U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

GEOLOGIC CONSTRAINTS ON METALLOGENY OF MAGMATICALLY UNDERPLATED LOWER CRUST IN THE IVREA-VERBANO ZONE, NORTHERN ITALY

by

Carl R. Thornber[1], James E. Quick[1], Adriano Mayer[2] and Silvano Sinigoi[2]

Open-File Report 93-504

[1]U.S. Geological Survey, Mail Stop 903, Federal Center, Denver, CO. 80225
[2]Istituto di Mineralogia e Petrografia, dell'Universita, Universita di Trieste, Piazzale Europa, 1, 1-34100, Trieste, Italy

1993

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INTRODUCTION

A large proportion of metal deposits in continental environments developed in association with regional tectonic extension accompanied by magmatism (cf., Sawkins, 1990). The age, deposition mechanisms, specific enviroments and types of ore are highly variable in these deposits. Stratiform and fracture-filling deposits were generated in the high fluid and heat flux sedimentary regimes of rift basins. Porphyry ore systems may be associated with felsic plutonism during large scale crustal melting in either intracontinental or back-arc extended regimes. Ni-Cu sulfide horizons in large mafic intrusive complexes associated with intracratonic rifting (e.g., Duluth Complex, Minnesota and Noril'sk, Siberia) comprise nearly 70% of the world's exploited resources and projected reserves of Nickel (De Young and others, 1985; Naldrett, 1989). More than 90% of the total world resources of Platinum Group Elements (PGE) occur in large, intracratonic layered mafic complexes (e.g. Bushveld, Great Dyke, and Stillwater) (Naldrett and Barnes, 1986; Naldrett, 1989). Although the tectonic settings in which these mafic complexes were emplaced remain enigmatic, recent workers have hypothesized that their emplacement may be linked to extensional tectonism (Irvine, 1992; Carr and others, in review).

Metallogenesis associated with magmatism in extented crustal environments may ultimately be tied to processes that occur near the crust-mantle boundary. Underplating of the crust by mantle-derived basaltic magmas is hypothesized as a driving mechanism for large-scale heat and fluid flux in active extensional regimes (Lachenbruch and Sass, 1985; Lachenbruch and others, 1985). Mantle-derived magmas in these terranes may either intrude the overlying crust to produce ores that are directly or indirectly associated with basaltic volcanism, or they may crystallize at lower to intermediate crustal levels where deposits of plutonic affinity result from in situ magmatic processes related to differentiation, fractionation and/or crustal assimilation. High P-wave velocities and deep seismic reflection profiles provide evidence that the lower crust of Phanerozoic and Proterozoic extensional terranes is underplated by layered mafic cumulates (Okaya and Thompson, 1986; Gans 1987; Fountain, 1989; Berhendt and others, 1990). Despite the growing evidence of its significant role in crustal evolution and as a fundamental control of continental-rift metallogeny, magmatic underplating remains a poorly understood process. Although large volumes of underplated rocks are in the lower crust of the Basin and Range Province, the Rio Grande rift, the Salton Trough, the Midcontinental rift and the Atlantic margin, there are no places in the United States where deep-crustal magmatic ore-forming systems may be studied directly.

The Ivrea-Verbano zone (IVZ) of northern Italy is one of the few places in the world where magmatically underplated deep crust is exposed at the earth's surface and thus presents an opportunity to evaluate first-order metallogenic processes related to crustal underplating. This terrane includes a steeply dipping section of Permian mafic plutonic rock, known as the Mafic Complex, which is interpreted to have been intruded at the base of the lower crust (Rivalenti and others, 1975, 1981, 1984; Fountain, 1976; Fountain and Salisbury, 1981: Sills, 1984; Fountain, 1989; Wedepohl and others, 1989; Voshage and others, 1990; Quick and others, 1992). Within the Mafic Complex, numerous Fe-Ni-Cu magmatic sulfide deposits were mined for nickel during the late 19th century and again during the Second World War, during which time approximately 30,000 tons of ore were extracted with ore-grade ranging between .3 and 1 wt% Ni (Ferrario and others, 1982 and Garuti and others, 1990). In some of these deposits PGE concentrations exceed 3000 ppb.

An integration of existing information on magmatic sulfide deposits and new geologic data is necessary to provide groundwork for more detailed investigation of ore-forming processes of the IVZ. In this report, we present a review of previous work pertaining to IVZ metallogeny. Geographic distribution, petrology and geochemistry of IVZ metal deposits are reviewed and correlated with new geologic mapping. Ongoing mapping has provided new perspectives on the internal structure and emplacement mechanics of the Mafic Complex that are consistent with a model of magmatic underplating during crustal extension. Based upon our preliminary assessment, further investigation should provide information which is pertinent to evaluating poorly understood aspects of metallogenesis associated with magmatic underplating beneath rifting continental terranes.

REGIONAL GEOLOGIC AND TECTONIC SETTING

This section provides a synopsis of the geologic and tectonic setting of the Ivrea-Verbano Zone as presented in greater detail by Quick and others (in review). Comprehensive reviews of the regional geology of the Ivrea-Verbano Zone are also presented by Zingg (1983), Fountain (1989), Zingg and others (1990), and Handy and Zingg (1991).

The Ivrea-Verbano zone (IVZ) is a 140-km-long, 5- to 15-km-wide, tectonically bounded sliver of plutonic and high-temperature, high-pressure metamorphic rocks in the Alps of northwestern Italy (Figure 1; Mehnert, 1975) that are thought to represent a cross-section through the lower continental crust and into the mantle. The steeply dipping IVZ section is comprised of three major lithologic components: (1) mantle peridotite (Shervais, 1979, Sinigoi and others, 1980; Rivalenti and others, 1981); (2) an igneous complex, up to 10 km thick and referred to as the Mafic Complex, comprised of predominantly gabbroic and also dioritic and granitic rocks (Rivalenti and others, 1981, 1984) and (3) amphibolite to granulite facies paragneiss grouped as the Kinzigite Formation (Schmid and Wood, 1976; Zingg, 1983). To the northwest, the IVZ is juxtaposed by the Canevese segment of the Insubric Line against metamorphic rocks of the Austroalpine Domain (Schmidt and others, 1987). To the southeast, it is separated from amphibolite-facies gneiss and late-Paleozoic volcanic and intrusive rocks of the Strona-Ceneri zone by the Cossato-Mergozzo-Brissago and Pogallo Lines (Boriani and Sacchi, 1974; Zingg, 1983; Handy, 1987). Final rotation into a subvertical orientation

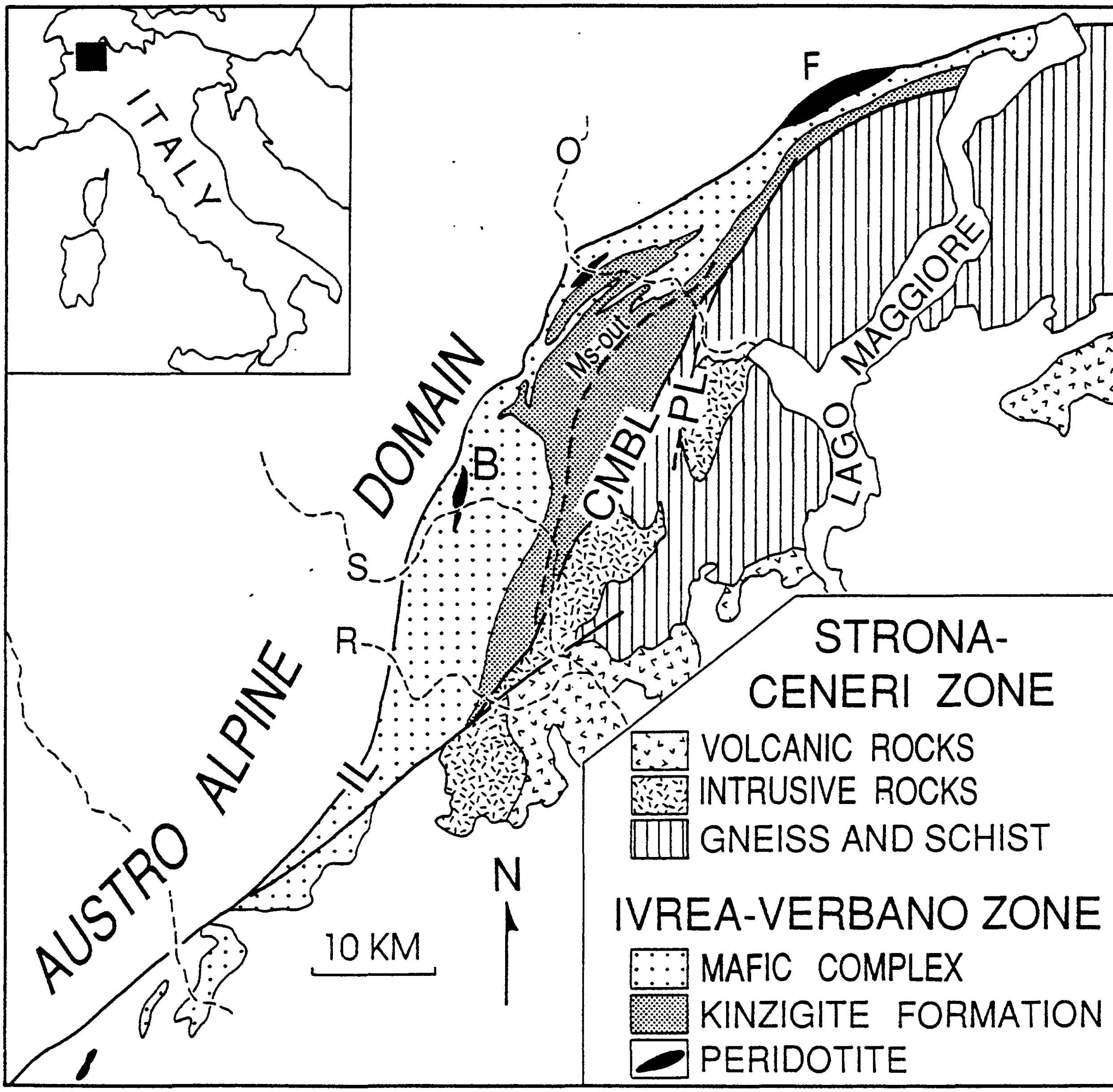

Figure 1. Geology of the southern Alps in the vicinity of the Ivrea-Verbano Zone based on Zingg (1983). Inset shows location of area in northern Italy. IL, Insubric Line; CMBL, Cossato-Mergozzo-Brissago Line; PL, Pogallo Line; B, Balmuccia Peridotite; F, Finero Peridotite; O, Ossola River; S, Sesia River, R, Serrera River; Ms-out, Muscovite-out isograd.

and emplacement into the upper crust occurred during Alpine transpression and lithospheric wedging (Nicolas and others, 1990; Zingg and others, 1990). Gravity and seismic reflection data suggest that the present geophysical expression of the Ivrea-Verbano Zone dips steeply to the southeast and flattens into a subhorizontal orientation at mid-crustal levels (20 to 30 km depth) beneath the Po Plain (Berckhemer, 1968; Nicolas and others, 1990).

The highest crustal levels occurring within the IVZ are represented by paragneiss of the Kinzigite Formation, which crop out along the southeastern margin of the zone (Figure 1). These rocks are interpreted to be the metamorphic equivalents of pelitic sediments, greywackes, arenites, carbonates and mafic volcanic rocks (Zingg,1983). Amphibolite-facies assemblages dominate in the southern IVZ and granulite-facies assemblages are more prominant in the north. The Kinzigite Formation is interleaved with and underlain by the Mafic Complex.

Several investigators have concluded that the Mafic Complex was magmatically underplated beneath continental crust (Rivalenti and others, 1981, 1984; Fountain, 1989, Hamilton,1989, Voshage and others, 1990). In the southern IVZ, where the Mafic Complex is thickest, the highest temperature assemblages and most extensive migmatization of Kinzigite Formation are near the Mafic Complex (Zingg, 1983; Sills, 1984). This is consistent with heating during emplacement and crystallization of the intrusive sequence. Geobarimetric calculations on igneous rocks in the southern portion of the Mafic Complex indicate that intrusion occurred at a depth of 20 to 25 km (Rivalenti and others, 1981).

Lensoidal bodies of mantle peridotite, which crop out for the most part near the Insubric Line (Figure 1), may represent fragments of subcontinental mantle (Shervais, 1979; Rivalenti and others, 1981; Sinigoi and others, 1980; Ottonello and others, 1984; Wedepohl and others, 1989). The east flank of the Balmuccia peridotite (Figure 1) has been reputed to preserve the contact between mantle rocks and pyroxenite cumulates of the Mafic Complex (Shervais, 1979; Rivalenti and others, 1984; Pin and Sills, 1986). The validity of assumptions that the Balmuccia peridotite was contiguous with the mantle at the time of magmatic underplating and that these magmas were consanguineous with diapiric intrusion of Balmuccia peridotite is questionable (Mayer and others, 1992). Detailed mapping is currently in progress to evaluate the hypothesis that these peridotite massifs may rerpesent Franciscan-Type "knockers" that were present in the crust prior to intrusion of the Mafic Complex. However, regardless whether the petrologic MOHO is exposed in the IVZ, previous investigations of field relations, phase relations and geobarometry clearly demonstrate that the Mafic Complex intruded the lower crust.

The timing of intrusion of the Mafic Complex is not well constrained but the most reliable data suggest that it was a Permian event, occurring sometime bewteen 290 and 250 Ma (c.f., Voshage and others, 1990 and references therein). Zircon data from chromite layers associated with the Finero peridotite suggest that magmatic or metasomatic activity continued in the northernmost IVZ until 200 - 210 Ma (vonQuadt and others, 1992). The tectonic setting of the Ivrea-Verbano Zone during this time period is uncertain. Based upon the calc-alkaline affinities of the both the Mafic Complex and granitic rocks of the adjacent Strona-Ceneri zone, previous workers have proposed a magmatic-arc environment (Hamilton, 1989 and Voshage and others, 1990). On the basis of structural data, Brodie and Rutter (1987) and Brodie and others (1989) have stressed the possible role of extensional tectonics in the Late Paleozoic to Early Mesozoic structural evolution of the Ivrea-Verbano Zone. Permo-Triassic extension within the Ivrea-Verbano Zone is consistent with widespread evidence for penecontemporaneous rift-related graben formation in the region (Dal Piaz, 1992). It must be emphasized, however, that crustal extension and a magmatic-arc setting are not mutually exclusive, as many neogene arcs are also regions of crustal extension (Hamilton, in press). The likelihood that the intrusion of the Mafic Complex was contemporaneous with large amounts of crustal extension is demonstrated by large and small scale synmagmatic deformation features combined with theoretical modeling for the development of analogous structures in ophiolitic gabbros (Quick and others, 1992; Quick and others, in review; Quick and Denlinger, in press).

GEOLOGY OF THE MAFIC COMPLEX

Prior to mapping reported by Sinigoi and others (1991), Quick and others (1992) and Quick and others (in review), interpretations of the geology of the Mafic Complex had been limited to studies of more accessible exposures within the Sesia and Mastellone Valleys (Figure 1). Rivalenti and others (1975, 1984) divided the Mafic Complex east of the Balmuccia Peridotite into Basal, Intermediate and Upper Zones which grade into the Main Gabbro and "Diorites"[3]. The Basal and Intermediate Zones (lowest ~700 m of the complex), consist of layered, foliated and synmagmatically deformed mafic and ultramafic rocks, and intercalated metasedimentary septa. Charnockitic rocks are locally associated with and interpreted to be partial melts of the metasedimentary septa. The Upper Zone (~1km thickness in the Sessia Valley) is separated from the Intermediate Zone by a major metasedimentary septum, and is composed of layered norite, garnet-bearing gabbro, anorthosite, olivine gabbro, and minor ultramafic cumulates. These rocks grade upward into the 5- 7-km-thick Main Gabbro with progressive loss of compositional layering. The Main Gabbro is composed of relatively homogeneous gabbronorite in which hornblende increases in abundance upwards. Upsection, the Main Gabbro grades into "Diorites", which constitute the uppermost part of the Sesia section, with the appearance and progressive increase upward in modal abundance of biotite.

The stratigraphy described in the preceding section is different from that in the Sessera Valley 10 km to the south (Sinigoi and others, 1991). There, approximately 4 to 5 km of layered amphibole gabbro constitute the deepest rocks in the complex. These are overlain by a <1-km thick zone of interlayered amphibole gabbro, norite and

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[3]"Diorites " is traditionally written with quotation marks to emphasise that this unit comprises an extremely heterogeneous group of biotite-bearing lithologies (Quick and others, in review).

metasedimentary septa (paragniess) followed by approximately 2 km of norites interlayered with lesser amounts of amphibole gabbro, charnockite, and anorthosite. The contrast of this stratigraphy from north to south indicates that important lateral lithologic variations exist in the Mafic Complex.

Figure 2 illustrates the gross structure in the central and southern portions of the Mafic Complex. The locations of Fe-Cu-Ni sulfide deposits that have been the subject of recent studies by Ferrario, Garuti and coworkers are indicated in this figure and discussed later in the context of their geologic association within the Mafic Complex. Data in the figure include attitudes on penetrative mineral foliation, layering defined by lithology, and mineral lineation. These data define a striking arcuate structure in the complex and indicate that its evolution was more dynamic than previously recognized. The current interpretation of this structure (Figure3; Quick and others, 1992) is that, while magmas were undoubtedly injected at various levels within the complex, a significant amount of magma ponded at the base of the crust and above denser crystal mushes deposited by previous melt batches. Synmagmatic deformation in the complex occurred as the crystal mush subsided and was displaced downward and outward, away from the locus of lower crustal intrusion. As a consequence of this deformation: (1) layers deposited on the floor of the magma chamber were deformed and rotated into upwardly concave shapes that dip toward the magma chamber; (2) feeder dikes that penetrated the cumulate pile near the magma chamber were rotated into an orientation parallel with the layering, but those that invaded farther from the magma chamber were less deformed and retained cross-cutting relationships; and (3) total deviatoric strain increased down-section so that primary magmatic structures and textures were modified or obliterated in the lowermost gabbros (Quick and Denlinger, in press). Septa of metasediments in the mafic complex were incorporated during intrusion of the overlying Kinzigite formation and were dragged downward and outward by the flow of partially molten cumulates. In the context of this model, anhydrous or hydrous pyroxenitic layers that host disseminated and massive sulfides could have originally been sills, dikes and irregular intrusive bodies, which were similarly transposed into parallelism with layering of the host rocks. Discussion of various types of IVZ ore deposits, their geologic associations and the implications of these new interpretations of the evolution of the Mafic Complex upon ore petrogenesis are provided in the following sections.

ORE DEPOSITS IN THE MAFIC COMPLEX

Ore bodies within the Mafic Complex consist of Fe-Ni-Cu-(Co) sulfides (± PGE and Au), Fe-Al-(Cr) spinels and Fe-Ti oxides (Bigioggero and others, 1979; Ferrario and others, 1982). Small concentrations of titaniferrous magnetite and ilmenite occur as centimeter thick layers within the lower layered portions of the complex and small lenses (a few centimeters thick) of Fe-Al -(Cr) spinel are found within and around peridotites, near the base of the complex. In contrast to many large gabbroic layered intrusions

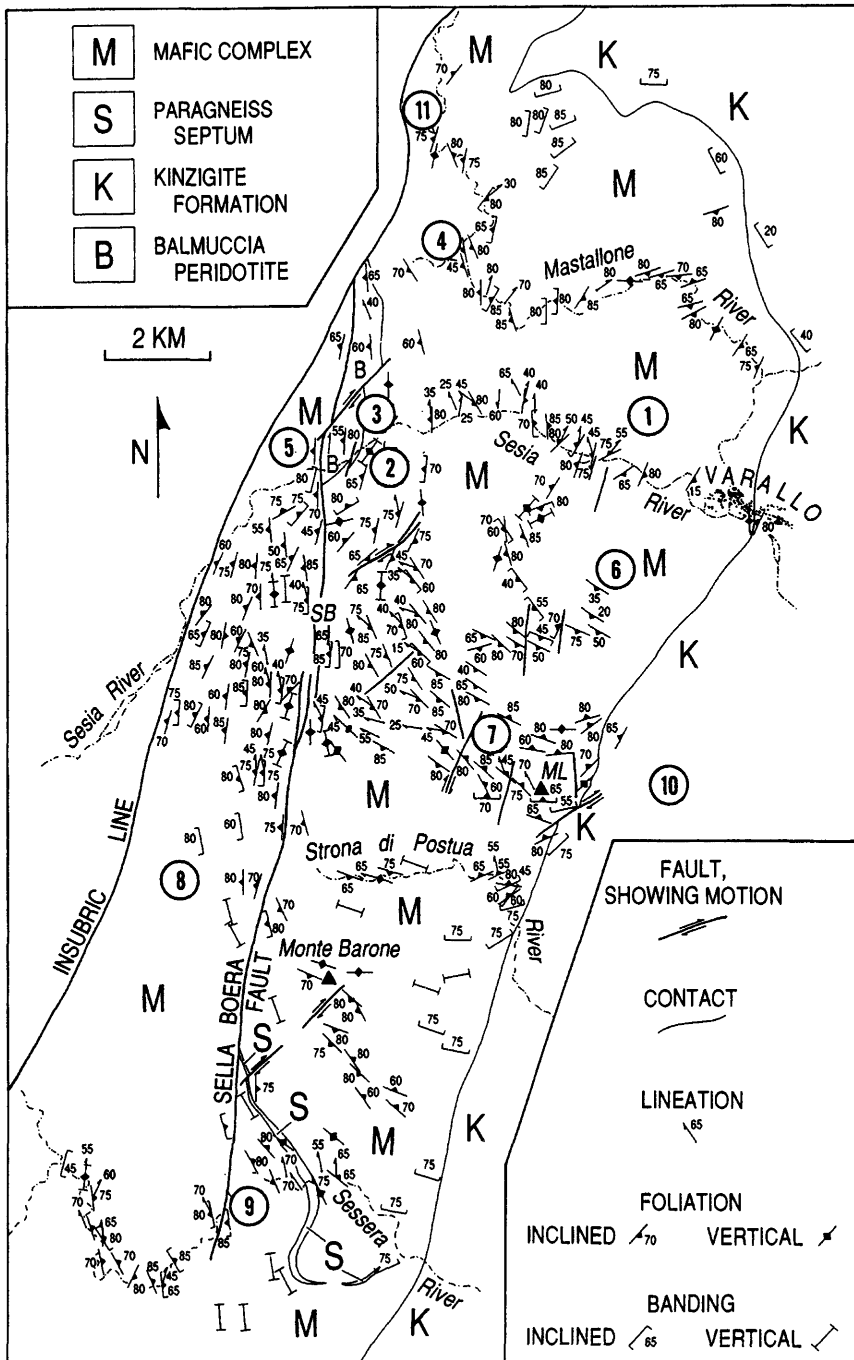

Figure 2. Structure of the southern Mafic Complex showing locations of Ni-Cu-Sulfide mines (Modified from Quick et al, in review). Rocks west of Insubric Line belong to the Austro-Alpine Domain. M, Mafic Complex; K, Kinzigite Formation; ML, Monte Luvot; SB, Sella Bora; Mine Locations: (1) Valmaggia, (2) Isola, (3) Bottorno, (4) Gula, (5) Guaifola, (6) Bec d'Ovaga, (7) Castello di Gavalla, (8) Sella Bassa, (9) Piancone, (10) Fei di Doccio, (11) Meula. Ore categories and host enviroments for each localitiy are presented in Table 1.

Table 1 List of sulfide mine localities in south and central portions of the Mafic Complex. Location numbers are as shown in Figure 2. Location names, ore categories and host environment descriptions compiled from Ferrario and others (1982), Garuti and others (1986) and Garuti and others (1990)

Location number	Location name	Ore category	Sulfide host environment
1	Valmaggia	III	Discordant amphibole-olivine-pyroxenite "pipe"
2	Isola	I	Lower zone of concordant pyroxenite between gabbro-norite layers, above felsic granulite
3	Bottorno	I	Concordant garnet-pyroxenite layer (with plagioclase-rich zones) between garnet-gabbros (with pyroxenite layers): above peridotite
4	Gula	I	Base of concordant amphibole-opxite between gabbro-norite layers, above garnet-plagioclase-rich layer and graphitic-schist septa
5	Guaifola	I	Pyroxenite below peridotite
6	Bec d'Ovaga	III	Discordant hydrous pyroxenite "pipe"
7	Castello di Gavalla	III	Discordant hydrous pyroxenite "pipe"
8	Sella Bassa	II	Lower zone of concordant amphibole-olivine-pyroxenite between amphibole-gabbro layers
9	Piancone	II	Hydrous pyroxenite
10	Fei di Doccio	III	Discordant hydrous pyroxenite "pipe"
11	Meula	I	Data not available

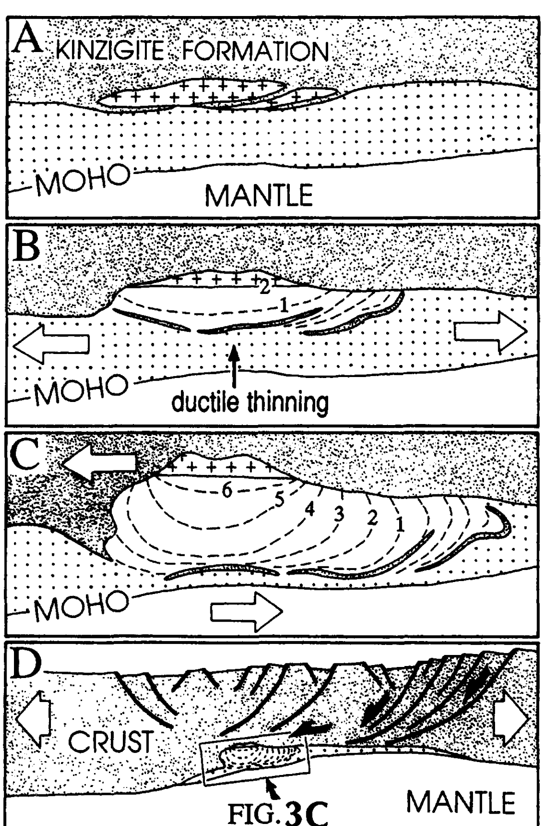

Figure 3. Evolution of the Mafic Complex (Modified from Quick et al., 1992). **A:** Gabbro melt (crosses) forms small magma body in Kinzigite Formation (shaded pattern) and above preexisting cumulates (dotted pattern). **B:** Crustal Extension. Examples of new cumulus layers shown as dashed lines. Stretching (large arrows) and local thinning of Mafic Complex causes subsidence of cumulates and septa derived from Kinzigite Formation . Septa and layer1 have subsided below the base of the magma chamber as layer 2 is deposited on the chamber floor. **C:** Simple shear during continued extension. Motion of Kinzigite formation relative to Mafic Complex and mantle shown by arrows. Layers 1 and 2 have subsided and moved far from the magma chamber and are overlain by successively younger layers 3 through 6. **D:** Hypothetical extentional enviroment accounting for shear of Mafic Complex during crustal underplating. Box indicates size and location of A-C and area represented by Figure 2.

elsewhere in the world, chromite seams or layers are not present in the Mafic Complex (Rivalenti and others, 1981, 1984).

Sulfide deposits occur in association with hydrous or anhydrous pyroxenitic rocks throughout the complex (Bigioggero and others, 1979; Ferrario and others, 1982; Garuti and Rinaldi, 1986a and 1986b, Garuti and others, 1986 , 1990). The locations of recently studied deposits that occur within the central and southern IVZ, where the Mafic Complex is thickest, are shown in Figure 2. These deposits are divided into three categories by Bigioggero and others (1979) on the basis of metal association and geologic setting. This petrogenetic grouping has been generally adhered to by subsequent workers. The geologic setting that is used as a key component in this classification scheme is based upon earlier and less extensive geologic mapping of the Mafic Complex than is now available. Nevertheless, this basis for categorizing IVZ ore deposits provides a useful context in which to review previous work on IVZ sulfide deposits. The sulfide deposit categories have been defined in the literature as follows.

I) Fe-Ni-(Cu) mineralization in pyroxenitic layers of the "Cyclic Units". "Cyclic Units" correspond to Basal and Intermediate Zones of Rivalenti and others, (1981). Pyroxenite layers are concordant with and intercalated with metasedimentary septa.

II) Fe-Cu-Ni mineralization in pyroxenitic layers of the Main Gabbro. These deposits were classified assuming that they occur within the Main Gabbro, as defined by Rivalenti and others (1975, 1981).

III) Fe-Ni-Cu mineralization in hydrous pyroxenitic "Pipes". "Pipes", also referred to as dikes, are isolated pods or discordant dikes of pyroxenite/hornblendite that occur within and above the transition zone from nonlayered gabbro-norites to "Diorites" near the top of the Mafic Complex. Also, a "pipe" occurs within the Kinzigite formation above the roof of the complex.

The location names (after Garuti and others, 1990) for each mine shown in Figure 2 are listed in Table 1. Table 1 also indicates each ore-deposit category, according to the scheme presented above, and a brief description of the host-rock environment compiled from previous workers.

Sulfide and Platinum Group Mineral (PGM) petrology and chemistry of samples from several mine sites have been studied in detail by Ferrario and others, (1982), Garuti and Rinaldi, (1986a and 1986b) and Garuti and others (1986). Transition metal geochemistry (Fe, Co, Ni, Pd, Pt, Rh, Ru, Ir and Os) along with Cu and Au concentrations in ore samples from numerous IVZ Cu-Ni-sulfide deposits have been evaluated by Garuti and others (1990). As presented herein, petrologic and geochemical characteristics of these deposits, along with salient interpretations, are compiled from these previous investigations.

The main ore assemblage reported for all IVZ sulfide deposits is, in order of decreasing abundance, pyrrhotite, pentlandite and chalcopyrite ($\pm$ pyrite, mackawinite and cubanite). Small grains of Pt-, Pd-, Ni-, Ag-, Pb-, and Bi-telluride grains and associated Co-, Ni-, Fe- and Ir-sulfoarsenides are irregularly distributed in pyrrhotite and pentlandite and are least abundant in Category I ores. In each of the three deposit categories, ore occurs as disseminated sulfides in primary textural association with mafic silicates and also as more massive bodies representing magmatic sulfides that have been concentrated by secondary processes.

Category I ore deposits occur at the base of the Mafic Complex within layers of pyroxenite. These pyroxenite layers are concordant with layers of foliated and synmagmatically deformed mafic rocks, metasedimentary septa and charnockitic rocks derived from melting of metasediments. Deposits of this group have been described from the abandoned mines of Isola, Gula, Guaifola, Bottorno and Meula (Figure 2). The sulfide-rich zones occur mostly close to or in contact with metasedimentary septa. In these pyrrhottite-rich deposits, sulfides are predominantly interstitial to pyroxene and occur as primary 0.5 to 10 mm aggregates amidst interstitial plagioclase, pyroxene and spinel (± amphibole and olivine). Frequent intergrowths of graphite, molybdenite and gold within primary sulfides have been interpreted to represent components derived from local assimilation of metasediments. Such sialic assimilation coupled with associated heat loss could promote sulfur saturation of mafic magma at the contact (Irvine, 1975; Garuti and others, 1990). Massive ore concentrations are limited to decimeter-sized nodules, produced by local accumulations of disseminated blebs. Sulfides of identical compositions are often concentrated in "low pressure shadows" defined by cleavage planes and fold hinges in deformed pyroxenite. This observation and that of high-temperature, ductile strain features within associated pyroxenes are interpreted by Garuti and others (1986) to indicate that sulfide liquid was concentrated not long after its segregation from the silicate magma and during near-solidus plastic deformation of the host pyroxenite.

The chemical composition of these deposits, compared to other categories, is characterized by low Ni (1-2 wt%), low Cu (0.1-0.5 wt%) and the overall lowest of PGE concentrations (in 100% sulfide; Figure 4). PGM are rare in this deposit category and are restricted in occurrence to later stage "mobilized" sulfide concentrations (Garuti and Rinaldi, 1986a). Garuti and others (1990) suggest that a steep positive slope of chondrite normalized PGE patterns; $[Rh/Ir]_{cn}$ of 6.5) may be characteristic of this group. Relatively low Ni/Co ratios in these samples (<10), along with lower Ni, Cu and PGE concentrations are attributed to differential partitioning of sulfophile elements as effected by a reduced magma/sulfide mass ratio (Campbell and Naldrett, 1979) in a magma which has assimilated sulfur from metasedimentary septa.

Category II ore deposits were originally defined as occurrences within pyroxenites concordant with foliated and layered gabbros and norites that are situated below more massive gabbronoritic rocks in the complex. This definition is potentially misleading because the only such occurrences described, at Sella Bassa and Piancone (Figure 2; Garuti and others, 1986) occur in the southern part of the Mafic Complex where more recent mapping shows that the section is not overlain by massive

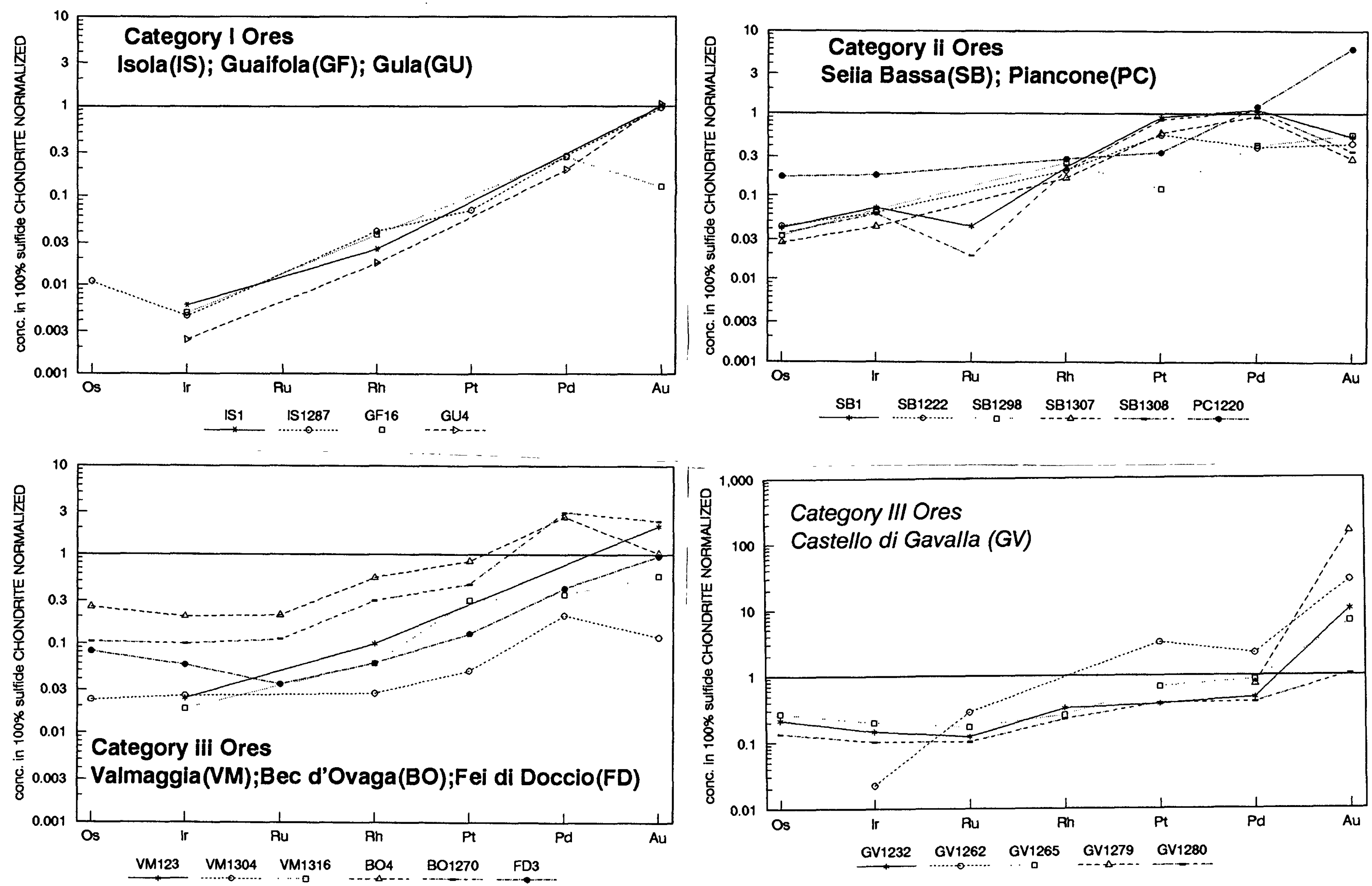

Figure 4. Platinum Group Element and Au signatures for samples of Ivrea-Verbano Zone Ni-Cu-Sulfide deposits of Category I, II and III affinities (Data from Garuti et al., 1990). Concentrations in 100% sulfide are normalized to chondritic values of Naldrett (1989) as reported by Garuti et al., (1990).

gabbronorite. The Sella Bassa mine is northwest of the area mapped in detail by Sinigoi and others (1991) who describe this terrane as dominated by layered amphibole gabbros. The mine site at Piancone, south of Sella Bassa, (Figure 2) has been subsequently referred to as a "Pipe" (Category III) by Garuti and others (1990) based upon chemical and petrologic criteria.

While details of geology in the Sella Bassa region are as yet unknown, Garuti and others (1990) indicate that Sella Bassa sulfides are not associated with septa of sedimentary rocks. The apparent lack of graphite and gold intergowths in sulfides support their conclusion that magmatic assimilation of sulfur and other components from crustal septa was negligable. The host rock is described as an amphibole-(olivine)-pyroxenite, with sulfides strictly associated with amphibole and interlayered with olivine-spinel-pyroxenites (Garuti and others, 1986). Massive sulfides occur as primary preciptitates which aggregate to form 1- to 3-cm-diameter nodular patches surrounded by hydrous silicate and as ore concentrated along shear zones (Garuti and Rinaldi, 1986a). The Sella Bassa sulfides have been interpreted to have originally segregated as immiscible melts from hydrous silicate magma. Textural relations suggest that sulfide precipitation was coincident with the crystallization of amphibole. Subsequent ore remobilization and concentration appear to have occurred in response to high temperature, synmagmatic deformation. At Sella Bassa, ore remobilization is accompanied by deuteric-like alteration of host rock, where sulfide veinlets are intergrown with amphibole, phlogopite, tremolite, chlorite and serpentized olivine. Garuti and others (1986) interpret this alteration as having a late stage magmatic origin, produced by fluids diffused along thermal and pressure gradients during deformation.

Compared to Category I deposits, the ore at Sella Bassa has higher concentrations of Ni (3.5 - 4.5 wt%) but not of Cu (0.21 - 0.31 wt%) and PGE are an order of magnitude richer (Figure 4). Sella Bassa also displays the greatest variety of PGM. This PGE mineralization is apparently restricted to intracrystalline intergrowths in remobililized pyrrhotite and pendlandite (Garuti and Rinaldi, 1986a; Garuti and others, 1990). The average $[Rh/Ir]_{cn}$ of 3.45 are the highest of IVZ ores analyzed and define a distinctly shallow, positive-sloping PGE pattern. Ni/Co ratios range from 20 to 30 at Sella Bassa and along with relatively high PGE concentrations are attributed to equilibration at greater magma/sulfide mass ratios (i.e. without local sulfur assimilation) that are more typical of other gabbro-related sulfide deposits (Naldrett, 1981).

Category III ore deposits , referred to as mineralized "pipes", are associated with hydrous pyroxenitic rocks that occur as pods or dikes within more massive gabbronorites and dioritic rocks comprising the upper portion of the Mafic Complex . A "Pipe" also occurs in the overlying Kinzigite Formation. The geology of these occurrences is not well exposed and has not been studied in detail. Localites of this type are described from Valmaggia, Bec d'Ovaga, Castello di Gavala and Fei di Doccio (Figure 2). The host rock in these deposits has a distinctive mineralogy dominated by olivine, amphibole, pyroxene and plagioclase with abundant accessory phases of spinel, phlogopite, biotite, apatite, graphite and "primary" carbonate. Olivine and pyroxenes display reaction textures in contact with amphibole and plagioclase. The high-grade ore comprises 1- to 3-cm-diameter nodular aggregates of sulfide in primary textural association with amphibole and mica. Minor phases of carbonate, graphite or apatite are only rarely intergrown with sulfides. In contrast to Category I deposits, the mobilized ore has textures indicative of late-stage crack and fissure filling, with sulfide cementing of a silicate breccia. At Valmaggia this is accompanied by deformation within the surrounding gabbronorite, along with late-stage lower temperature alteration similar to that described at Sella Bassa.

Category III deposits are richest in both Nickel (4.0 to 10.7 wt%) and Cu (0.8 to 11.8 wt%). PGE concentrations are variable with an average similar to Sella Bassa (Figure 4). Pt contents in excess of 3000 ppb have been analyzed in ore at Castello di Gavala. PGE tellurides are reported to occur in association with sulfides of both primary and secondary affinity and Ni- Co- and Ir-arsenides are resticted to intergrowths with primary sulfides. Au contents are relatively high in this group, particularly so at Castello di Gavala where samples range from 15 to >200 ppm Au. $[Rh/Ir]_{cn}$ values of 1.07 to 2.84 are low compared to Sella Bassa and PGE patterns have variable positive slopes (Figure 4). Likewise Ni/Co ratios are variable (from 15 to 50) but generally higher than in other types of deposits, consisitent with high magma/sulfide mass ratios. The volatile-rich character of the host rocks (i.e., CO_2, H_2O, F), along with high concentrations of incompatible elements and P_2O_5 have led recent workers to suggest an origin of primitive alkaline affinity. This hypothesis, forwarded by Garuti and others (1990) involves low-degree partial melting of an enriched mantle that was subsequent to and independent of magmatism which produced the bulk of the mafic complex. These authors imply that PGE profiles of the "pipes" are the most primitive and unfractionated of IVZ ore occurrences, but are unable to explain the relative partitioning apparent within PGE and the enriched concentrations of Cu and Au by this model.

DISCUSSION

Previous interpretations of ore petrogenesis in the IVZ were based on limited field data and the assumption that the Mafic Complex was comprised of multiple unrelated intrusions. Consistent with this framework, different categories of mineralized pyroxenites have been interpreted to be genetically unrelated (e.g., Ferrario and others, 1982; Garuti and others, 1990). New geologic mapping suggests that the entire complex evolved slowly but continuously, by underplating during crustal extension. While the detailed geologic settings of IVZ ore deposits remain to be resolved, overall indications of the structural evolution of the Mafic Complex suggest that the three previously defined categories of ore-bearing-pyroxenites may be genetically linked.

As pointed out by Garuti and others (1986), sulfide components in all three groups of ore-bearing pyroxenitic rocks are associated with fabrics indicating mobilization coincident with high-temperature synmagmatic deformation. These authors also emphasize that the parental magmas of ore-bearing assemblages were volatile-rich and that these volatiles were likely to have evolved into ore-bearing fluids of late-stage magmatic affinity that were propagated along pressure and temperature gradients to produce sulfide breccias and low-temperature alteration products in Category II and III deposits. Numerical modelling by Quick and Denlinger (1993) indicates that large-scale, ductile deformation in partially molten cumulates, with geometries similar to those of the mafic complex, induces pressure gradients that drive intersititial melts upward and back toward the magma chamber. As a consequence, volatiles and magmatophile elements (including Cu and Au), which tend to be concentrated in late stage melts, should be transported toward the roof of the complex. This sense of fluid migration is consistent with the sequencial enrichment of volatile and magmatophile components observed in Category I, II and III ore-bearing lithologies and their relative position from deeper to shallower parts of the complex (Figure 2).

It is plausible that crystallization of ore-bearing pyroxenites was initiated at the contact between magma and crustal septa, as the latter were incorporated during intrusion into the overlying Kinzigite formation, near the roof of the complex. The initial segregation of primary sulfide may have occurred as a result of assimilation and fluid influx from septal anatexis. Partially molten and volatile-rich lithologic packages were dragged downward and outward from the magma chamber and transposed into parallel layers at the base of the complex. Immiscible sulfide droplets were concentrated in low pressure shadows of folds and shears that developed within the deformed pyroxenite. Such occurrences are characterisitic of Category I ores, which are restricted to concordant layers deep within the complex. These represent an endmember in a dynamic process at high pressure and temperature that drives volatile-rich insterstitial melts and ore-bearing fluids upward. The other endmember is characterized by Category III ore deposits, which have the highest concentration of volatiles, incompatible elements and Cu-Ni-(Pt) mineralization in the complex. These deposits occur as isolated pods and crosscutting dikes within biotite-rich massive rocks, which comprise the upper part of the complex, and also in lower levels of the overlying crustal rocks. Some pods of Catergory III ore could represent volatile rich pockets that were formed as boudins during ductile deformation of original pyroxenitic layers. As fluids richest in volatiles, incompatible elements and ore-components are squeezed out during continued deformation along downward P-T gradients, the partial pressure of volatiles may exceed the confining pressure of the overlying crystal mush and thus produce crosscutting dikes or diatreme-like injections of volatile-rich ore-bearing fluids. In this sense, a number of category III deposits might be properly referred to as "Pipes".

CONCLUSIONS

A confluence of evidence suggests that the Mafic Complex was intruded in Permian time at deep levels ($\geq$20 km) within extending continental crust. The IVZ may be unique in providing an opportunity to study mineral deposits through an intact, 10 km-thick section of lower crust. It presents, therefore, an excellent opportunity to study ore-forming processes beneath continental rifts and to develop a model for the mineral potential of the magmatic complexes thought to exist beneath large parts of the United States. Added significance for these deposits stems from their similarity to PGE-rich deposits of the Merensky Reef of the Bushveld Complex and the J-M Reef of the Stillwater Complex.

The research of Garuti, Ferrario and coworkers, provides a wealth of information on the petrology, chemistry and deposition-related characteristics of sulfide deposits in the IVZ Mafic Complex. Geologic investigations in progress suggest that large-scale ductile deformation of the complex may have been as important as purely magmatic processes in ore genesis. Near the base of the complex, crosscutting vein and dike relationships may have been transposed and obliterated by progressive deformation, so that sulfide bearing pyroxenites appear to be concordant. Pressure gradients established by progressive deformation of cumulates may have forced migration of ore-bearing fluids, resulting in remobilization and concentration of sulfides. Deformation may also have forced the mobilization of larger amounts of volatile-rich material that intruded higher crustal levels as ore-bearing "pipes". These possibilities need to be tested by detailed studies of mineral occurrences. The processes that effect the physical partitioning of these metals between sulfides and mafic liquids, as influenced by assimilation and by subsequent fluid migration during remobilization under high P-T conditions are poorly understood. Also, the ultimate sources of precious metals (PGE and Au) and Ni and Cu in these deposits remain to be resolved.

Future studies of IVZ metallogenesis should focus on the structural and chemical characteristics of ore deposits as a function of depth in the crust. A sensible approach would be to exploit the results and interpretations of new geologic data by doing detailed mapping, petrology and geochemistry of ore-bearing pyroxenites occurring along strike within the arcuate structure from the base to the top of the complex (e.g., localities 3, 2, 7 and 10 in Figure 2). Such an approach could be augmented by Re-Os, Nd-Sr and stable isotopic data to help evaluate the continuity of age and source characteristics between different ore categories.

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