964b). Subsequent investigation revealed several other significant features characteristic of thermal metamorphism of sulphides. The evidence is summarized below.

(1) The chilled margin of the dyke against the orebody is pseudo(-)tachylitic in texture, with very few plagioclase phenocrysts displaying a flow lineation parallel to the vertical slickensides developed in the chilled zone. The glass: crystal ratio of the chilled zone for an arbitrary width of $\frac{1}{2}''$ varies between 5:1 and 10:1. In contrast, the dyke border against dolomite country rock shows numerous tiny plagioclase microlites with a glass: crystal ratio between 2:1 and 0.5:1, implying a much slower rate of cooling in the second case.

(2) A $\frac{1}{2}''$ thick banding, parallel to the contact and oblique to the original band of the ore, is particularly noticeable in galena-rich parts of the orebody along the dyke contact.

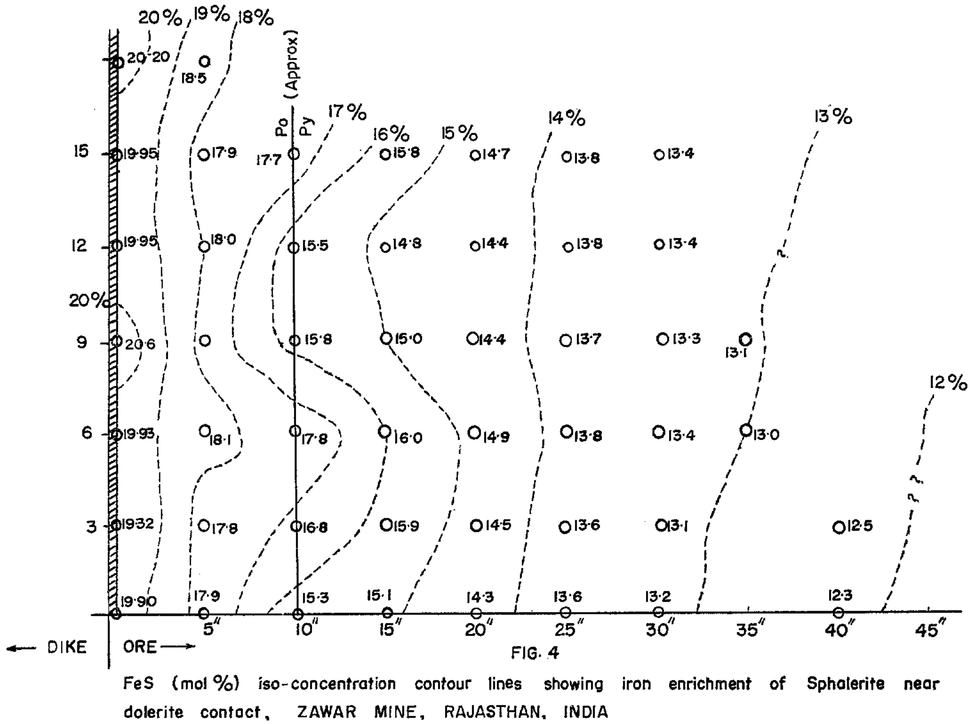

Fig. 2. FeS iso-concentration lines (mol% FeS in sphalerite) plotted on vertical section across the dyke-ore contact; 2nd level, Zawar mine, Rajasthan

(3) Veinlets of sulphides, about a centimeter thick, and 10—15 cm long often protrude into the dyke. Following Brett and Kullerud's suggestion (1964) that such 'veins' might originate by selective fusion of material, five such veins were chemically analyzed and their compositions plotted on the 730 °C diagram (Fig. 1); while three lie within the liquid field, two are widely distant, suggesting perhaps that mechanisms other than partial melting were also responsible for contributing ore material into the dyke.

(4) Magnetite grains at the dyke border along the ore-dyke contact are converted to pyrite with residual rutile and/or högbomite. Sometimes richly titaniferous borders of augite grains suggest migration of the released TiO_2.

(5) A spectacular degree of iron enrichment is noted in sphalerite from the contact zone. Fig. 2 shows the FeS isoconcentration lines (in sphalerite) from the aureole. Increase in iron content of sphalerite in this case perhaps indicates both increased temperature and higher $fs_{2(9)}$

(6) Pyrite grains along the contact in the sulphide ores are dissociated to pyrrhotite and ultimately to magnetite (cf. Sales and Meyer 1951).

(7) Abundance of chalcopyrite and pyrrhotite blebs is also noted in sphalerites from the contact zone. (The 'normal' Zawar sphalerite contains very little chalcopyrite and no pyrrhotite at all.). A few inches away from the actual interface such blebs are confined only to those sphalerite grains which are in contact with, or contain inclusions of, pyrite (Fig. 3). This clearly demonstrates renewed equilibration among what was originally a stable pyrite-sphalerite assemblage. Kullerud suggests (personal communication, 1965) that sulfurization of sphalerite leads to the formation of S-rich chalcopyrite which, at any temperature is less soluble in sphalerite than the S-poor variety, and is consequently ex-solved.

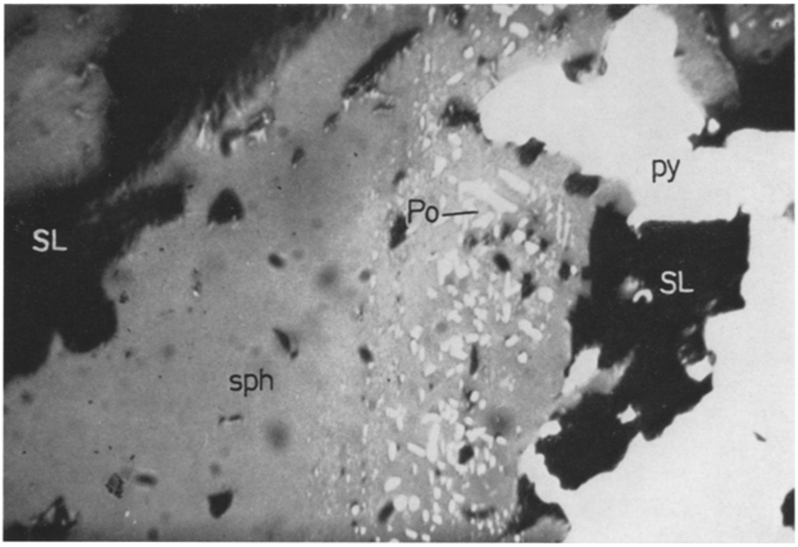

Fig. 3. Pyrrhotite 'ex-solution' blebs in sphalerite confined to pyrite-sphalerite contact, indicating reequilibration between the two minerals during subsequent heating by the dyke. Note decrease in size of blebs away from the boundary. Specimen two inches from contact, 4th level, Zawar mine. Reflected light, 300x. Py = pyrite, Po = pyrrhotite, Sph = sphalerite

(8) Sphalerite samples inches away from the interface are unusually rich in cadmium (Misra 1964). This perhaps indicates significant volatile transport of the element from the hotter region. Theoretical consideration of the relative volatility of cadmium (Krauskopf 1964) lends credence to the view.

(9) Assuming equilibrium between Ti-magnetite and Fe-ilmenite grains of the intrusive, a preliminary estimate of the temperature of intrusion was made from Buddington and Lindsleys' (1964) curve. The temperature calculated was of the order of 850 °C (Vol % Ti-Mgnt 7.25, Fe-Ilm 6.19; % TiO_2 — 31.4).

Type II — Metamorphism Post-Ore but Pre-Intrusive

Numerous strata-bound massive sulphide deposits of the Canadian Shield in Ontario and Quebec were intruded by members of the Keweenawan dyke swarms probably long after these orebodies were metamorphosed during the Kenoran Orogeny (Roscoe 1965, Gilmour 1965). The intensity of regional metamorphism, as registered by the country rock, varies from place to place and, if the massive sulphides are (as many geologists believe) co-eval with the Keewatin volcanics, these also presumably underwent the same intensity of regional metamorphism (Hutchinson 1965). The Late Diabase dykes, on the other hand, are clearly post-metamorphic. Horne, Quemont, Normetal, Mattagami, Willroy, Geco, Mine de Poirier, and the Northern Exploration mines in Ontario and Northwestern Quebec were chosen as these are situated in terranes of different metamorphic grades.

The nature of the problem is almost identical in all these cases: structurally, the diabases appear to have cut across the orebodies but are themselves mineralized along their margins; veinlike protrusions of sulphide material extend into the dykes — sometimes as much as 20—30 feet; and the generally fresh diabases are extensively altered wherever they cut across the orebodies. These features have been repeatedly cited by several workers (Price 1934, 1935; Suffel 1935; Miller 1965) who contend that these were 'antecedent' dykes (cf. Stillwell and Edwards 1956).

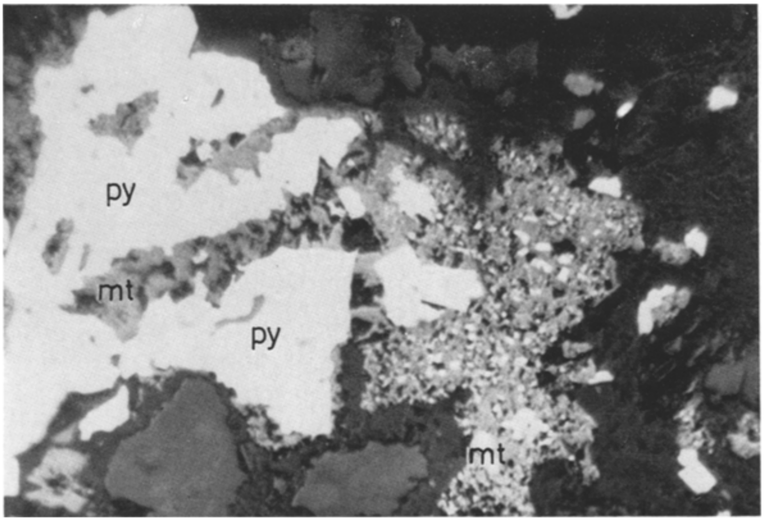

Fig. 4. Breakdown of pyrite(py) to magnetite(mt) along the contact of the ore body with the dyke. Horne mine, Noranda. Reflected light, 150x

Horne Mine, Noranda, Quebec

The orebodies lie concordantly within the rhyolitic tuffs which form a part of the slightly metamorphosed Keewatin volcanic pile in the area. The effects of thermal metamorphism due to the N-S Late Diabase have been studied in detail by Mookherjee and Suffel (1968). The salient features of their findings are as follow:

(1) A contact metamorphic aureole characterized by (a) increased 'monoclinicity' of pyrrhotite, (b) dissociation of pyrite to pyrrhotite to magnetite (Fig. 4), (c) copious development of chalcopyrite blebs in sphalerite, (d) a second generation of pyrite at the expense of pyrrhotite and ferromagnesian silicates, with concomitant formation of Mg-rich silicates and release of rutile in the second case, and (e) enrichment in chalcopyrite.

(2) Complementary sulfurization of the diabase edge registered by the pyrite stringers with bleached walls and by the conversion of primary magnetite to pyrite + rutile.

(3) Occurrence of euhedral sphalerite grains with marginal overgrowth of plagioclase microlites in the chilled margin of the dyke indicates their *in situ* growth, presumably due to volatile transfer of zinc sulphide.

(4) More intense chilling of the diabase edge against the sulphide wall, as reflected in the larger proportion of glassy material along such contact.

Mookherjee and Suffel (1968) further noted that the ore "veins" from the main lode into the dyke were essentially monomineralic with an extremely deformed (Fig. 5) or recrystallized mosaic of chalcopyrite, and ended against the coarse grained interior of the diabase. These were believed to be the result of plastic flowage of chalcopyrite. Massive sulphide patches within the diabase, with magnetite coronas and a depletion in the lighter S^{32} isotope, were interpreted as xenoliths.

Quemont Mine, Quebec

The Quemont deposit, north of the Horne Creek Fault and the Horne deposit, is traversed by an E-W diabase which is demonstrably younger than the N-S diabase that cuts across the Horne orebodies. Samples were collected from the 26th and the 29th levels while those from the 320 level were supplied by R. Weeks, Geologist, Quemont mine.

The contact relation between the diabase and the orebody at different levels is interesting. Specimens from the 29—120 west stope show

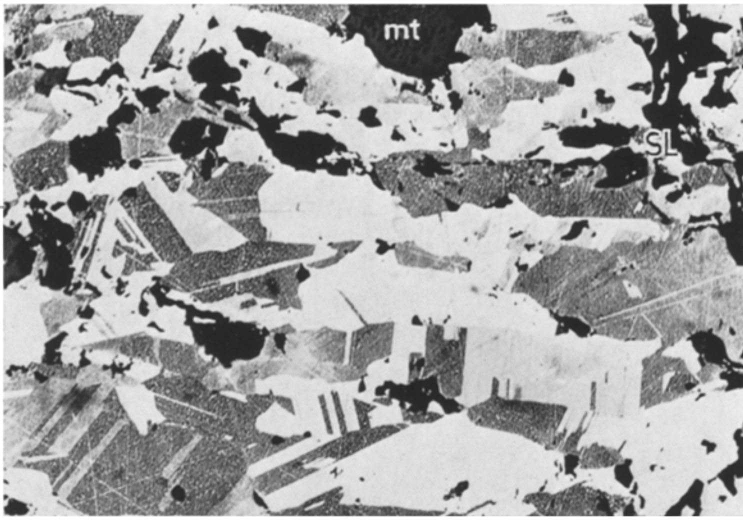

Fig. 5. Flattened and elongated chalcopyrite producing a banded structure. Note differential etching (with aqua regia vapour) of chalcopyrite grains, with strain-free untwinned (recrystallized) grains practically unetched. From sulphide 'veins' into the dyke. Horne mine, Noranda. Incident light 100x. Mt = magnetite, sl = silicate

extensive pyritization of the diabase margin for a thickness of about 1″. The original interface is sometimes still discernible by a faint relict line and the chilled margin is completely obliterated. The pyrite is coarse, and contains zonally arranged inclusions of high Mg-chlorite, amphiboles, and scattered 'islands' of fine-grained amphibole-chlorite-rutile-carbonate aggregates. The same interface at higher levels is marked by a thin band of fibrous carbonate and actinolite aligned perpendicular to the wall, and pyritization of the diabase border is incipient. The chilled margin is marked by a trail of pyroxene phenocrysts 'frozen' in a cryptocrystalline matrix. Occasionally, angular fragments of pyrite, caught up along the dyke border, cause swerving of the trail of pyroxene phenocrysts around their edges and corners (Fig. 6). The amphibole-carbonate veins along the contact in the upper level perhaps mean that materials removed due to pyritization could migrate upwards or elsewhere and precipitate out in a suitable place.

Pyrrhotite blebs in sphalerite, and cubanite along the pyrite-chalcopyrite grain contact are noted in the ores immediately adjacent to the dyke.

Normetal, Quebec

The Normetal occurrence shows a somewhat different regional setting. At the surface the rhyolites are found metamorphosed to quartz-mica/sericite-schist and from deeper levels of the mine higher grades of metamorphism have been reported (Claude Bertrand, personal

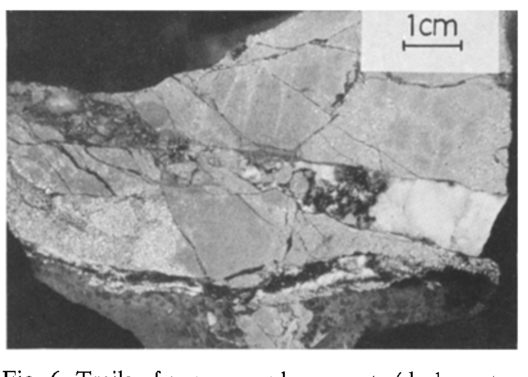

Fig. 6. Trails of pyroxene phenocrysts (dark spots, bottom), "frozen" in glassy matrix around a caught-up fragment (bottom, centre) of sulfide ore. Polished dyke-ore contact specimen. 300 L, Quemont mine

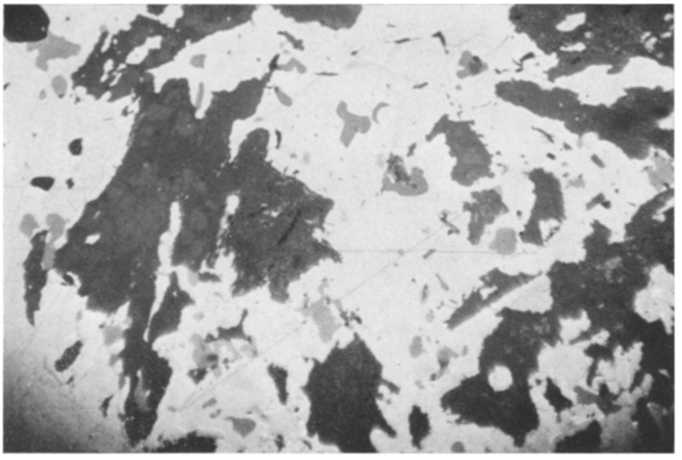

Fig. 7. Pyrrhotite coronas (white) around silicate islands (dark) floating in sulphide (sphalerite = light gray, chalcopyrite = white) matrix. Massive sulphide ore from dyke contact. Normetal mine. 80x, incident light

communication). The orebody is a sheet-like mass, concordant with the enclosing rhyolite, and is persistent up to a great depth maintaining a near-vertical attitude. The Abana Dyke, as it is called, cuts across the orebody at all the levels and is invariably chilled at the border. Stringers of ore into the dyke and of the dyke into the ore are common. Occasionally chalcopyrite "veins", $\frac{1}{4}''$ thick, penetrate up to five feet into the diabase (cf. Horne). However, unlike the Horne, no apparent 'replacement fronts' have been reported from the Normetal mine, and pyritization of the diabase wall is also very insignificant.

On the other hand, spectacular evidence of sulfurization of the silicate gangue material is furnished by the pyrrhotite rims surrounding silicate 'islands' which are altered to fine-grained aggregates of anthophyllite, amesite, and abundant rutile needles (Fig. 7). The rims faithfully follow the configuration of the irregular patches and thus confirm their reaction origin. Further evidence of sulfurization are furnished by the pyrrhotite 'blebs' and pyrite pseudo-exsolution 'blebs' in sphalerite which are strikingly similar to those produced experimentally by Barton and Toulmin (1966) and are ascribed to sulfurization.

The reciprocal reactions releasing sulfur are recorded along the contact by the conversion of pyrite to magnetite $\pm$ pyrrhotite, and of sphalerite to gahnite. These two reactions are most conspicuous within $1''$ from the contact. Other textural evidence of re-equilibration under heat effect are (a) occurrence of residual patches of ilmenite within magnetite inclusions in sphalerite; electron probe investigation, as well as color variation of the enclosing sphalerite grains, indicate absorption of iron from the magnetite inclusions; (b) enlargement and 'euhedralization' of chalcopyrite exsolution blebs (in shalerite) into 'cubes', suggesting reorganization and perhaps high-temperature phase transformation (Fig. 8); these chalcopyrite 'cubes' (?) often contain tiny cubanite lamellae or minute specks of valleriite.

Chalcopyrite within the "veins" in the dyke are texturally very different from those of the 'normal' orebody; pear-shaped, bi-convex twin lamellae and sphalerite starlets are plentiful (Fig. 9). Both these features are believed to be the effects of pressure which induces deformation twins and promotes the removal of foreign ions from mineral structures (Hardy and Heal 1954).

The main difference between the Normetal occurrence and the other examples cited so far is that at Normetal there had not been sufficient

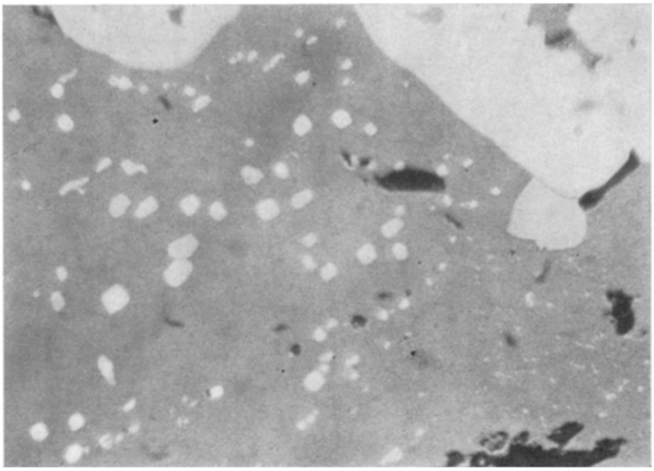

Fig. 8. Chalcopyrite exsolution 'cubes' in sphalerite, suggesting coalescence and high temperature modification due to heat. Ore from dyke contact, Normetal mine. Reflected light, 250x

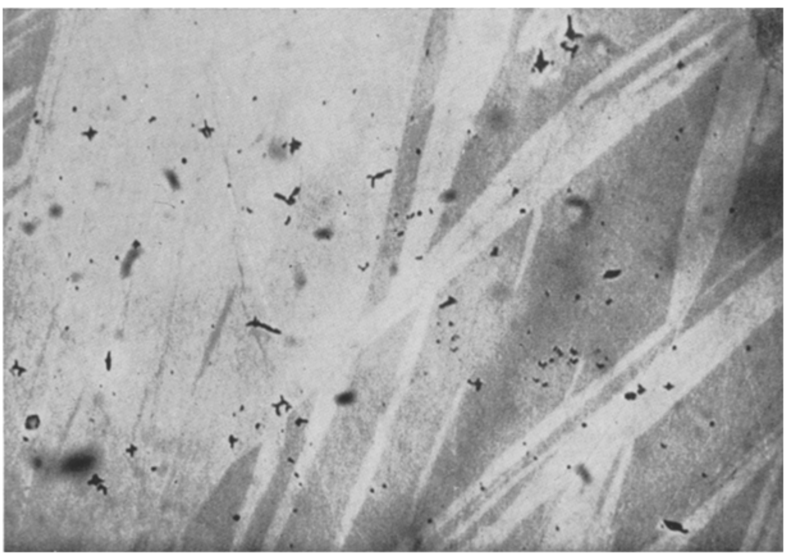

Fig. 9. Bi-convex twin lamellae and exsolved sphalerite starlets in chalcopyrite from ore "veins" in the dyke, Normetal mine. Both twinning and ex-solution are believed to have been promoted by deformation. Incident light, 450x, nicols partly crossed

sulfurization of the diabase: instead, the silicate 'islands' within the ore and the sulphides themselves were sulfurized. This is perhaps due to the lack of suitable channels of migration (a fact borne out by the rarity of fretted margin of the diabase) which confined the released sulphur within the orebody and thus brought about the silicate-sulphur and sulphide-sulphur reactions cited above (cf. Kullerud and Yoder 1965; Naldrett 1966).

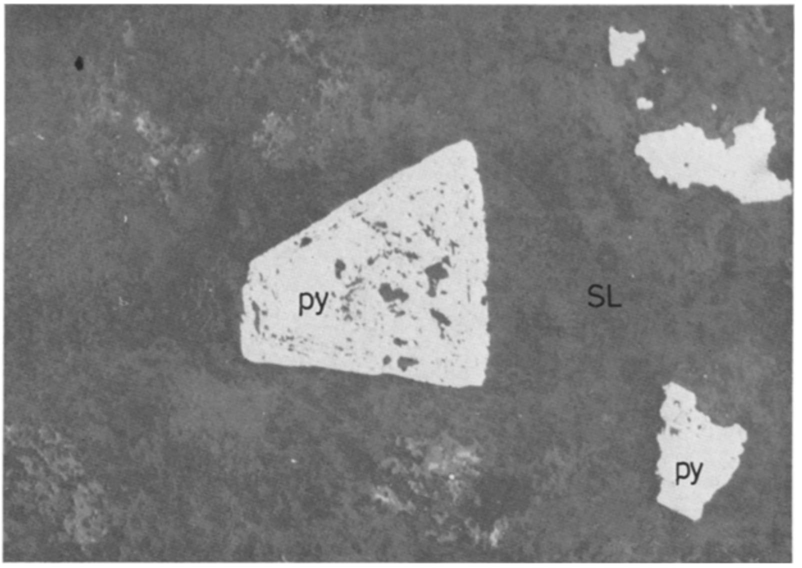

Fig. 10. Pyrite porphyroblasts (py) formed due to thermal metamorphism. The inclusions are zonally arranged, in contrast with those in Fig. 11. Incident light, 100x, Mattagami mine

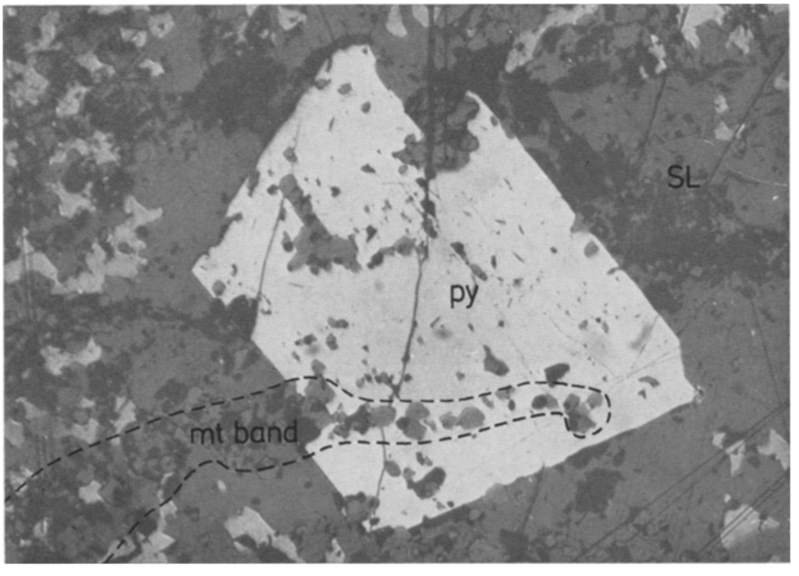

Fig. 11. Pyrite porphyroblasts (py) formed due to regional metamorphism. Note that the trail of magnetite inclusions within the porphyroblasts is *continuous* with the external S-plane defined by a magnetite band. Incident light, 150x Mattagami mine

Mattagami Lake Mine, Quebec

A predominantly Zn-rich orebody, the Mattagami Lake occurence is characterized by coarse-grained, banded sphalerite-pyrrhotite ore with some chalcopyrite and large porphyroblastic pyrite 'eyes' sparsely distributed all over the orebody. The porphyroblasts display correlatible si-se fabric of magnetite inclusion (Fig. 11) trails and thus point to their metamorphic derivation. Further, inclusions of Zn-mica in sphalerite, interleaving of sphalerite with amphiboles, and unusually elongated forms of pyrrhotite and sphalerite indicate pre-tectonic crystallization of the sulphides, although some chalcopyrite shows evidence of late-, or post-tectonic recrystallization in fold arches.

A younger generation of pyrite porphyroblasts is abundant in the contact aureole. But the fabric of the inclusions is entirely unrelated to the external S-planes (banding). The inclusions consist of zonally or crystallographically arranged silicate minerals (Fig. 10). The distinction between the two types of porphyroblasts (compare Figs. 10 and 11) is vital in understanding the effects of thermal and regional metamorphism on sulphides.

Original banding of the sulphide orebody is cut across at an angle by the dyke. The sulphide wall is often visibly sheared along the contact and no significant chalcopyrite enrichment is noticeable. This is quite different from the situation at Horne and other places where the immediate contact regions are enriched in chalcopyrite. It is therefore believed that shearing of the sulphide wall (along the intrusive contact), admittedly strong evidence in favour of post-ore emplacement of the intrusive, would persist only in orebodies deficient in mobile materials like chalcopyrite and galena.

A sulphide xenolith within the diabase was found to be rimmed with pyrite; beyond the rim, chalcopyrite specks and stringers extend into the dyke (cf. Starostin 1964). Pyrrhotite within the xenolith shows 90% 'monoclinicity' (i.e., a two-phase intergrowth with 90% Po_{mc} + 10% Po_{Hex}).

Sulphide 'injections' within the dykes are characteristically monomineralic, with deformed or recrystallized chalcopyrite and some pyrrhotite.

The Mattagami Lake occurrence, thus, displays practically all the essential features of thermal metamorphism previously described, in addition to revealing the sheared nature of the sulphide wall along the contact, preserved due to the compositional character of the orebody.

Willroy and Geco Mines, Manitouwadge, Ontario

These orebodies occur in entirely different lithologic and tectonic settings. The country rocks are high grade gneisses, the orebodies are coarse-grained, and pyrrhotite is the chief iron sulfide instead of pyrite. As at Mattagami Lake mine, pyrite porphyroblasts are scattered all over and perhaps represent the effect of localized concentration of sulphur released during regional metamorphism. Silicate minerals, mostly micas and amphiboles, show evidence of para-crystalline deformation and ruptures (Fig. 12) into which chalcopyrite is mobilized. On the other hand, twin lamellae of sphalerite and exsolution 'rods' and 'threads' of chalcopyrite in sphalerite are cut across by amphibole needles, implying the late origin of the silicates.

N-S Keweenawan dykes intersecting the NO.3 Willroy orebody have been studied in detail by Graham (1967). He reported (a) a systematic increase in the "monoclinicity" of pyrrhotite towards the diabase contact, (b) increase in chalcopyrite along the immediate contact, (c) development of pyrite porphyroblasts in the aureole, and (d) a decrease in iron content of sphalerite from 19 mol% at 75″ to 13 mol% at 4″ from the interface. The last finding is just the opposite of what has been recorded from Zawar (see Fig. 2).

The dyke-orebody relationship at the Geco mine has been studied from two exposures: one in the 8—40 stope drift where a 2′8″ thick olivine dolerite (No. 38) with chilled edges and sheared sulphide walls has been sampled; the other was encountered at the 10—40 stope, S-roof, 18th—19th lift above 10—50 level. *Unbroken pyrite euhedra* in the sulphide wall and in the chilled edge (both highly sheared) bear testimony to a late sulphurization. The most conspicuous textural change in the aureole is the sphalerite-chalcopyrite intergrowth, presumably of exsolution origin, in the form of sphalerite 'emulsion' ranging in size from nearly sub-microscopic dust to discrete grains 10—15 microns across.

The second exposure at the 10—40 stope (Fig. 13) clearly displays the difference between ore "veins" in the dyke and dyke apophyses in the

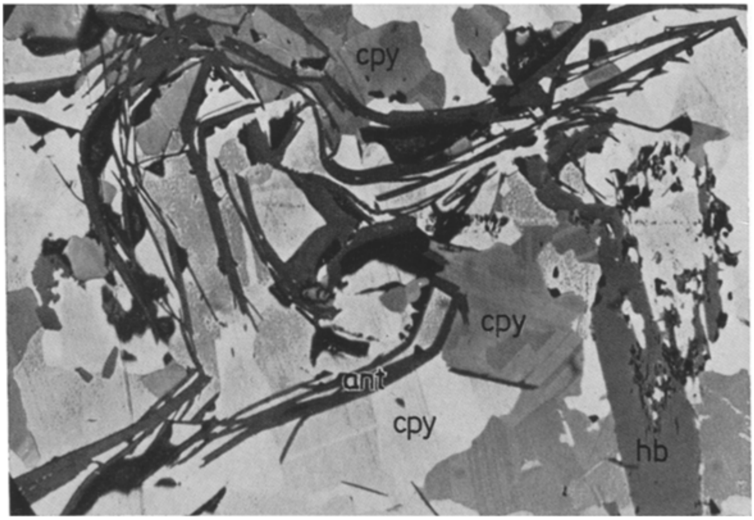

Fig. 12. Syntectonic crystallization of amphiboles (hb = hornblende, ant = anthrophyllite) in sulphide matrix. Chalcopyrite (gray and white) within fold arches and those 'replacing' thick hornblende prisms (centre, right) are recrystallized, untwinned. Willroy mine. Incident light, 80x, etched with aq. reg. vapour

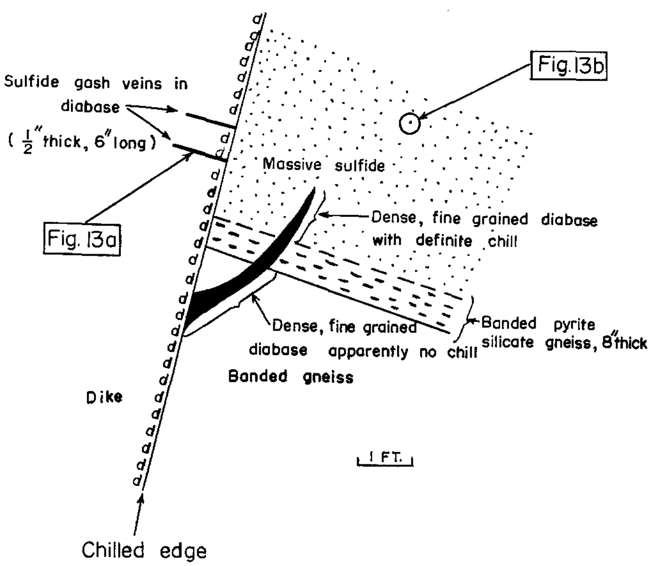

Fig. 13. Vertical section along 10—40 stope wall, Geco mine, Manitouwadge. Dyke apophyse cutting across concordant layers of biotite-gneiss and massive sulphide ores

orebody: while the former occupy straight, sharp fractures normal to the wall, the latter are sinuous and pinch out. The dyke apophyses, which cut across both the gneiss and the massive sulphide, are differentially chilled against the silicate and sulphide walls and consist of olivine and zoned plagioclase phenocrysts aligned parallel to the wall and embedded in an essentially glassy matrix. The walls of the thin apophyses, however, do not show any thermal effects.

The chilled edge of the main dyke has a narrow bleached outer margin (about 2 mm thick), that is studded with small pyrite crystals, clearly indicating extraction of iron from the glassy selvage by sulphur vapor (cf. Horne).

The nature of sphalerite-chalcopyrite intergrowth is strikingly similar to that produced experimentally by Roberts (1963) by heating mixtures of the two minerals under pressure, and is also similar to the intergrowth pattern studied by Starostin (1964) from sulphide xenoliths. Also, this type of intergrowth is absent in the 'normal' ore and in the ores in contact with the narrow dyke apophyses. The conclusion therefore seems justified that this is a thermally induced texture.

Ore veins within the dyke, as shown in Fig. 13a, are strikingly different from the 'normal' Geco ore (Fig. 13b), both texturally and mineralogically. These consist of a fine-grained graphic intergrowth of chalcopyrite, pyrrhotite, and sphalerite, the last being studded with a profusion of chalcopyrite blebs. The mottled intergrowth of the three minerals shows a conspicuous banding parallel to vein walls. The proportions of the three minerals are more or less constant in all the polished sections studied.

Textural features are, thus, clearly indicative of crystallization from a quaternary (Cu-Fe-Zn-S) sulphide melt under pressure. Although quantitatively insignificant, these sulphide veinlets perhaps represent the first recorded occurrence of sulphide melt in *nature*. A detailed report on these materials will be published elsewhere.

Type III — Intrusive Pre-, or Syn-Metamorphic

General Considerations

The effects of post-intrusive regional metamorphism could be any or all of the following:

(a) Obliteration of the chilled zone, either by reconstitution or due to replacement by sulphides, metamorphically activated.

(b) Fracturing of the usually competent dykes, and more widespread injection of the softer or more ductile of the sulphide minerals along the fractures.

(c) Some sulphide-silicate- reactions along the interface and at the xenolith borders, if the intensity of metamorphism is high enough.

(d) If the intrusive is converted into a schistose rock, emplacement of sulphides along these planes would be more pronounced near the contact and surrounding the xenoliths.

The following examples of this type of relationship were examined:

Joutel and Northern Explorations, Quebec

These two newly opened mines offer a rare opportunity for studying the deformation characteristics of sulphides and dyke-ore-metamorphism interrelationships. Banded sulphides, concordant and co-axially folded with cherty and chloritic layers, display different degrees of competency depending on the relative proportions of different sulfides, though multicomponent bands tend to achieve some degree of differentiation. Trails of discontinuous silicate boundins, in various stages of formation, 'float' in the deformed sulphide matrix where the pyrrhotite specially shows a strong preferred orientation. The fold styles in different pure sulphide bands are shown in Fig. 14. Folded chalcopyrite bands are often 'ptygmatic' in nature, distinguished by extreme contortion, irregularity of trends of the axes, and by the lack of any obvious relation between the folds of the chalcopyrite bands and that of the matrix. The pyrite bands (Fig. 14c) with their infolding and uniform thickness in limbs and crests, indicate flexural origin of the folds. Thus, different sulphide bands seem to have yielded by different mechanisms.

In the Northern Exploration mine numerous occurrences were encountered where the banding of the ore against dykes was found to have been dragged into asymptotic curves near the interface so that in plan the bands appear parallel to the contact plane. This clearly indicates a pre-intrusive age of the banding. Sometimes the dyke-ore contact was irregular and without any visible chill, while chilling was evident around small projections of the ore into the dyke. Obliteration of the chilled edge and irregular nature of the contact plane (in

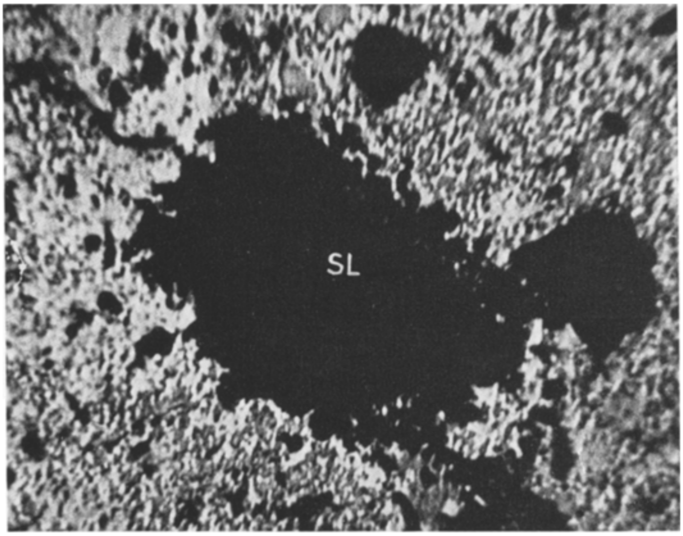

Fig. 13a. Micro-texture of the sulphide veins into the dyke, as shown in Fig. 13. Graphic (pseudoeutectoid?) intergrowth of sphalerite, chalcopyrite and pyrrhotite surrounding a corroded inclusion (black) of dyke material. Incident light 100x

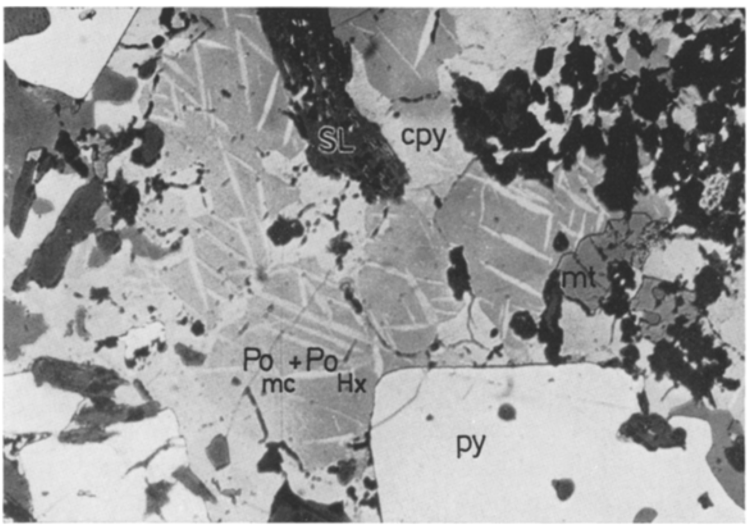

Fig. 13b. Micro-texture of 'normal' Geco ore. Pyrite (white), chalcopyrite (greyish white), twophase pyrrhotite (gray, with white lamellae), and some sphalerite and silicates. Location of sample shown in Fig. 13. Incident light, 50x

contrast with the usual knife-edge contact described in the earlier sections) are both believed to be due to metamorphic mobilization.

Metamorphic mobilization due to post-intrusive deformation is brought out with remarkable clarity in some exposures at the Joutel mine also known as Mine de Poirier. Fig. 15

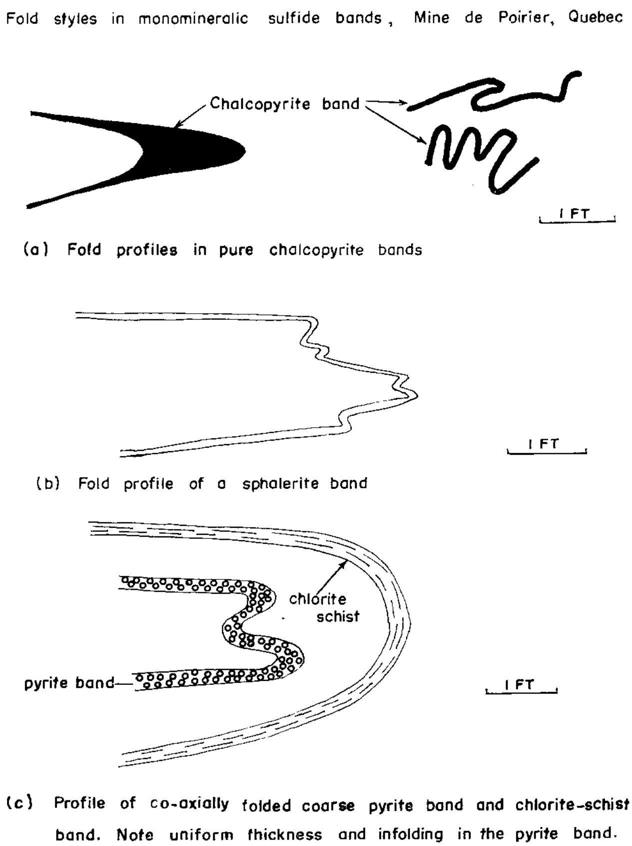

Fig. 14. Fold styles in monomineralic sulphide bands, Joutel mine, Quebec

shows the flowage of sphalerite-pyrrhotite banded ore, without any disruption of the continuity of the bands into fissures that were occupied by quartz veins and subsequently reopened. Relatively greater mobility of chalcopyrite under pressure is again registered by its occurrence at the farthest tip of the opening. Similarly, Fig. 16 demonstrates that sulphide bands, while being 'buckled into' fractures in the dyke under pressure, retained their physical continuity with the main body — clear evidence of plastic deformation.

The concordant nature of sulphide bands with silicate layers and the conformity of fold axes in all types of banding strongly indicate a primary nature of the sulphide bands. Angular intersection and 'dragging' along the intrusive contact, as well as occasional preservation of the chilled border, then, clearly show the post-ore age of the intrusive. Subsequent deformation, which could only bring about some fracturing in the competent dyke, also initiated flowage of plastically deformed sulphides into such fractures. It should be noted that primary bands subsequently behaved as flowage bands during deformation.

Mattagami Lake Mine, Quebec

Specimens from the contact of a schistose, supposedly pre-ore dyke were examined. Along the contact a 1″ thick magnetite band (similar to the magnetite corona around sulphide xenoliths at the Horne Mine) occurs in the orebody, parallel to the interface. Original banding of the orebody, observable beyond the magnetite band, is at an angle to it. Incipient migration

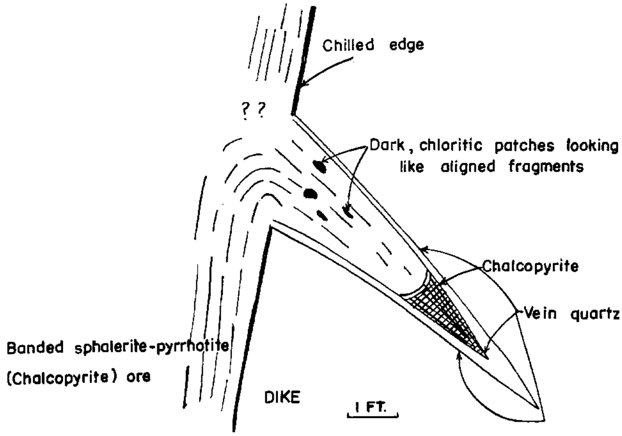

Fig. 15. Flowage of banded sulphide ore into a gash opening in a dyke. The opening, originally filled with quartz, was re-opened to accommodate plastically mobilized sulphide ore. Note (a) *continuity* of orebody sulphide bands into the opening, (b) chilled edge of the dyke, and (c) concentration of chalcopyrite at the tip of the opening. Deformation and regional metamorphism later than the post-ore dyke. 700 level, Joutel mine, Quebec, wall section

of chalcopyrite ($\pm$ pyrrhotite) along the cleavage planes within the schistose dyke was noticed.

It is therefore believed that this dyke was also post-ore, but later subjected to metamorphism and deformation. The magnetite band along the contact was a relict from an earlier thermal metamorphic episode when iron sulphide minerals along the contact were dissociated into magnetite. The deformed nature of the sulphides along schistosity planes of the intrusive is evidence of subsequent syntectonic migration of the sulphides.

Meta-Diabase—Massive Sulphide Contact a the Horne Mine, Noranda Quebec

Until recently the metadiabases were universally accepted as pre-mineralization, primarily because these were extensively replaced by the sulphides (e.g., in the 'H' orebody), in sharp contrast with the usual knife-edge boundary of the Late-Diabases against the ores. Because of the extremely complicated ramifying nature of the metadiabase all through the upper portions of the mine, the structural relationship between these and the orebodies is quite varied; H, Lower H, F, and many others are found to be dissected by an intricate swarm of metadiabase dykes; No. 16 orebody conforms closely to the structure of a metadiabase dyke, and the B orebody is completely surrounded by metadiabase with mineralized shear zones which extend beyond the metadiabase and well into the orebody (4th level). While at many places chilled edges provide a sharp contact against the ore, highly irregular fretted contacts with tongues of sulphides into the dykes are much more common (Price 1934).

A preliminary investigation by Darling (G. G. Suffel 1968, personal communication) seems to indicate that relics of thermal metamorphic effects, similar to those along the Late Diabase contact, are occasionally preserved. It is therefore suspected that widespread replacement of the metadiabase was perhaps brought about by *later* metamorphism and is *not* due to later emplacement of the orebodies.

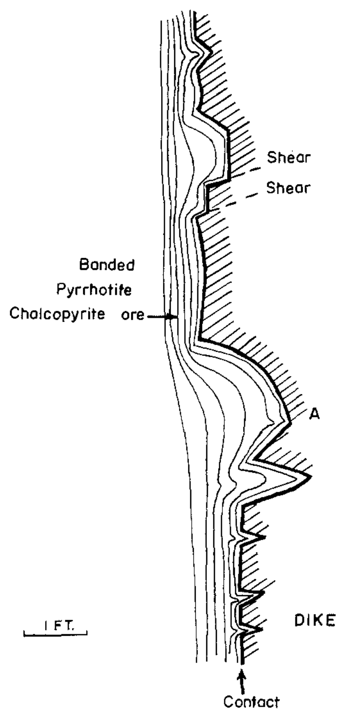

Fig. 16. Irregular dyke-ore interface caused by 'buckled in' sulphide bands into fractures in the dike. Sulphide bands retain their continuity and gradually flatten out. Original gash-like nature of the curvature at "A" is betrayed by minute kinks at the tip of adjacent sulphide band. Note that the number of kinked bands is directly related to the size of the opening. Wall section, 1100 Level, Joutel mine, Quebec.

Pyrite-Magnetite Equilibria and the Role of P_{S_2} during Thermal Metamorphism of Sulphide Bodies

Pyritization of magnetite on the diabase side, and magnetitization of pyrite on the ore side of the interface are noticeable in most of the cases studied, often in a single polished section. This raises some interesting thermodynamic considerations.

Firstly, it seems reasonable to conclude that although the interface behaved as a semi-permeable membrane, it nevertheless acted as a system boundary, on either side of which the two reversible reactions could take place despite their physical proximity. However, where the chilled margin of the dyke is unruptured and thus practically impervious (e.g., at Normetal), sulphur(g) cannot be treated as a mobile constituent of the orebody in the contact aureole. Pyrrhotite, pyrite, and magnetite would co-exist stably in such an assemblage and $S_{2(g)}$ must be considered as a component in the application of mineralogical phase rule. Conversely, where the chilled margin of the intrusive is fretted and rendered pervious, f_{S_2} within the ore in the contact zone would be externally controlled and sulphur would behave as a truly 'mobile' component (cf. Banno and Kanehira 1961). Migration of the vapor phase ($S_{(g)}$ + some volatile sulphides) towards the 'hotwall' side can be ascribed to thermal transpiration (Sosman 1950) by which a gas under constant pressure, in a medium having small pores, travels towards the region of highest temperature. However, local concentration on a microenvironmental scale could conceivably occur and might account for the second generation of pyrite porphyroblasts in the contact aureole. P_{O_2} within the ore side of the interface could be controlled both by the externally imposed condition (fluid phase of the intrusive) and by the internal mineralogical composition (primary magnetite).

Secondly, it tends to confirm the suggestion of Kullerud and Donnay (1967) that contrary to popular belief, magnetite-pyrite conversion may not be a redox-controlled reaction, maghemite (γ-Fe_2O_3 with omission inverse spinel structure) being the residual product along with pyrite according to the reaction $3\,Fe_3O_4 + S_2 \rightleftharpoons 4\,Fe_2O_3 + FeS_2$: for, although the 'magnetites' affected by sulphurization have not been studied in detail, their optical properties appear distinct from those of normal magnetite.

Pre-Ore Dykes

Relationship between orebodies and pre-ore intrusives has been extensively discussed by Lewis (1955). Depending upon the relative competence, a dyke may be brecciated and can, thus act as a host or channelway for ore solutions, or it may act as a dam pounding ore solutions at the contact. In any event, a pre-ore dyke is sure to exert some kind of structural/lithological control on ore localization. An interesting suggestion has been made by

Dunham (1952), who observed that in Northern England some sulphide mineralization was perhaps brought about by the circulation of 'fossil' hydrothermal fluid along fissures occupied by Tertiary dykes. "These orebodies lie alongside the margin of the dykes in positions which they could not have occupied before or during the injection of the molten matter" (Lamplugh 1903).

Pre-ore dykes would be characterized by a uniform degree of chilling against both silicate and sulphide walls. There would be no thermal metamorphic reconstitution of the sulphides along the contact. Sulphide veinlets and replacement patches could be abundant within the dyke, selective replacement of specific dyke minerals being more common.

Pre-ore metamorphism and deformation would increase the chances of more thorough permeation of the dyke by sulphides. Pseudomorphic replacement of metamorphic silicates of the dyke rather than its original constituents points to post metamorphic mineralization.

Post-ore metamorphism, on the other hand, might bring about some of the sulphide-silicate reactions outlined earlier and is likely to activate and mobilize some additional sulphides into the intrusive. Evidence of deformation of the sulphide minerals would help to differentiate the present situation from the previous one.

Criteria for Recognizing Ore-Dyke-Metamorphism Age Relationships

With the foregoing examples in view, it is possible now to state the criteria for recognizing the time relationships among intrusives, orebodies, and regional metamorphism.

Case I: — Intrusive Post-ore, — Dyke and Orebody both Unmetamorphosed/Post-Metamorphic, or Orebody slightly Metamorphosed

(1) Presence of chilled contact with or without slickensides: degree of chilling against the sulphide wall would be more conspicuous than that against the silicate wall; a quantitative measure of the difference would be reflected in the (measured) glass: crystal ratios of the chilled zones against the two types of wall (Zawar, Horne).

(2) Sulphurization of the chilled edge of the dike in various degrees, leading to one or all of the following reactions:

(a) $S_{2(g)} + Fe_{(\text{glassy selvage})} = FeS_2 \pm Fe_{1-x}S$ (in form of stringers) (viz. Horne, Normetal)

(b) $S_{2(g)} + \begin{bmatrix} FeO(Fe,Ti)_2O_3 \\ \text{magnetite} \end{bmatrix} = Fe_{1-x}S + FeS_2 + TiO_2 + \gamma - Fe_2O_3$ (Viz. Zawar, Horne)

The released TiO_2 may form rutile, högbomite, etc. or may diffuse into the pyroxene to form an outer rim of titanaugite (viz. Zawar).

(c) $S_{2(g)} + (Fe, Mg)$ silicates $=$ pyrrhotite $\pm$ pyrite $+$ Mg-rich silicates like anthophyllite, amesite, etc. (viz. Horne).

(3) Occasionally, detached or semidetached xenolithic blocks might be detected within the dykes. These could be distinguished from post-intrusive 'replacement fronts' by the following evidence:

(a) A magnetite corona around the xenoliths (viz. Horne, Mattagami). Derivation of the magnetite from sulphide is proved by textural evidence and by Ti-free composition.

(b) Strong 'monoclinicity' of pyrrhotite. Both (a) and (b) are consistent with the experimental observation of Desborough and Carpenter (1965) that natural hexagonal pyrrhotites when heated in an oxidizing environment, are converted into magnetite and hexagonal Fe_7S_8, the latter being transformed to monoclinic structure during cooling. A crystallizing dyke surrounding a sulphide xenolith could indeed serve as an oxygen reservoir.

(c) Lattice-like intergrowth between sphalerite and chalcopyrite (viz. Geco) which is similar to the texture produced by Roberts (1965, Fig. 3) on chalcopyrite—sphalerite aggregate and by Filimonova (1964) on natural intergrowth.

(d) Disseminated halo of pyrite surrounding the xenoliths. (viz. Horne).

(e) Depletion in the lighter sulphur isotope (viz. Horne).

(4) Veinlets of sulphides into the dyke (Fig. 17a). These may have diverse origin, e.g., sulphurization of the chilled zone along cracks (Horne), selective melting (Geco), flowage of plastically mobilized component of the orebody, (Horne Normetal), etc.

(5) Some isolated sphalerite euhedra with overgrowth of plagioclase microlite (Horne) indicate transfer of volatile sulphides across the interface.

(6) Re-equilibration on the sulphide side of the interface may find expression in the following textural and mineralogical features:

(a) Dissociation of pyrite and pyrrhotite to magnetite (Fig. 17a) along the interface. All stages of alteration can be seen. Frequent optically-iso-oriented patches of pyrrhotite in magnetite matrix, Ti-free composition of the magnetite, and textural relation of magnetite with pyrite unequivocally establish the trend of reactions.

(b) The released sulphur, if unable to escape into the dyke to pyritize its border, may react with the silicate gangue and the sulphide minerals in the contact zone to bring out the following changes:

(i) React with the silicate gangue to produce a pyrrhotite rim around the gangue inclusion, while converting the Fe-Mg silicates to predominantly Mg-rich silicates like anthophyllite amesite, etc.; abundant tiny needles of rutile are released during the process (Normetal). It may be mentioned here that abundance of anthophyllite as gangue mineral near intrusive contact has been reported by several workers (Viz. Watson 1963) without perhaps realising the significance.

ii) It might sulphurize the pre-existing pyrrhotite to a composition close to Fe_7S_8 so that subsequent cooling would produce monoclinic pyrrhotite. Regular increase in the monoclinicity of pyrrhotite is, therefore, to be expected near the contact (viz. Willroy, Horne, Mattagami).

iii) Reaction of iron-rich sphalerite with S-vapour (at fugacity of S greater than that of the FeS-ZnS join) leading to the formation of pyrrhotite lamellae and patches within sphalerite, thus simulating exsolution intergrowth (Zawar; see Barton and Toulmin 1963, Fig. 6b)).

iv) Formation of a new generation of disseminated pyrite in the contact zone whose late origin is proved by zonally arranged inclusions of sulphide and silicate minerals, often optically isooriented. Those that are derived by reaction with pyrrhotite contain minute blebs of chalcopyrite, establishing the ternary composition of pyrrhotite in the Cu-Fe-S system.

(c) Sulphide-sulphide or sulphide-silicate reactions are manifest in the following textural/mineralogical features of the contact zone:

i) chalcocite + pyrite = bornite + chalcopyrite (Butte, Sales and Meyer 1951)

ii) chalcopyrite + pyrrhotite = cubanite + pyrite (Horne)

iii) sphalerite + aluminosilicates → gahnite (Normetal)

iv) sphalerite + magnetite (inclusion) = marmatite + ilmenite (inclusion) (Normetal)

v) sphalerite + pyrite = zoned marmatite (with pyrrhotite + chalcopyrite blebs) +pyrite (Zawar, Horne, Willroy)

(7) Shearing of the sulphide wall, is preserved only when galena and chalcopyrite are absent or rare in the adjacent part of the orebody (cf. Mattagami); otherwise these two minerals would be plastically mobilized into the sheared zone and annealed, resulting in the enrichment of these minerals along the contact (Horne, Zawar).

(8) The thermally dissociated (pyrite→magnetite) zone less than 1″ thick, or the chalcopyrite/galena enriched zone, often forms a conspicuous banding parallel to the dyke-ore interface. Where the orebody is originally banded, this secondary banding runs askew to the primary banding of the ore body (cf. Zawar, Horne).

(9) Nature of twinning in chalcopyrite in sulphide ores along an intrusive contact is somewhat different from that of the normal ore (Normetal, Noranda). Abundance of spindle-shaped twin lamallae in such ore could either represent-deformation—twinning consequent upon flowage of chalcopyrite into the sheared contact, or these might be 'thermal twins' (Cahn

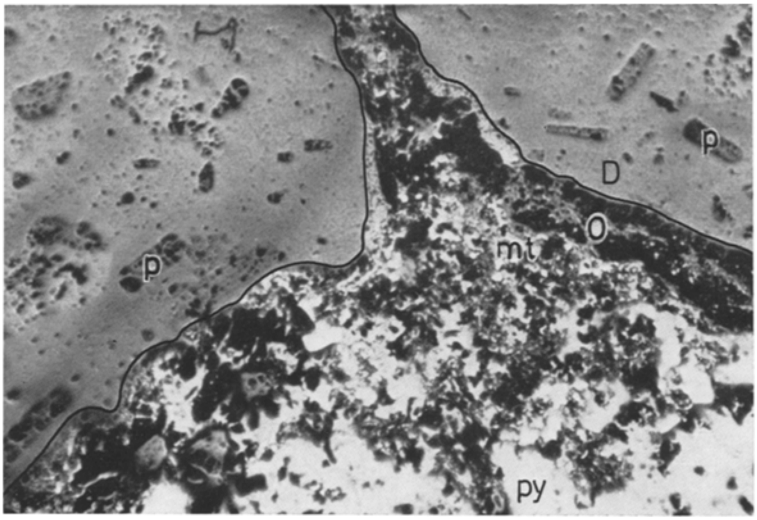

Fig. 17a. Photomicrograph of a dyke-ore contact specimen, unaffected by any later metamorphism. Pyrite dissociated to magnetite and ore vein injected into the dyke. Chilled margin with few plagioclase phenocrysts in glassy matrix. Horne mine, Noranda. Incident light, 200x

1954, 1964). However, occasional swelling, and absorption and blunting of twin lamellae similar to those in thermally treated mechanical twins in metals, perhaps indicate a similar mode of origin.

(10) Sometimes (Ames 1962), depletion in S^{32} might takes place in thermally metamorphosed sulphide, presumably due to escape of the lighter fraction. However, such depletion might not be detected due to the mixing of older and new generations of pyrite in the contact aureole.

(11) Yarosh *et al.* (1967) demonstrated loss of photoluminescence in sphalerite from dyke contact aureole. This may also constitute a significant criterion if it is found to be the case in other occurrences.

(12) Partial or complete destruction of fluid inclusions constitutes another valuable criterion (Lockerman 1962) that has been utilized by Shatagin (1968) to determine dyke-ore age relationships.

Case II — Dyke Post Ore, Metamorphism Preceding Intrusion

Any or all the evidence of thermal effects along the interface might be missing, depending upon two factors:

(a) The intensity of regional metamorphism which might already have brought about re-equilibration among silicates and sulphides in the orebody as a whole, — reconstitutions which otherwise would have been expected along the intrusive contact only. Such reconstitution includes conversion of sphalerite to gahnite, sulphide-silicate reactions providing pyrrhotite, Mg-rich silicate, and rutile, etc.

(b) The time gap between the peak of metamorphic intensity and intrusion. Since the temperature at the interface at the time of intrusion is dependent on the initial temperature difference between the intrusive and the host rock, a relatively shorter gap between the peak of metamorphism and intrusion would mean slower cooling and hence a less prominent chilled border of the intrusive.

Case III — Intrusive Post-Ore, Pre-Metamorphic

(1) More widespread replacement and penetration of the intrusive by sulphides than in cases I and II.

(2) Occasional pseudomorphous replacement of metamorphic minerals of the intrusive by sulphides (e.g., of biotite by chalcopyrite,

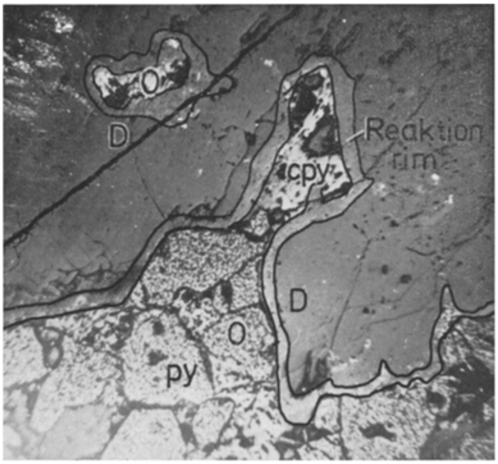

Fig. 17b. Photomicrograph of a dyke-ore contact specimen, affected by later metamorphism; dyke is recrystallized, chill obliterated, and a fine-grained reaction rim occurs along sulphide-silicate contact. Geco mine. Incident light, 100x

Fig. 18) pointing to *late* mobilization of the sulphides.

(3) The chilled edge might be eaten away by replacing sulphides or reconstituted (Fig. 17b) beyond recognition (e.g., Mine de Poirier and Northern Exploration).

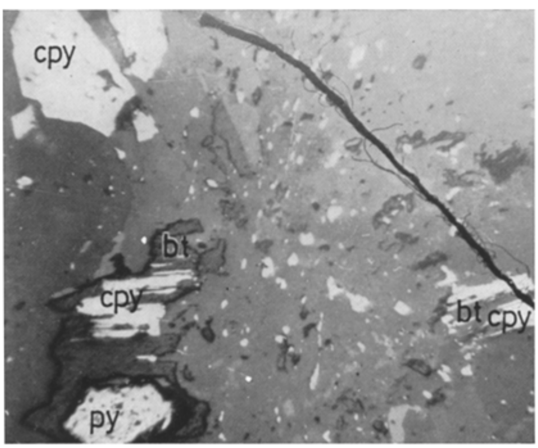

Fig. 18. Pseudomorphous replacement of biotite (bt) in a metamorphosed basic dyke by chalcopyrite (cpy), suggesting late mobilization of sulphides. Dyke post-ore, pre-metamorphic. Geco mine. Incident light, 250x

Case IV — Dyke Pre-Ore, Unmetamorphosed

(1) No difference in the degree of chilling against sulphide and silicate wall.

(2) None of the thermally activated reactions cited in cases I and II.

(3) Possibility of selective replacement of specific minerals in the dyke.

(4) No element/mineral redistribution near the contact.

(5) Thermal metamorphism of the country rock. Inclusions of silicate country rocks in sulphides might also retain evidence of thermal metamorphism if suitably located. In contrast, products of wall-rock alteration should be free from such effects.

Case V — Dyke Metamorphosed, Pre-Ore

In effect it would be a case of replacement of basic metamorphic rock by sulphide mineralization, leading to:

(a) Replacement of metamorphic silicates by sulphides,

(b) Smears and films of sulphides along cleavages of the metamorphic rock.

(c) Lack of any effect of deformation on sulphides.

Case VI — Dyke Pre-Ore, Metamorphism Post-Ore

(1) No difference in the degree of chilling against sulphide and silicate wall.

(2) None of the thermally activated reactions cited in cases I and II.

(3) Sulphide-silicate reactions along the interface.

(4) Replacement and injection of the dyke by sulphide.

(5) Wall-rock alteration products also metamorphosed.

(6) Numerous corona structures of sulphide-silicate reactions within the dyke.

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