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NI-CU SULFIDE MINERALIZATION IN THE TURNAGAIN ALASKAN-TYPE COMPLEX: A UNIQUE MAGMATIC ENVIRONMENT

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INTRODUCTION

Nickel is a scarce commodity in the Canadian Cordillera, and there are currently no active nickel mines in British Columbia. The most notable past producer was the Giant Mascot (Pacific Nickel or Pride of Emory) mine (1958-1974) near Hope which processed some 4.2 million tonnes of sulfide ore averaging 0.77 wt. % Ni, 0.33 wt. % Cu, 0.68 g/t Au and 0.34 g/t PGE (platinum-group elements). The ore resided in an ultramafic phase of the Spuzzum pluton (*see* Nixon and Hammack, 1991).

The Turnagain ultramafic complex (Figure 1) hosts one of the few magmatic nickel occurrences of economic potential in British Columbia (Hancock, 1990; Nixon and Hammack, 1991). The geological setting of the sulfide mineralization is unusual in that it is hosted by an Alaskan-type complex, a magmatic environment that is not generally noted for its sulfide potential. In the case of the Turnagain complex, it appears that a unique set of genetic circumstances were responsible for the precipitation of substantial Fe-Ni-Cu sulfides from the parental magmas. The principal factors that appear to have promoted sulfide saturation in the Alaskan-type environment are considered below. It is suggested that the most important control on the formation of magmatic sulfides may ultimately derive from the rocks that host the intrusion, and hence have fundamental significance for exploration.

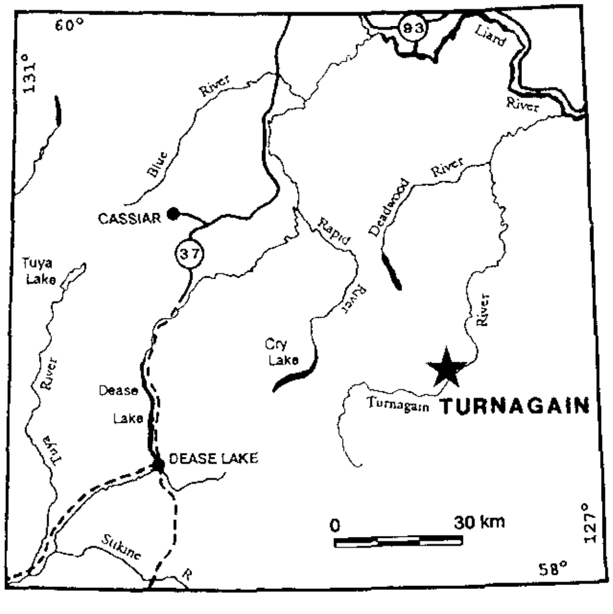

Figure 18-1. Location of the Turnagain Alaskan-type complex.

GEOLOGICAL ENVIRONMENTS FOR MAGMATIC SULFIDE DEPOSITS

Magmatic sulfide ores hosted by mafic and ultramafic rocks have historically been the principal source of world nickel production. Considering the recent discovery of high-grade Ni-Cu-Co deposits at Voisey's Bay, Labrador, such sulfides seem destined to remain the dominant producer of nickel in the foreseeable future. However, with the advent of innovative leaching and electrorefining techniques for metal extraction in recent years, low-grade, bulk-tonnage operations are now feasible for low-cost recovery of nickel and associated base and precious metals in sulfide ores. Owing to these developments, there are several prospective environments for mafic-ultramafic-hosted nickeliferous sulfide deposits in the Cordillera that warrant further attention. The most significant mafic-ultramafic rock packages occur in the oceanic (ophiolitic) and volcanic-arc terranes that were accreted to the margin of North America in the Early Mesozoic.

The geological environments of magmatic sulfide deposits may be classified according to tectonic and petrochemical affiliations. The vast majority of the world's magmatic nickel deposits are hosted by tholeiitic to komatiitic extrusive rocks and their intrusive equivalents (reviewed by Naldrett, 1989). These include important occurrences in Archean greenstone belts (*e.g.* Kambalda, Western Australia), rift-related settings (*e.g.* Thompson Nickel Belt, Manitoba), intrusions related to flood basalts (*e.g.* Noril'sk-Talnakh, Siberia), and large stratiform intrusions (*e.g.* Bushveld Complex, South Africa and Sudbury, Ontario). Among the environments traditionally regarded as least favourable for significant magmatic Ni-Cu sulfide deposits are those associated with ophiolites, kimberlites, carbonatites and other alkaline associations, and Alaskan-type complexes.

In this respect, it is interesting to note that the anorthositic Voisey's Bay intrusive suite was also formerly categorized as an unfavourable exploration environment for important Ni-Cu sulfide deposits. Yet, if predicted reserves are accurate, the Voisey's Bay troctolite body hosts one of the richest Ni-Cu sulfide deposits in the world. The lesson from Voisey's Bay is that, given apparently favourable genetic circumstances, even traditionally unimportant environments for magmatic Ni-Cu sulfide deposits, like that of the Alaskan-type Turnagain complex, may contain economically important sulfide mineralization. The impact of specific geologic variables conducive to sulfide saturation in Alaskan-type parental magmas are considered below following a review of the exploration history and geology of the Turnagain complex.

EXPLORATION HISTORY OF THE TURNAGAIN COMPLEX

Fe-Ni-Cu sulfides in the Turnagain complex were first discovered in 1956 at a showing on the banks of the Turnagain River. Little work was done until 1966 when Falconbridge Nickel Mines Limited acquired the claims. Between 1966 and 1973 extensive geological and geophysical surveys identified a number of sulfide showings (MINFILE 104I 014, 038, 051, 117-120 and references therein) that were subsequently tested by a program of short diamond drill holes (McDougall and Clark, 1972; Clark and McDougall, 1973}. Many mineralized outcrops were tested only by packsack drilling and some important semi-massive sulfide zones, such as the "Discovery" showing on the Turnagain River, were apparently never drilled successfully. The geological studies initiated by Falconbridge culminated in a Ph.D. dissertation by Clark (1975) and resulting publications (Clark, 1978, 1980). Interest in the PGE potential of the Turnagain complex in the mid to late 1980's led to additional geochemical sampling and geological mapping (Page, 1986; Nixon *et al.*, 1989). Maximum PGE values for the sulfide showings were reported as 461 ppb Pt and 1455 ppb Pd (Page, 1986). Renewed interest in the property began in 1996 when Bren-Mar Resources Limited initiated geophysical and geological work, including diamond drilling to more adequately test mineralized areas. To date, some 2500m of drilling have identified narrow (1m) intersections of semi-massive sulfides grading up to 1.4 wt. % Ni and 0.07 wt. % Co within much broader zones of disseminated mineralization (Livgard, 1996). Chalcopyrite-rich grab samples from the Discovery showing have yielded maximum grades of 1.6 wt. % Cu. From both the recent drilling and surface sampling, it is clear that disseminated sulfide mineralization in the Turnagain complex is more widespread than previously indicated.

REGIONAL SETTING

The regional geological setting of the Turnagain complex is somewhat enigmatic (Figure 2). In the most recent revision of the Cry Lake map sheet (Gabrielse, *in press* and personal communication, 1997), which builds upon earlier work (Gabrielse, 1985, 1991), the Turnagain complex is shown to be hosted by a westward-facing, folded and faulted, Cambrian to Mississippian metasedimentary succession that defines the miogeoclinal margin of Ancestral North America (Figure 2A). The wallrocks of the Turnagain complex, in part, are taken as equivalents of the fine-grained clastics of the Road River and Earn Groups. These rocks are overlain in turn by Upper Paleozoic to Triassic metavolcanic and metasedimentary sequences of unknown terrane affinity. The Kutcho Fault separates the latter rocks from the Early Jurassic Eaglehead pluton that forms part of Quesnellia, and oceanic accretionary complexes of the Cache Creek Terrane. Mid-Cretaceous plutons of the Cassiar Batholith intrude Lower Paleozoic and older strata of the miogeocline.

This interpretation of the regional geology implies that the Turnagain body, and an associated ultramafic to dioritic "ring complex" to the south that has a well-defined metamorphic aureole (Clark, 1975), have intruded rocks of the miogeocline. In all other cases (in British Columbia at least), Alaskan-type complexes are confined to the accretionary arc terranes of Quesnellia and Stikinia, and these terranes are faulted against Ancestral North America. Thus, a supra-subduction zone setting is required for the North American margin at the time of intrusion of the Turnagain complex. The age of the Turnagain complex potentially places constraints on this interpretation and is currently being investigated using ^{40}Ar-^{39}Ar dating techniques.

An alternative interpretation of the regional geology proposed in Figure 2B, places the Turnagain complex within an imbricated sequence of rocks thrust eastward onto the miogeoclinal margin of North America. This interpretation is possible because stratigraphic assignments are based largely on lithological similarities, and the contentious units (discussed below) have no age control. The rocks next to the Kutcho Fault that are designated as Upper Paleozoic to Triassic comprise a tightly folded package of interbedded felsic ("quartz-eye") to intermediate volcanic rocks, shale, siltstone, chert, volcanic greywacke and conglomerate, and minor carbonate (Clark, 1975; Gabrielse, *in press*). Their lithological mix and structural style strongly resemble rocks found further south that form the Lay Range Assemblage (Mississippian to Permian), widely regarded as the basement of Quesnellia (Monger, 1973; Ferri *et al.*, 1993), and this correlation is favoured here. However, another possibility (not shown in Figure 2) is that these rocks are atypically deformed and metamorphosed volcanic-sedimentary assemblages of the Upper Triassic Nicola-Takla arc.

The wallrocks of the Turnagain complex are black carbonaceous slates and grey graphitic phyllites. In Figure 2B, these rocks are considered to be correlative with the Middle to Late Triassic "black phyllite" unit which occurs near the base of the Nicola Group in the Quesnel Lake area (Bloodgood, 1987, 1988; Bailey, 1988; Panteleyev *et al.*, 1996). This interpretation, therefore, requires a fault (thrust?) between the Cambro-Ordovician Kechika Group and Triassic slate and phyllite. The exact location of this inferred fault is unknown and has been arbitrarily placed at the top of the Kechika Group where it delineates the easternmost limit of Quesnellia.

The eastern margin of the Turnagain complex is marked by a reverse fault; shear-bands observed in footwall slates indicate an eastward direction of motion. The nature of the southwestern contact of the Turnagain complex, observed only in drill core and inferred from aeromagnetic data, is uncertain (Clark, 1975). However,

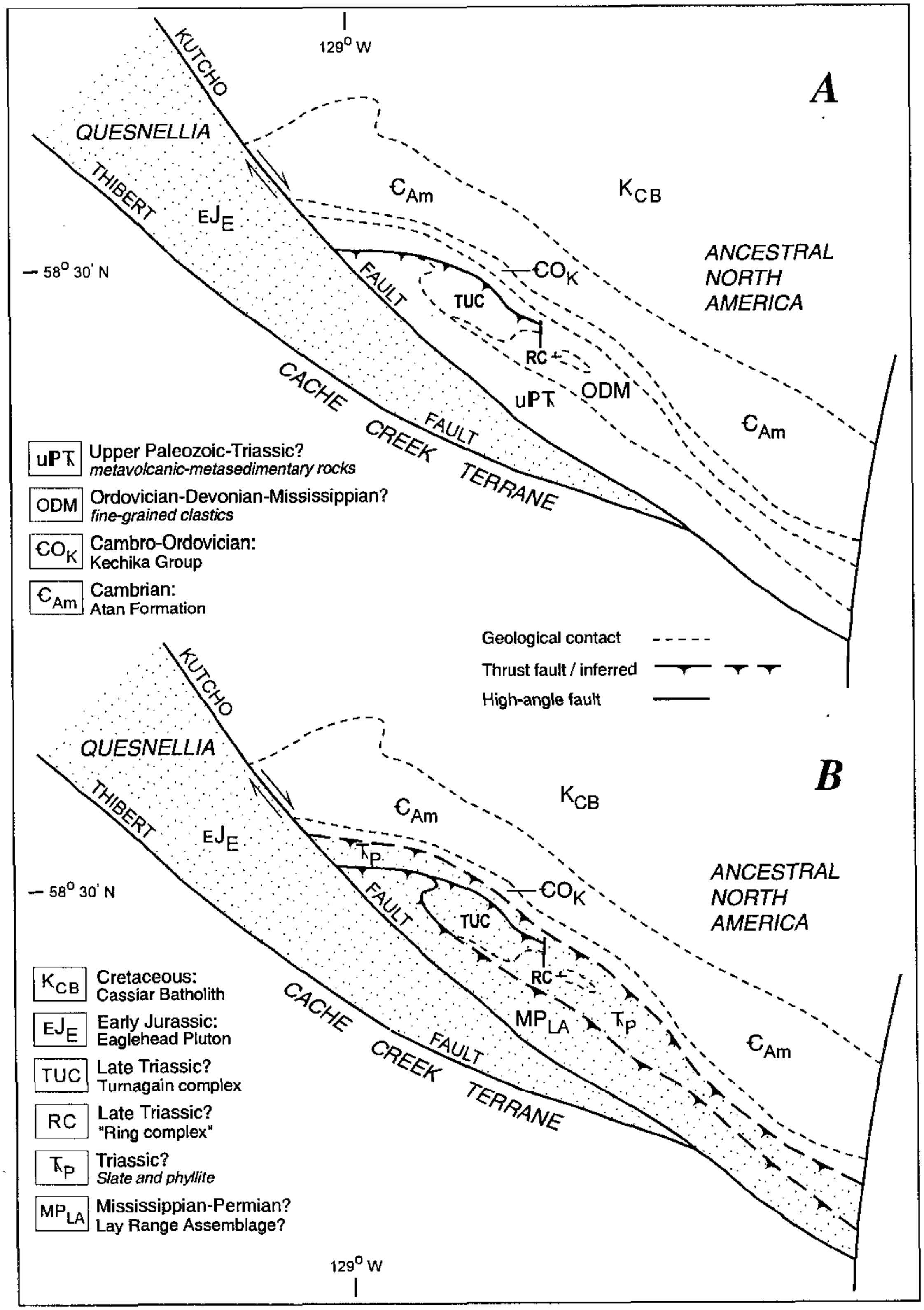

Figure 18-2. Regional geology of the Turnagain Alaskan-type complex according to A. Gabrielse (*in press*); B. this study.

the northwestern contact of the complex is interpreted herein as a thrust fault that places Lay Range Assemblage on ultramafic rocks. Strongly laminated metasedimentary and metavolcanic rocks in the hangingwall of this fault contain garnet, amphibole and oligoclase-andesine, indicating a metamorphic grade of uppermost greenschist to lowermost amphibolite facies. Similar lithologies also containing amphibole-bearing assemblages were mapped south of the Turnagain River by Clark (1975), and allow this fault to be extended along strike where it separates these higher grade rocks from underlying slate and phyllite of lower to middle greenschist facies. The inferred geometry of this fault plane at the northwestern extremity of the ultramafic complex, and difference in metamorphic grade, is consistent with an easterly directed thrust fault. It is noteworthy that the Polaris Alaskan-type complex, which intrudes similar lithologies further south in the Lay Range, is also involved in an eastward-verging deformation (*ca.* 186 Ma) at the leading edge of Quesnellia that reflects the earliest stages of accretion (Nixon *et al.*, 1997).

IS THE SULFIDE-RICH TURNAGAIN INTRUSION REALLY AN ALASKAN-TYPE COMPLEX?

As indicated above, the Turnagain intrusion is unusually well-endowed in sulfides for a Alaskan-type complex. The only other sulfide deposit of presumed Alaskan-type affinity known to the author is found in the Early Paleozoic Salt Chuck intrusion, Prince of Wales Island, southeastern Alaska. In contrast to the Turnagain Ni-Cu sulfides, the Salt Chuck ore is Ni-poor and Cu-rich [Cu/(Cu+Ni) = 0.99] and hosted by biotite-bearing magnetite clinopyroxenite and gabbro (Gault, 1945; Loney and Himmelberg, 1992). During its intermittent mining history, the Salt Chuck mine (1905-1941) produced some 0.3 million tonnes of sulfide ore with an estimated grade of 0.95 wt. % Cu, 1 ppm Au, 5 ppm Ag and 2 ppm Pd (Holt *et al.*, 1948). The principal ore minerals are bornite and lesser chalcopyrite. Minor platinum-group minerals (PGM) identified by Watkinson and Melling (1992) include kotulskite (PdTe), temagamite (Pd_3HgTe_3), sopcheite ($Pd_3Ag_4Te_4$) and auriferous sperrylite ($PtAs_2$). Although the Cu-rich nature of the ore and origin of the PGM have been related to hydrothermal remobilization of magmatic sulfides, the mechanism for concentrating the copper and precious metals is debatable: Loney and Himmelberg (1992) advocated a magmatic process (fractional crystallization) whereas Watkinson and Melling (1992) favoured a hydrothermal origin.

The classification of mafic-ultramafic complexes as Alaskan-type is *not* based on the presence or nature of sulfides or PGM but rather on silicate mineralogy, as outlined by Taylor (1967) and Irvine (1974). The IUGS classification scheme for ultramafic rocks is shown in Figure 3. Cumulate silicate assemblages that characterize the Alaskan-type association lie along the olivine-clinopyroxene join and comprise dunite, wehrlite, olivine clinopyroxenite and clinopyroxenite; orthopyroxene is characteristically lacking. The only other common silicate to appear in ultramafic lithologies is amphibole, which forms hornblende clinopyroxenite, clinopyroxene hornblendite and minor hornblendite. Plagioclase may be found in minor amounts in olivine-poor ultramafic lithologies and becomes a dominant constituent in associated mafic rocks (hornblende- or clinopyroxene-bearing gabbro and diorite). Accessory phases commonly include mica (phlogopite-biotite), apatite, and spinel (chromite in olivine-rich rocks; magnetite in amphibole- or clinopyroxene-rich rocks); primary sphene, ilmenite and rare zircon and quartz may appear in feldspar-rich cumulates and/or late-stage segregation veins. Magnetite may locally become a dominant cumulate phase and an economically viable commodity (*e.g.* Tulameen complex, Findlay, 1969; Nixon *et al.*, 1997).

CLASSIFICATION OF ULTRAMAFIC ROCKS

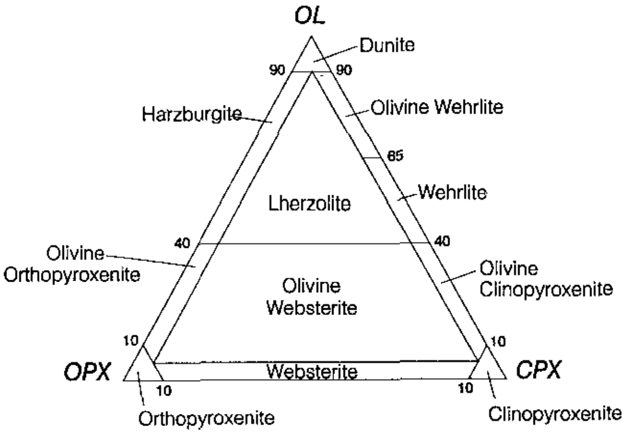

Figure 18-3. Classification of ultramafic rocks (modified after Le Maitre, 1989}.

Other features typical of Alaskan-type complexes include a crude internal zonation of ultramafic and mafic lithologies (hence the common reference to zoned complexes in the literature), a general lack of layering in outcrop (Duke Island is a notable exception) which is so typical of stratiform complexes, an absence of high-temperature tectonite fabrics like those that pervade obducted ophiolitic mantle, the common occurrence of fault-bounded contacts, and, where intrusive contacts have been established, thermal aureoles of hornblende hornfels (or amphibolite-grade regional metamorphism where deformation occurred while the intrusion was still hot, *e.g.* Polaris complex, Nixon *et al.*, 1997).

The key features of Alaskan-type complexes portrayed by the Turnagain intrusion include the following:

- ultramafic cumulates are restricted to mixtures of olivine and clinopyroxene with minor chromite, rare amphibole and trace phlogopite; orthopyroxene is absent
- centimetre-scale layering is comparatively rare
- localized chromitite layers (<1m in length) in the dunite have been entirely remobilized to form

schlieren and syndepositional folds, features that are characteristic of all Alaskan-type occurrences in British Columbia

- clinopyroxene compositions are diopsidic (Clark, 1975, 1978) and comparable to other Alaskan-type intrusions

Taken together, these features are sufficient to warrant the Alaskan-type classification for the Turnagain complex.

GEOLOGY OF THE TURNAGAIN COMPLEX: A SYNOPSIS

The generalized geology of the Turnagain complex is shown in Figure 4. The body is elongate (8km x 3km) and broadly conformable to the northwesterly-trending structural grain. The principal lithologies comprise dunite, wehrlite and olivine clinopyroxenite and represent crystal cumulate sequences. Minor hornblende clinopyroxenite and hornblendite appear restricted to the northwestern and southwestern parts of the complex, and clinopyroxenite commonly forms dikes. Unlike many other Alaskan-type complexes, gabbroic to dioritic members of the intrusive suite are lacking. Common accessory minerals include chromite in dunite, and trace amounts of phlogopite, especially in clinopyroxene-rich rocks. Among the oxide phases, cumulus or intercumulus magnetite is conspicuously absent, except for grains intergrown with primary sulfides, and primary ilmenite has only been identified in hornblende-rich rocks (Clark, 1975, 1978).

Dunite occupies the eastern and central portions of the body and is flanked by wehrlite and olivine clinopyroxenite. The ultramafic rocks are generally fresh to mildly serpentinized; however, more intense serpentinization and talc-carbonate alteration are common along faults and restricted zones within the complex. The central part of the ultramafic body is intruded by granodiorite to diorite, and hornblende±clinopyroxene-plagioclase porphyry dikes and sills. The latter are documented in drill core near the southwestern contact of the complex (Clark, 1975).

Primary layering in clinopyroxene-rich cumulates, reflecting variations in the modal abundance of olivine and pyroxene, is comparatively well-developed in outcrop, and at a larger scale, at the northwestern end of the complex (Figure 4). The layering has moderate to steep dips and is truncated by the faulted eastern boundary of the complex. Millimetre- to centimetre-scale layering in the dunite core is evident locally where concentrations of chromite crystals have accumulated. These chromitite horizons are discontinuous and commonly remobilized and intruded by thin dunite dikes. Despite localized zones of well-developed layering, way up criteria are inconclusive and the internal structure of the Turnagain complex is poorly understood.

Contacts between dunite and surrounding clinopyroxene-rich rocks are gradational to sharp. The latter relationship, observed at the northwestern margin of the dunite, was interpreted as evidence for intrusion of wehrlite-clinopyroxenite cumulates by the dunite (Clark, 1975). Such relationships, however, may be of local significance only, and confined to a narrow time interval when dunite and pyroxenite were being deposited penecontemporaneously in different parts of the complex. Another possibility is that the dunite at this contact is a discordant metasomatic body formed locally by replacement of pre-existing cumulates, as documented in other Alaskan-type complexes (*e.g.* Duke Island, Irvine, 1974). In general, the gradational contacts observed elsewhere, the occurrence of interlayered dunite and wehrlite, and the wehrlite-clinopyroxenite dikes so prevalent throughout the main dunite mass are consistent with deposition of clinopyroxene-rich cumulates after the dunite was formed. In this regard, it is also worth noting that olivine compositions determined by Clark (1975) in the dunite are generally more magnesian (Fo>88 mol. %) and more enriched in nickel than those in pyroxenitic cumulates (Fo<88 mol. %), as would be expected during the normal course of fractional crystallization. It was also shown by Clark (*ibid.*) that olivines coexisting with primary sulfides are more depleted in nickel than olivines in sulfide-free rocks due to the preferential partitioning of nickel into the sulfide phase.

SULFIDE MINERALIZATION

The main occurrences of massive to semi-massive Fe-Ni-Cu sulfide mineralization are shown in Figure 4. In addition to these prospects, disseminated primary sulfides are widespread in pyroxenitic rocks. With few exceptions, economically interesting sulfide concentrations are largely hosted by wehrlite, olivine clinopyroxenite and clinopyroxenite. Dunite is practically devoid of significant sulfide mineralization. However, sulfides in the Discovery and Cliff showings, in particular, are hosted by serpentinite that may originally have been dunite. In the case of the Davis #2 showing at the northwestern end of the complex, primary sulfides are hosted by clinopyroxene hornblendite and hornblendite.

Primary sulfides, in decreasing order of abundance, comprise pyrrhotite, pentlandite, chalcopyrite and trace bornite (Clark, 1975). Their textures are diagnostic of the precipitation of an immiscible sulfide melt from a silicate liquid: intercumulus and blebby sulfides in disseminated zones coalesce to form continuous networks enclosing cumulate silicate grains, and these net-textured sulfides locally occlude silicates altogether to form massive accumulations. In coarse-grained rocks, spheroidal to amoeboid sulfide globules are poikilitically enclosed in clinopyroxene or hornblende. Drill intersections reveal centimetre-scale layering of massive and semi-massive sulfide concentrations in zones up to one metre wide, and these concentrations yield the highest assays (>1 wt. % Ni). Locally, there is evidence in drill core for limited remobilization of primary sulfides along fractures and veins, correlated with a general increase in the pyrrhotite/pentlandite ratio (Clark, 1975). Thus, remobilized sulfide appears to be comparatively Ni-poor but may be relatively Cu-rich.

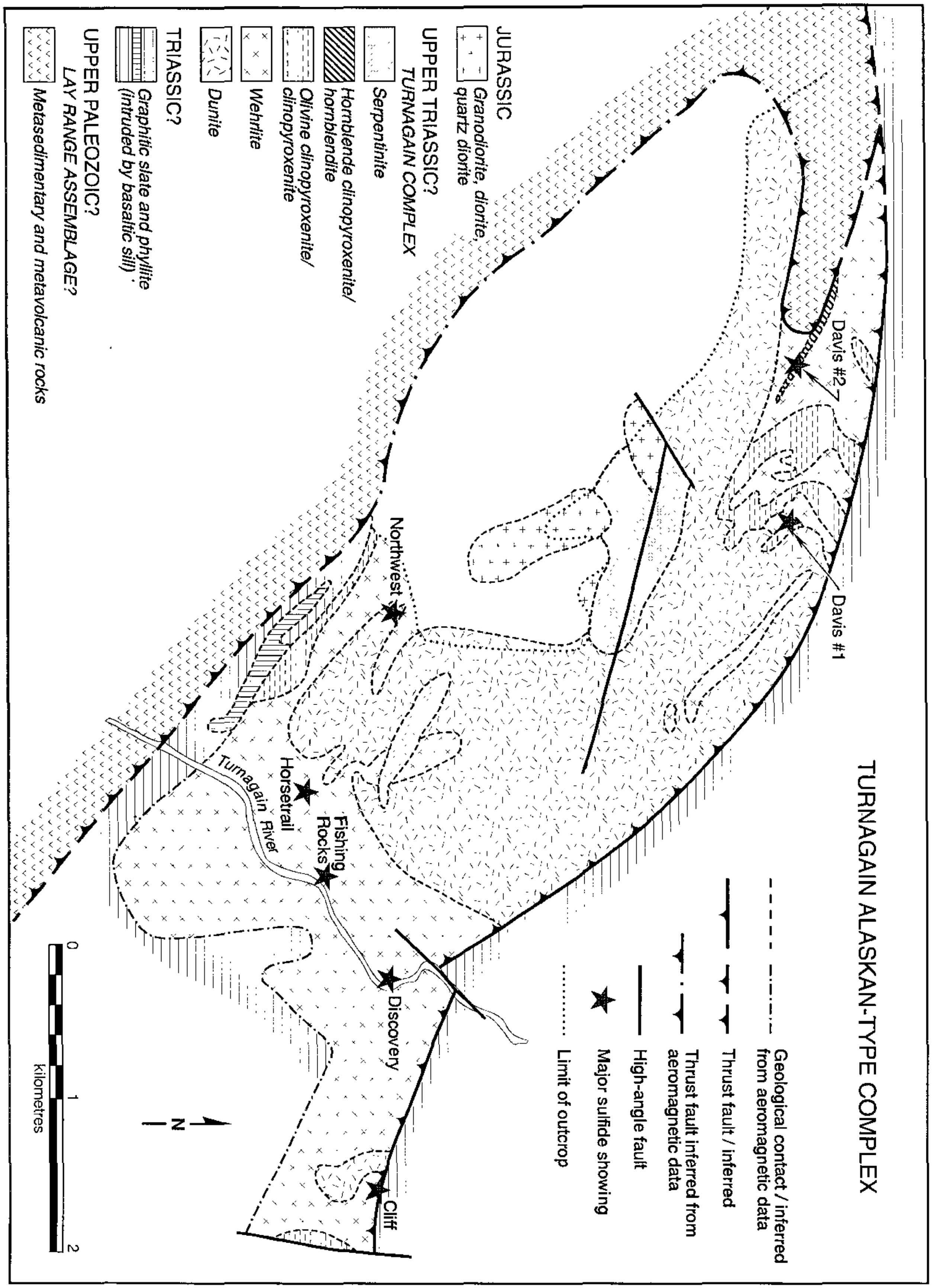

Figure 18-4. Simplified geology of the Turnagain ultramafic complex showing major occurrences of sulfide mineralization (modified after Clark, 1975).

Secondary sulfides include violarite ($FeNi_2S_4$), valleriite $4(Fe,Cu)S.3(Mg,Al)(OH)_2$, pyrrhotite, pyrite, rare molybdenite and possibly mackinawite [$(Fe,Ni)_9S_8$] (Clark, 1975). These minerals are widely distributed as fine disseminations of irregular grains in variably serpentinized rocks, or concentrated in veins and fractures. Clark related their origin to precipitation from hydrous fluids during serpentinization.

It is noteworthy that both primary and secondary sulfides in the Turnagain complex are associated with graphite. The fact that graphite preferentially occurs in serpentinized zones with fine-grained secondary sulfides, forms halos around sulfide veins, and commonly coats fractures and faults, led Clark (1975) to suggest that the graphite was introduced from an external source by CO_2-rich aqueous solutions that became reduced and deposited graphite during the serpentinization process. A viable source of carbon is the graphitic sediments that host the intrusion. Although most of the textural evidence points to a hydrothermal origin for the graphite, the inclusion of graphite flakes in semi-massive to massive primary sulfides, albeit in partially serpentinized host rocks, suggests that some of the carbon may have been introduced at the magmatic stage. This may have been effected by incorporation of xenoliths and/or screens of fine-grained graphitic wallrocks which have been encountered in recent drilling (B. Downing, personal communication, 1997). As indicated below, contamination by carbon-rich wallrocks may be a key mechanism whereby magmas of Alaskan-type affinity precipitate economically significant quantities of primary Fe-Ni-Cu sulfides.

ORIGIN OF MAGMATIC SULFIDES IN ALASKAN-TYPE MAGMAS: PROBLEMS AND POSSIBILITIES

On the basis of the sulfide mineralogy and textural evidence summarized above, it is clear that the main concentrations of Fe-Ni-Cu sulfides in the Turnagain complex are of magmatic origin, and conform to the products predicted to form during fractional crystallization of both silicate and sulfide melts. Clark (1975, 1980) concluded that the key factor responsible for unusual concentrations of sulfides in the Turnagain intrusion was a high initial content of sulfur in the primitive magma(s), reflecting extensive melting of a sulfide-enriched region of the upper mantle.

The bulk composition and oxidation state of a magma have been shown to be important factors, among others, governing the separation of an immiscible sulfide liquid from a silicate melt (*e.g.* Naldrett, 1989). It is suggested below that:

- the extremely high MgO content previously proposed for primitive Turnagain magma(s) may be seriously overestimated
- external factors may have played a crucial role in determining the oxidation state of the melt, and thereby promoting conditions conducive to the formation of sulfide deposits in Alaskan-type magmas with nominal amounts of dissolved sulfur

Primitive Alaskan-type magmas

The primitive magmas that produced Alaskan-type complexes are generally considered to be highly magnesian [in terms of the ratio $100Mg/(Mg+\Sigma Fe^{+2})$ or Mg#] with high MgO contents (ultrabasic), and mildly alkalic and hydrous (*e.g.* Findlay, 1969; Irvine, 1974; Clark, 1980). These compositional attributes have to be deduced from crystal compositions since no direct samples of primitive Alaskan-type magmas have been identified, and few volcanic equivalents have been proposed (*e.g.* Irvine, 1973). It is therefore extremely important to distinguish cumulus from post-cumulus (*i.e.* intercumulus) minerals, since only the former potentially yield compositional information that is directly pertinent to initial liquid compositions, assuming subsolidus re-equilibration of such phases is insignificant. The composition of primitive magma deduced for the Turnagain complex is easily the most magnesian (Mg#≥85) and MgO-rich (32 wt. %; Clark, 1980) of any parental liquid composition inferred for Alaskan-type complexes. In fact, these particular attributes match those of komatiitic melts.

The hydrous and alkali-rich character postulated for primitive Turnagain magmas seems reasonable in view of the occurrence of phlogopite and hornblende in olivine-rich rocks. In the case of the Turnagain complex, however, these phases appear to be exclusively *intercumulus* in nature and thus yield information that is only directly relevant to pore fluids within the cumulate pile rather than presumably more primitive melt in the main magma chamber. The author has observed trace amounts of rare euhedral phlogopite enclosed by olivine in the dunites of both the Tulameen and Polaris Alaskan-type complexes. In these cases, at least, the alkalic (potassic) nature of their primitive magmas is firmly established. Another facet commonly regarded as evidence for an alkaline affinity is the diopsidic nature of clinopyroxene, which usually occurs as both an intercumulus and cumulus phase. Pyroxenes of this composition, however, are not restricted to alkaline magmas. For example, recent experimental work has shown that diopsidic clinopyroxenes similar to those found in Alaskan-type complexes may crystallize from *subalkaline* melts under high water pressures (Gaetani *et al.*, 1993). From these considerations, the hydrous nature of primitive Alaskan-type magmas appears to be well established, and it is probably necessary to consider a range of alkali contents appropriate to both alkali-rich subalkaline and mildly alkaline magmas.

The interpretation that the primitive liquid for the Turnagain complex was komatiitic rests exclusively on the composition of the most Mg-rich olivine in dunite (reported as ~95 mol. % Fo; Clark, 1980). For comparison, the most Mg-rich olivines in other complexes are ~91 mol. % Fo (*e.g.* Duke Island, Irvine, 1974; Tulameen complex, Findlay, 1969). Although the Turnagain olivine is indeed a cumulus phase, such an Mg-rich composition is not necessarily representative of the liquid from which it crystallized. The total range of olivine compositions in dunite varies from 87 to ~96.5 mol. % Fo. Clark showed that the most Mg-rich olivine compositions (~95-96.5 mol. % Fo) were the result of *subsolidus* cooling and Fe-Mg exchange between olivine and chromite in chromite-enriched dunite, with the result that olivine within and adjacent to chromitite layers became markedly more Mg-rich. This process has also been documented in the Tulameen complex where olivine in chromitite layers changed composition from ~ 91 to 95 mol. % Fo (Nixon *et al.*, 1990). Excluding chromite-enriched samples, only two dunites in the Turnagain complex, both with normal proportions of chromite (1-2 vol. %), have olivine compositions in the range 93-94 mol. % Fo, whereas 11 dunites have olivines in the range 90-92 mol. % Fo. With one exception, the more Mg-rich olivines (≥~92 mol. % Fo) lie within the central part of the Turnagain dunite where there is abundant evidence for disturbance of chromitite layers, reflecting gravitational collapse and transport of cumulates previously deposited on the walls of the magma chamber. It is therefore likely that such processes have redistributed Mg-rich olivine grains that were formerly equilibrated with chromitite layers during subsolidus cooling. Such cryptic Mg-rich olivine accumulations would be expected to be localized and relatively thin (centimetre-scale). Also, for such olivines to preserve their heritage, sedimentation and cooling at the site of deposition must have been fairly rapid so as to effectively expel pore fluid and prevent re-equilibration with more Fe-rich olivine in surrounding cumulates. The fact that these cryptic olivine xenocrysts are less magnesian than olivines in chromitites implies either that subsolidus re-equilibration with chromitite was incomplete, or that they have partially re-equilibrated to their new chromite-poor environment. Thus, the composition of olivine that crystallized from primitive magmas may have been significantly less Mg-rich than Fo_{95}. Small differences in olivine composition are extremely important because they translate into extremely large differences in the estimated MgO content of coexisting melt. For example, all things being equal, an olivine composition of 91 mol. % Fo would be expected to crystallize from a primary mantle-derived melt containing about 12-15 wt. % MgO (i.e. basaltic to picrobasaltic composition; *cf.* Irvine, 1973) as compared to the komatiitic values of 32 wt. % MgO that have been proposed. There is therefore no compelling evidence to support the proposition that unusually high-MgO liquids were responsible for the deposition of sulfides in the Turnagain complex. The question as to whether these magmas were anomalously enriched in sulfur, as suggested by Clark, cannot be addressed with the data presently available. However, other factors that control sulfide precipitation, such as oxidation state, are explored below.

Oxidation State and Sulfide Precipitation

It has been shown that the oxidation state of a magma, as reflected, for example, by the Fe^{+3}/Fe^{+2} ratio of the melt, strongly influences the speciation of sulfur in the melt, which in turn governs the precipitation of magmatic sulfides (reviewed by Wallace and Carmichael, 1992). It has been shown in recent years that certain types of magmas are intrinsically more oxidized than others, and that the oxidation state of the upper mantle is heterogeneous (*e.g.* Carmichael, 1991). In general, tholeiitic magmas and their differentiation products, such as the large stratiform intrusions associated with major magmatic Ni-Cu deposits, have relatively low oxidation states, near or significantly below the synthetic quartz-fayalite-magnetite (QFM) oxygen buffer. In comparison, volcanic arc magmas typically have higher oxidation states appropriate to that of the nickel-nickel oxide (NNO) buffer or higher, and strongly alkaline magmas are inherently the most oxidized, commonly extending well above NNO to the magnetite-hematite (MH) buffer. Observations from natural magmatic systems indicate that the *relative* redox states of parental magmas are generally maintained over the course of crystallization, and over the high-temperature part of the subsolidus cooling interval.

The dissolution of sulfur in a given melt composition is sensitive to the redox state of the melt. At redox conditions near the NNO buffer, there is a marked solubility minimum for sulfur in silicate melts. Under reducing conditions below this transition point, the main dissolved sulfur species is sulfide (S^{2-}) whereas in melts more oxidized than the transition point, the dominant species is sulfate (SO_4^{2-}). Experimental studies have shown that the fugacity of oxygen exerts the dominant control on sulfur speciation, the effects of temperature, pressure and melt composition being relatively minor (*e.g.* Carroll and Rutherford, 1988). For tholeiitic magmas crystallizing at or below the QFM buffer, for example, the dominant sulfur species at magmatic temperatures will be sulfide (>80%ΣS), and sulfur saturation will produce an immiscible Fe-Ni-Cu sulfide liquid phase. It is important to note that immiscible monosulfide solution may dissolve appreciable amounts of oxygen (largely controlled by fO_2), and that on cooling, such melts crystallize Fe-Ni-Cu minerals accompanied by a small quantity of magnetite (<4 wt. %; Doyle and Naldrett, 1987). The amount of magnetite exsolved is directly dependent upon ambient redox conditions.

At progressively higher oxidation states, the capacity of the same melt composition to produce immiscible sulfides on cooling is dramatically impaired. In extreme cases, such as the sulfur-rich trachyandesite magmas erupted in 1982 from El Chichon, Mexico, and dacitic pumice ejected in 1991 from Mt. Pinatubo, Philippines, highly oxidizing conditions (near the MH buffer) induced the crystallization of primary anhydrite. Thus, other things being equal, the oxidation state of the magma may play a deterministic role in the ability of silicate melts to produce magmatic sulfide deposits.

In the case of Alaskan-type complexes, the oxidation state of their primitive magmas is poorly known. From their hydrous and relatively alkali-rich nature inferred above, and supra-subduction zone environment (valid for complexes in British Columbia, at least), they would be expected to have oxidation states appropriate to NNO or higher. This would, of course, explain to some degree why such complexes are generally devoid of magmatic sulfide deposits.

Some indication of the oxidation state of Alaskan-type magmas appears to be reflected in the composition of chrome spinel. Irvine (1974) showed that chromites in Alaskan-type complexes have moderately high Cr/(Cr+Al) ratios, similar to those of the major stratiform intrusions, but that their ferric iron contents expressed as $Fe^{+3}/(Cr+Al+Fe^{+3})$ are distinctly higher, which he related to an intrinsic property of the parental magma. Irvine also noted that one such property that could account for chromites enriched in ferric iron was the oxidation state of the melt. Thus, the compositions of early formed chromite in many Alaskan-type complexes is compatible with inferences made above concerning the oxidation state of their primitive melts.

The compositions of early crystallizing chrome spinels in the Turnagain complex appear anomalous in that they have higher Cr/(Cr+Al) ratios and lower ferric iron contents than other Alaskan-type complexes (Clark, 1978). In particular, their $Fe^{+3}/(Cr+Al+Fe^{+3})$ ratios are comparable to the chromites of stratiform intrusions. Following Irvine (1974), Clark cautioned against interpreting these spinel compositions solely in terms of a lower oxidation state for primitive Turnagain magmas, but noted that such an explanation would be consistent with the unusual absence of magnetite in crystal cumulates and the low proportion of magnetite (1-2 vol. %) exsolved during the cooling of primary immiscible sulfide ores. From the available data, therefore, it appears that an anomalously low oxidation state for Turnagain magmas relative to other Alaskan-type complexes is a tenable hypothesis. The higher chrome contents of Turnagain spinels may reflect a *slightly* more magnesian parental magma composition.

Given the general proposition that primitive Alaskan-type magmas are relatively oxidized (at or above the NNO buffer), either the Turnagain magma represents partial melting of an anomalously reduced upper mantle source region, or some process operating after melts left their source served to reduce their oxidation state to levels more appropriate for sulfide-enriched mafic magmas. The latter possibility is particularly intriguing since the wallrocks of the Turnagain complex are slates and phyllites enriched in graphite, and significant contamination by wallrocks appears to be a likely mechanism. As noted earlier, evidence that graphitic wallrocks were in fact incorporated into the Turnagain magma chamber has been observed in drill core. Since it has been found that carbon dissolves in mafic melts primarily as carbonate (CO_3^{2-}) species (Fine and Stolper, 1985), it could promote the reduction of formerly more oxidized melts. For example, addition of carbon at magmatic temperatures may induce the formation of a vapour phase because of the extremely low solubility of carbon dioxide in basaltic melts at shallow crustal pressures. The composition of the initial vapour will be rich in carbon species (CO-CO_2) and relatively poor in water (Mathez, 1989). In the case of a relatively oxidized magma (*e.g.* NNO buffer), the dominant species in the vapour phase will be CO_2 (Mathez, *ibid.*) and degassing reactions of the type:

$$CO_3^{2-}(\text{melt}) \quad = \quad CO_2(\text{vapour}) \quad + \quad O^{2-}(\text{melt})$$

would lead to net loss of oxygen from the magma chamber. Moreover, processes that tend to change the oxidation state of a melt will have more impact on the potential for sulfide saturation if the original oxidation state of the magma was near the sulfide-sulfate transition point. As pointed out above, this redox condition (i.e. near the NNO buffer) seems appropriate for the primitive magmas associated with Alaskan-type complexes. If the intimate intergrowths of graphite and sulfides noted earlier in olivine-rich cumulates of the Turnagain complex were formed at magmatic temperatures, this could place rigorous constraints on the maximum oxidation state of the graphite-sulfide-silicate melt system. If the inferences drawn above are correct, then clearly other types of mafic magma that are not normally associated with significant sulfide deposits could be emplaced in environments that induce economic mineralization.

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