Geoscience Canada

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Volume 10, Number 1, March 1983

URI: https://id.erudit.org/iderudit/geocan10_1art02

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Duke, J. M. (1983). Ore Deposit Models 7. Magmatic Segregation Deposits of Chromite. *Geoscience Canada*, *10*(1), 15–24.

Ore Deposit Models 7. Magmatic Segregation Deposits of Chromite

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Introduction

Chromite is a vital industrial commodity. Its importance derives mainly from the fact that it is the only ore mineral of chromium which is an essential constituent of stainless and some other steels as well as of certain nonferrous alloys. Chromite is also an industrial mineral that is used in its natural form in the manufacture of refractory bricks for furnace linings and as a foundry sand. It is the raw material for the production of chromium chemicals used in a variety of applications, such as electroplating, leather tanning, pigments and dyes. The suitability of chromite for various applications is determined in part by its chemical composition. For example, until recently a relatively high chromium to iron ratio was a requirement for metallurgical grade chromite (i.e., Cr/Fe≥2.8:1). However, advances in smelting technology have meant that this is no longer a critical factor, and ferrochrome is now produced routinely from chromite ores with substantially lower ratios (e.g., Cr/Fe ~ 1.5:1).

Canadian requirements for chromiuim materials are met entirely from imports. Chromite ores and concentrates for use in refractory applications account for roughly one half of Canadian consumption in weight terms. The balance is largely in the form of ferrochrome for use in the iron and steel industry, whereas chromium chemicals make up a relatively small portion of imports. Chromite has been identified as a strategic mineral in many of the industrialized nations that have no domestic production capacity because (1) chromite supply is dominated by a few countries and is perceived to be subject to disruption, and (2) chromium or chromite is irreplaceable in certain applications, and in others substitution would impose penalties of increased cost or decreased performance.

Chromite is mined almost exclusively from massive to heavily disseminated segregations in ultramafic or mafic igneous rocks. Elluvial and alluvial deposits derived by the erosion of such rocks account for a minor proportion of total production. Hard rock chromite ores are usually assigned to one of two classes on the basis of deposit geometry, as well as the petrologic character and tectonic setting of their host rocks. *Stratiform* deposits are sheet-like accumulations of chromite that occur in layered ultramafic to mafic igneous intrusions. The intrusions are typically of Precambrian age and occur in intracratonic terranes. *Podiform* deposits are irregular but fundamentally lenticular chromite-rich bodies that occur within alpine peridotite or ophiolite complexes (Thayer, 1964). This terminology is not entirely satisfactory because certain important deposits have characteristics of both classes. Nevertheless, it is used widely in the literature and I have retained it here. Podiform deposits currently account for about 55% of world production, with the most important deposits in the USSR, Albania, Phillipines, Turkey and India. There are relatively few productive stratiform deposits but, although they are marginally less important than the podiform ores in terms of total production, they account for more than 98% of world chromite reserves. In this brief review, I will attempt to summarize the important geological characteristics of stratiform and podiform chromite ore deposits and present some of the models that have been proposed for their genesis.

Characteristics of Stratiform Chromite Deposits

The intrusions that host the important stratiform chromite deposits occur within intracratonic terranes. In some cases they intrude granitic or gneissic basement rocks, and in others they intrude supracrustal rocks which rest upon sialic basement. The intrusions fall into two broad categories in respect to morphology. The first includes essentially tabular bodies that were emplaced as horizontal sill-like intrusions in which the igneous layering is generally conformable to the floor (e.g., Stillwater, Kemi, Bird River). The second group are the funnel-shaped intrusions in which the igneous layering dips at a shallow angle towards the centre, giving a synclinal crosssection (e.g., Muskox, Great Dyke, Bushveld).

The chromite deposits typically comprise thin, laterally extensive chromite-rich layers in the lower parts of the intrusions. Despite local irregularities, the chromite-rich layers are generally conformable to, and form an integral part of, the igneous layering that characterizes such intrusions. The individual layers of massive chromite (chromitite) range from less than 1 cm to more than 1 m in thickness, but their lateral dimensions are measured in kilometres or tens of kilometres. Orebodies may comprise a single chromitite layer or a number of closely spaced layers separated by ultramafic rock which contains disseminated chromite.

Typical chromitites are composed of from about 50% to more than 95% fine-grained (~0.2 mm) cumulus chromite with interstitial olivine, orthopyroxene, plagioclase, clinopyroxene or their alteration products. Brown mica is a common albeit minor constituent. The chromite tends to be euhedral to subhedral against interstitial silicates, but shows evidence of mutual interference during crystal growth against other chromite grains (Figure 1a).

Cameron and Desborough (1969) have pointed out that there is a tendency to stress the similarities of vertical distribution and petrologic association of chromitites in layered intrusions when in fact the differences are quite striking. Therefore, I have briefly described the most important productive stratiform chromite deposits below. These are the Bushveld Complex of South Africa, the Selukwe and Great Dyke deposits of Zimbabwe, the Kemi deposit in Finland and the Campo Formoso and Jacurici Valley deposits of Brazil. Also described are two non-producing deposits that are important strategic resources in the North American context: the Stillwater Complex of Montana and the Bird River Sill in Manitoba.

Bushveld Complex

The mafic rocks of the Bushveld complex extend over an oval-shaped area about 480 km by 380 km in the Kaapvaal craton in South Africa. The layered rocks outcrop in three crudely arcuate bands referred to as the eastern, western and northern Bushveld, which are superficially similar but differ considerably in detail. It is believed that the complex was emplaced as seven shallow, partly overlapping conical intrusions, which eventually coalesced into three larger magma chambers corresponding to the eastern, western and northern segments (von Gruenewaldt, 1979; Vermaak and von Gruenewaldt, 1981). The mafic rocks have been dated at 2095±24 million years by the Rb-Sr method (Hamilton, 1977).

The Bushveld complex includes a sequence of layered igneous rocks that locally exceeds 9000 m in thickness, and which has been divided into the marginal, lower, critical, main and upper zones. A

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complete description of the igneous stratigraphy is not warranted here, but some of the salient features are summarized in Figure 2. The lower part of the sequence is predominantly ultramafic in character with bronzitites and harzburgites being the principal rock types in the lower zone and the lower subzone of the critical zone. The base of the critical zone is currently defined by a sharp increase in the abundance of postcumulus plagioclase in bronzitite. The base of the upper subzone of the critical zone marks the main cumulus appearance of plagioclase, and the overlying rocks in the layered series are generally mafic in character and include norites, anorthosites, gabbronorites, and minor gabbro and pyroxenite. The base of the upper zone corresponds to the cumulus appearance of magnetite.

Chromite is a cumulus mineral in parts of the lower zone but is not ubiquitous (Cameron, 1978). Chromite-rich rocks and, in particular, chromitite seams are largely restricted to the critical zone. Cameron and Desborough (1969) defined numerous "chromitic intervals" within the critical zone where chromite is present in amounts in excess of 1%. The rock types within the "chromitic intervals" have chromite as the only cumulus mineral (i.e., chromitite), or chromite accompanied by bronzite, plagioclase, olivine, bronzite and olivine, or bronzite and plagioclase.

There are many tens of chromitite layers in the critical zone, but the total number is uncertain due to the difficulty in correlating between sections. Individual seams may be a single chromitite layer or several closely-spaced layers separated by layers or "partings" of pyroxenite or anorthosite (e.g., Cameron and Desborough, 1969). The chromitite seams range in thickness from less than 1 cm to more than 2 m with the majority falling towards the lower end of the range.

Two seams in the lower subzone of the critical zone account for the bulk of the chromite production and reserves. The LG6 seam is continuous over a strike length of 70 km in the western Bushveld (where it is also called the Magazine or Main seam) with an average thickness of 0.8 m. In the eastern Bushveld the LG6 is known as the Steelpoort seam and has a strike length of 90 km. It has a thickness of 0.6 to 1.3 m where mined (Buchanan, 1979). A second seam is mined in the eastern Bushveld: this is the F chromitite which has a strike length of 35 km and a thickness of 1.3 m. The ore reserves of the LG6 seam to a depth of 300 m have been estimated at 752 million tonnes, and those of the F chromitite are 312 million tonnes (Buchanan, 1979). Average grades range from 46.0 to 47.6% Cr_2O_3 and Cr/Fe ratios are about 1.6:1.

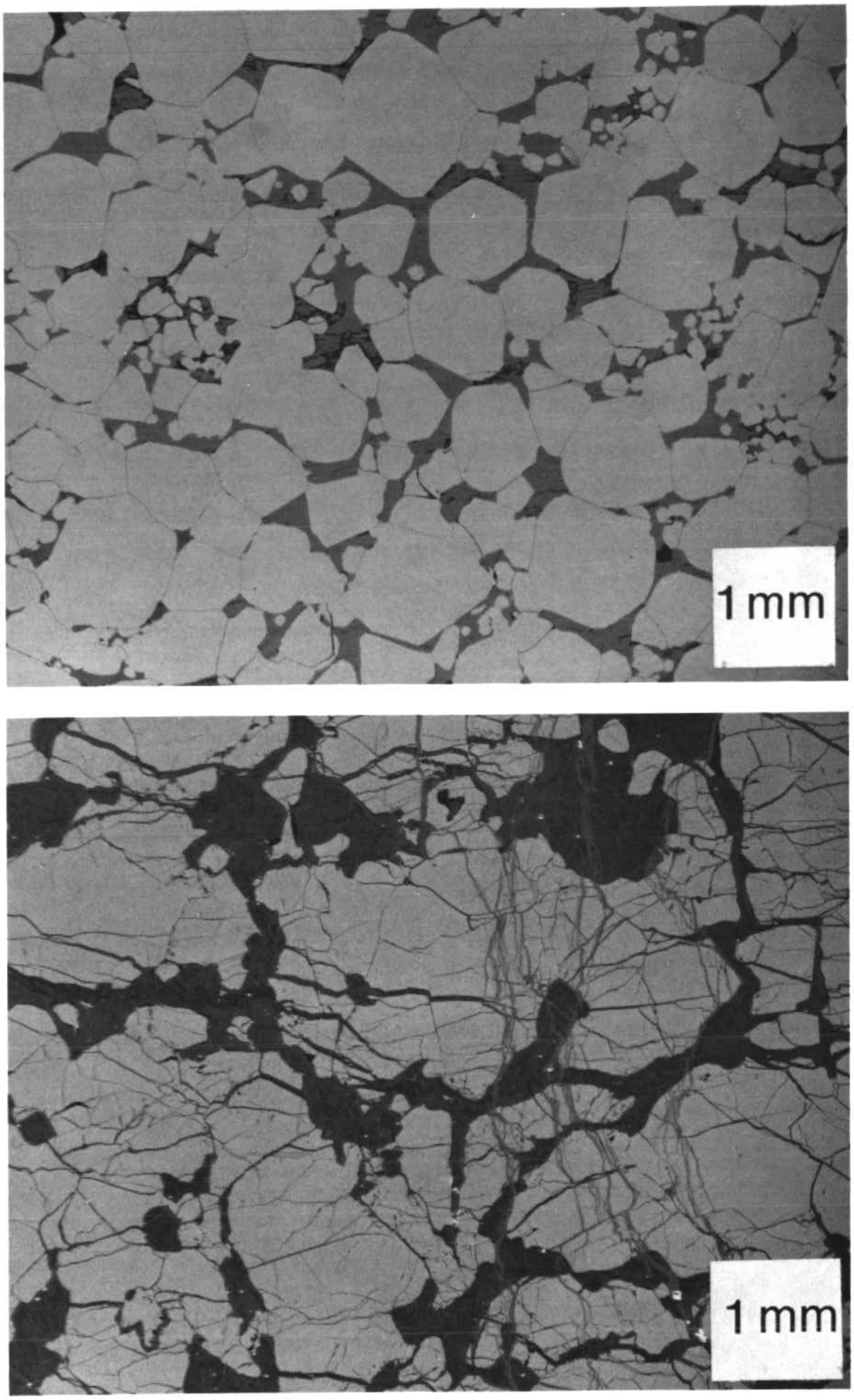

Figure 1: *Contrasting chromite textures in stratiform and podiform ores. (a) Fine-grained, massive chromite from the A chromitite zone of the Stillwater complex, Montana. The cumulus chromite exhibits euhedral to subhedral boundaries against intercumulus silicate minerals (dark grey) but shows effects of mutual interference during crystal growth against other chromite grains. (b) Coarse-grained, massive chromite from the Sterrett Mine, St. Cyr, Quebec. Note the extremely irregular shapes of the chromite anhedra.*

Great Dyke

The Great Dyke of Zimbabwe is 530 km in length and averages about 6 km in width. It is in fact not a dyke at all but rather a series of four coalescing funnel-shaped bodies which are, from north to south, the Musengezi, the Hartley, the Selukwe and the Wedza complexes(Worst, 1958). Each complex consists of a lower ultramafic layered series and an upper mafic layered series. In the Hartley complex, the largest of the four, more than 2100 m of ultramafic rocks and 900 m of mafic rocks are observed. The layering dips gently inward at the margins of each complex and flattens out toward the centre, giving the bodies a synclinal form in cross-section. Each of the complexes is thought to represent an intrusive centre, and Hamilton (1977) reported a Rb-Sr age of 2461 ± 16 million years.

Worst (1958) observed that the ultramafic series comprises a number of cyclic units and Wilson (1982) has outlined 14 such units in the Hartley complex. The ideal sequence within each unit is, from the base upward, chromitite, dunite, harzburgite, olivine bronzitite, bronzitite (Figure 3); however, cumulus bronzite is absent towards the base of the layered series, whereas dunite and chromitite are missing from some of the upper units. The top of the ultramafic series is marked by websterite in each complex and this is overlain by mafic rocks.

Chromite is a widespread cumulus mineral in the olivine-bearing rocks of the ultramafic series in amounts less than about 5%, but it is only rarely observed in bronzitite. The chromitites, however, generally contain in excess of 90% cumulus chromite with minor cumulus olivine and postcumulus orthopyroxene (Wilson, 1982). Wilson has observed 11 chromitite seams in the Hartley complex which range in thickness from 2 to 12 cm. The chromitite differs from that in most other stratiform deposits in respect to the coarse grain size (>2 mm) of much of the contained chromite.

Stillwater Complex

The Stillwater Complex is a steeply-dipping, tabular intrusion which outcrops over a strike length of 48 km and a width of up to 5.5 km. The intrusion was probably emplaced as a horizontal sheet about 2701 million years ago (DePaolo and Wasserburg, 1979), but was subsequently faulted and tilted into its present configuration. The exposed part of the intrusion has been subdivided from the base upward into the Basal Zone, the Ultramafic Zone, the Banded Zone and the Upper Zone (Jones *et al.*, 1960). However, the upper part of the intrusion is unconformably overlain by early Paleozoic sedimentary rocks, and so the original nature of the upper contact and the total thickness are unknown.

It is the Ultramafic Zone that is of interest in the present context. The Zone averages 1070 m in thickness and has been subdivided into a lower Peridotite Member and an upper Bronzitite Member (Jackson, 1961). The Peridotite Member is made up of as many as 15 cyclic units which are characterized by the upward sequence poikilitic harzburgite (olivine cumulate), granular harzburgite (olivine-bronzite cumulate) and bronzitite (bronzite cumulate). These cyclic units, which range from 3 to 381 m in thickness (Page, 1977), are illustrated in Figure 3. The lower poikilitic harzburgite parts of at least 13 of these cyclic units contain "chromitite zones" that range in thickness from less than 2 cm to almost 4 m (Jackson, 1968). The lower half of each "chromitite zone" is essentially massive chromite, whereas the upper half is composed of alternating layers of chromitite and olivine chromitite. The "reserves" of the most important deposit, the Mouat mine, are reported to be 4 million tonnes grading 22.5% Cr_2O_3 with Cr/Fe ratio of about 1.6:1 (Kingston *et al.*, 1970).

Kemi

A number of layered intrusions about 2436 million years old occur at the unconformable contact between Archean basement gneisses and overlying Karelian schists in northern Finland (Piirainen, 1978; Piirainen *et al.*, 1974). Four of these intrusions (Kemi, Koitelainen, Penikat and Tornio) host stratiform chromite deposits, but only those at Kemi are currently being mined.

The Kemi intrusion is a steeply-dipping, lenticular body at least 15 km in length and 2 km across at its widest point. It comprises a lower ultramafic zone and an upper mafic zone which are of similar average thickness. The ultramafic rocks, which have undergone widespread alteration,

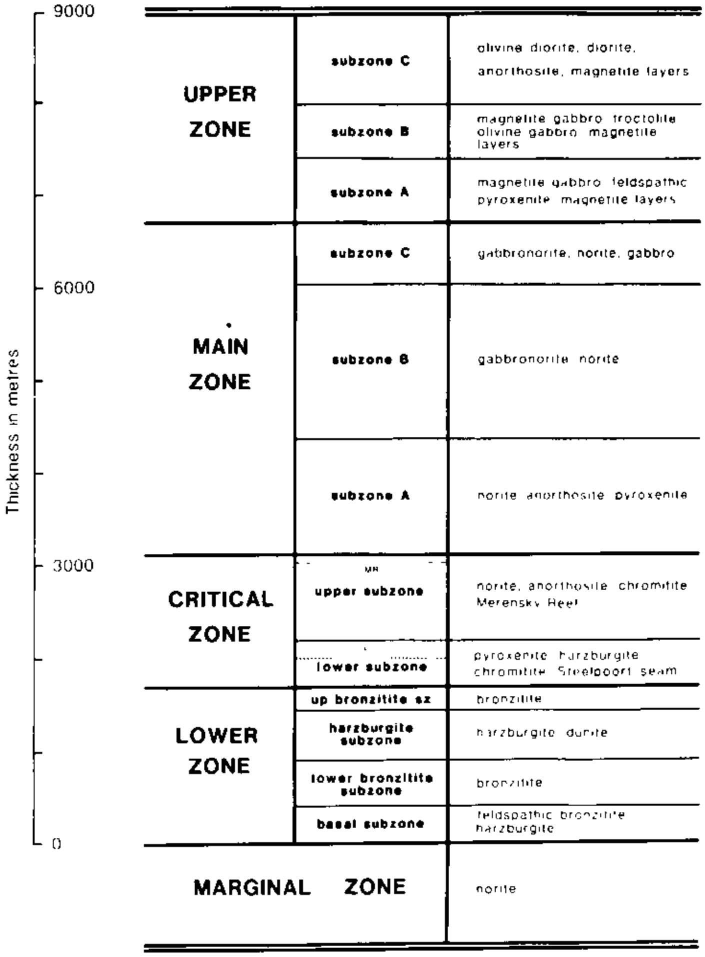

Figure 2: *Informal subdivision of the Bushveld complex, South Africa (after Vermaak and von Gruenewaldt, 1981) which alone accounts for more than one-third of world chromite production and two-thirds of reserves. The approximate stratigraphic positions of the Steelpoort chromite seam and the Merensky platinum reef are shown.*

include dunite, peridotite and pyroxenite as well as chromitite, whereas the mafic zone consists mainly of gabbro and norite with minor anorthosite and pyroxenite (Kujanpää, 1980). Layering is well developed in both zones but it is not known whether any cyclic units occur; a conformable chromitite layer occurs in the lower part of the ultramafic zone. Over much of the intrusion it is a few centimetres to a few metres thick; however, over a strike length of 4.5 km in the widest part of the intrusion, there are several successive swellings where the layer attains thicknesses of 30 to 90 m (Kujanpää, 1980). It is these swellings that constitute the orebodies, eight of which have been identified. The main chromitite layer has peridotite or its altered equivalent (serpentinite or talc-carbonate rock) in both the footwall and hangingwall. The peridotite above the ore contains numerous thin chromitite layers, and is overlain in turn by pyroxenite and more peridotite. Much of the ore is brecciated, particularly in the lower parts of the principal orebodies, but igneous textures are typically preserved and there is little evidence of plastic deformation. It seems likely that the remarkable thickening of the chromitite was largely a magmatic phenomenon rather than a result of tectonism.

The Kemi ore reserves are reported to be about 50 million tonnes averaging 26% Cr_2O_3 with a Cr/Fe ratio of 1.55:1 Although the grade is low in comparison to the deposits in southern Africa, the extraordinary width of the orebodies makes them suitable for mining by relatively inexpensive open pit methods, and deposits of the Kemi type should constitute an attractive exploration target.

Selukwe

The chromite deposits of the Selukwe schist belt were the first to be discovered in what is now Zimbabwe and probably were the world's most important single source of chromite during the first half of this century. The Selukwe ultramafic complex, not to be confused with the Selukwe complex of the Great Dyke (see above), is a highly deformed stratiform intrusion that lies within the Sebakwian Group in the Rhodesian craton and is about 3500 million years old (Cotterill, 1979). The ultramafic succession is up to 1000 m thick, and includes dunite, chromitite and pyroxenite. Cotterill (1979) reports the presence of cyclic units in which dunite is overlain suc-

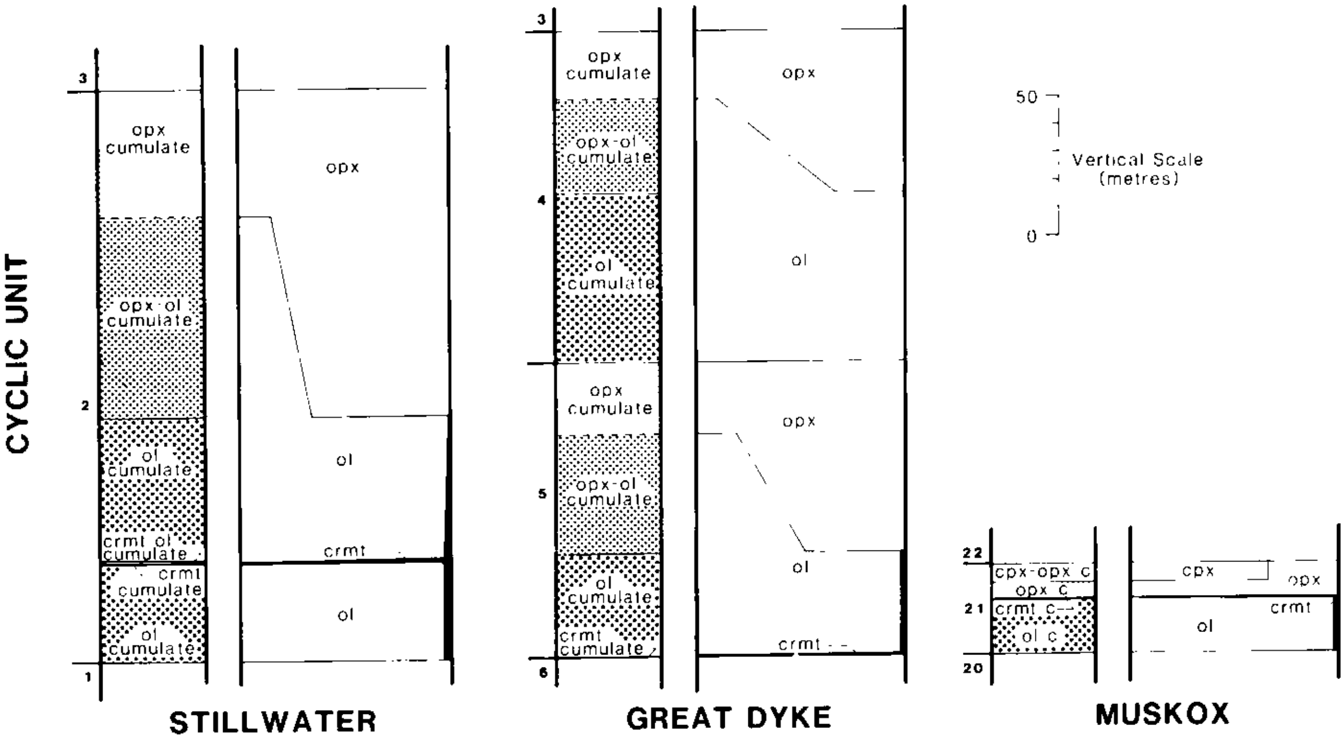

Figure 3: *Position of chromite layers within the cyclic units of the Great Dyke (Wilson, 1982), Stillwater complex (Jackson, 1968), and Muskox intrusion (Irvine and Smith, 1969).*

cessively by olivine pyroxenite and pyroxenite. Chromitite layers, where present, occur in the olivine cumulates at or near the contact with pyroxenite.

The Selukwe deposits have certain features in common with ores occurring in ophiolite complexes and are often referred to as podiform deposits in the literature. The individual orebodies have an elongate, lenticular form and average about 300 m in length, 60 m in depth and 10 m in width (Cotterill, 1969). Moreover, the grain size in much of the massive ore is very coarse (up to 4 mm), and is thus similar to that in podiform ores.

Campo Formoso and Jacurici Valley

The Campo Formoso chromite deposits are located 350 km northwest of Salvador in the State of Bahia, Brazil and have been an important source of chromite since 1962. The deposits occur within a metaperidotite body at least 40 km long and up to 1.1 km wide (de Deus *et al.*, 1982). The ultramafic rocks are underlain by granulites of the Archean Caraiba Group and are unconformably overlain by younger quartzites and phyllites of the Jacobina Group. The ultramafic rocks are intruded by the 2000 million year old Campo Formoso granite which defines the minimum age for the deposits. The ultramafic complex has been metamorphosed to greenschist facies and little remains of primary textures and minerals. However, Hedlund *et al.*(1974) believed that the body consisted mainly of peridotite and chromitite with minor pyroxenite and gabbro layers. Chromite occurs in massive chromitite, in net-textured olivine chromitite and disseminated in metaperidotite. Hedlund *et al.*(1974) described a measured section at the Coitezeiros A mine where 5 layers of chromitite 0.3 to 1.4 m thick occur over a stratigraphic interval of 10 m. Measured, indicated and inferred ore reserves exceed 55 million tonnes. Much of this is low grade (15-20% Cr_2O_3), but there is a significant proportion of massive ore which averages 38% Cr_2O_3 with Cr/Fe = 1.9:1 (de Deus *et al.*, 1982).

The Jacurici Valley chromite district is about 80 km east of Campo Formoso. The chromite deposits occur in ultramafic-mafic sills which intrude granulites, gneisses and migmatites of the Archean Pedra Vermelha complex (de Deus and Viana, 1982). The sills outcrop discontinuously over a strike length of 70 km and have a maximum thickness of 300 m. In the Medrado sill, the layered sequence comprises, from the base upward, harzburgite, chromitite, harzburgite, bronzitite and norite. The chromitite is 7 m thick and is made up of 80% cumulus chromite with intercumulus diopside making up the balance. Measured, indicated and inferred reserves amount to 3 million tonnes grading from 33 to 42% Cr_2O_3 with Cr/Fe in the range of 1.3 to 2.4.

Bird River Sill

The chromite deposits of the Bird River Sill in the Lac du Bonnet area of southeastern Manitoba have been explored periodically since their discovery in 1942, but have never been mined. The sill occurs within supracrustal rocks of the Archean Rice Lake Group. The sill and its host rocks have been folded about a broad anticlinal axis, resulting in dips of 65° to 90°. The sill has been longitudinally segmented by numerous faults, with the segments having an aggregate strike length of about 25 km. It averages 1 km in thickness and comprises, from the base upward, a Marginal Group composed mainly of olivine gabbro, a Layered Ultramafic Series, and a Layered Gabbro Series (Trueman, 1971, 1980). Trueman (1980) described the igneous stratigraphy at the Chrome Property where the layered succession is 580 m thick. The Layered Ultramafic Series there is 200 m thick, and is dominated by dunite towards the base and peridotite in the upper part. A total of 21 chromitite layers occur in the Series and most of these are grouped towards the top. The peridotite becomes somewhat feldspathic just beneath the main chromitite layers. Cumulus plagioclase occurs in the uppermost Layered Ultramafic Series, and the contact with the overlying Layered Gabbro Series is described as transitional. The latter series includes gabbro, anorthositic gabbro and anorthosite with minor granophyre.

Characteristics of Podiform Chromite Deposits

The ideal ophiolite succession comprises, in descending order, marine sediments, pillowed basaltic lavas, sheeted diabase dykes, noncumulate and cumulate mafic rocks, ultramafic cumulates and ultramafic tectonites (Figure 4). In most cases, the succession has been dismembered by faulting and one cannot be sure that all alpine peridotites are in fact ophiolitic. Most ophiolites are clearly allochthonous and are believed to represent transported fragments of oceanic lithosphere. The ultramafic cumulates are composed of dunite, wehrlite and clinopyroxenite that accumulated at the floor of a relatively shallow crustal magma chamber. The tectonites are mainly foliated harzburgite with pockets of dunite, and represent depleted mantle which has undergone partial melting and from which a basaltic melt fraction has been extracted. The contact between the ultramafic cumulates and tectonites is thepetrologic Moho, or the boundary between crust and mantle.

The chromite deposits occur almost exclusively within the ultramafic rocks of the ophiolite succession. They are most abundant in the tectonites, but also occur in the lowermost parts of the cumulate sequences. Dickey (1975) indicates that there is a tendency for the abundance of podiform deposits to increase towards the top of the tectonite. The immediate host rocks of the chromite are commonly dunitic; thus the deposits occurring within harzburgitic tectonites are normally within an envelope of dunite a few centimetres to a few metres thick.

The morphology of podiform chromite deposits is irregular and unpredictable. Thayer (1964, p. 140) observed that "Although many podiform chromite deposits have shapes that defy description, the majority might be characterized as tabular lenses, irregular pencils, or combinations of these two basic forms."Individual pods range from a few kilograms to several million tonnes in size, but bodies exceeding one million tonnes are rare. An ore deposit normally comprises a number of discrete pods. For example, the Kavak Mine in Turkey includes 21 orebodies that total about 2 million tonnes of ore with an average grade of 28 to 30% Cr_2O_3 (Ergunalp, 1980). The podiform bodies are commonly, but not always, conformable to the foliation or layering of the host rocks. Cassard *et al.*(1981) divided the New Caledonian deposits into discordant, subconcordant and concordant types depending upon their orientation with respect to the penetrative-fabric of the enclosing peridotite. They also noted that concordant orebodies are more deformed and more regular in shape than discordant ones.

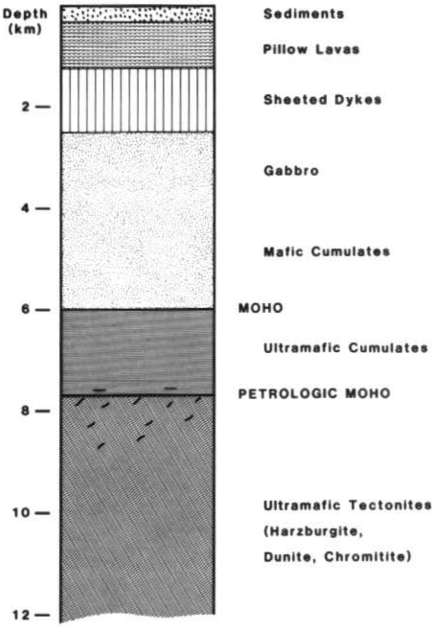

Figure 4: *Ideal ophiolite succession. Podiform chromite bodies tend to be most abundant in the uppermost part of the tectonite unit but also occur at depth and in the lowermost cumulates.*

The podiform chromite ores are texturally diverse. Disseminated chromite in the ultramafic cumulates is very similar in grain shape and size to that observed in stratiform intrusions, whereas that in the tectonite often occurs as large, elongated anhedra (Greenbaum, 1977). Heavily disseminated chromite in both the ultramafic cumulates and tectonites often displays typical cumulate textures (Thayer, 1969), rhythmic layering (Greenbaum, 1977) and graded layers. The chromite in massive ore tends to occur as coarse-grained, interlocking anhedra; grain sizes on the order of 5 to 10 mm are not uncommon (Figure 1b). Perhaps the most striking feature of podiform ores is the remarkable nodular texture which is characterized by loosely-packed, ellipsoidal chromite nodules 5 to 20 mm in diameter in a dunite matrix. Thayer (1969) found the nodules to be aggregates of smaller grains (up to 3 mm), and Greenbaum (1977) observed that the cores of some nodules from the Troodos complex consisted of an intergrowth of skeletal chromite and secondary silicate minerals. In any event, the nodular texture is widely viewed to be a primary magmatic feature (Thayer, 1969; Greenbaum, 1977; Bergath and Weiser, 1980).

Johan and his coworkers have documented the occurrence of a fascinating suite of inclusions in chromite from podiform deposits in Cyprus, New Caledonia, Oman and Saudi Arabia (e.g., Johan *et al.*, 1982). Among the silicate mineral inclusions are olivine, ortho- and clinopyroxene, pargasite, sodic mica, albite and jadeite. Equilibration temperatures deduced from the coexisting pyroxenes are 1050° ± 20°C. Aqueous fluid inclusions are ubiquitous, and indicate rather high temperatures of formation, and may imply a role for a fluid phase in the precipitation of chromite from the magma.

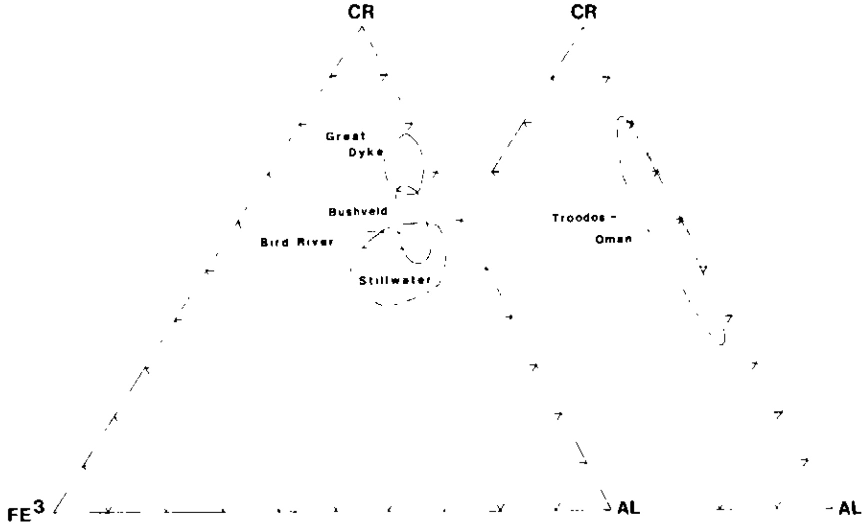

Figure 5: *Proportions of trivalent cations in chromite from certain stratiform (left) and podiform deposits. Data from Worst (1958), Cameron (1967), Gait (1964), Jackson (1969), Greenbaum (1977) and Brown (1980).*

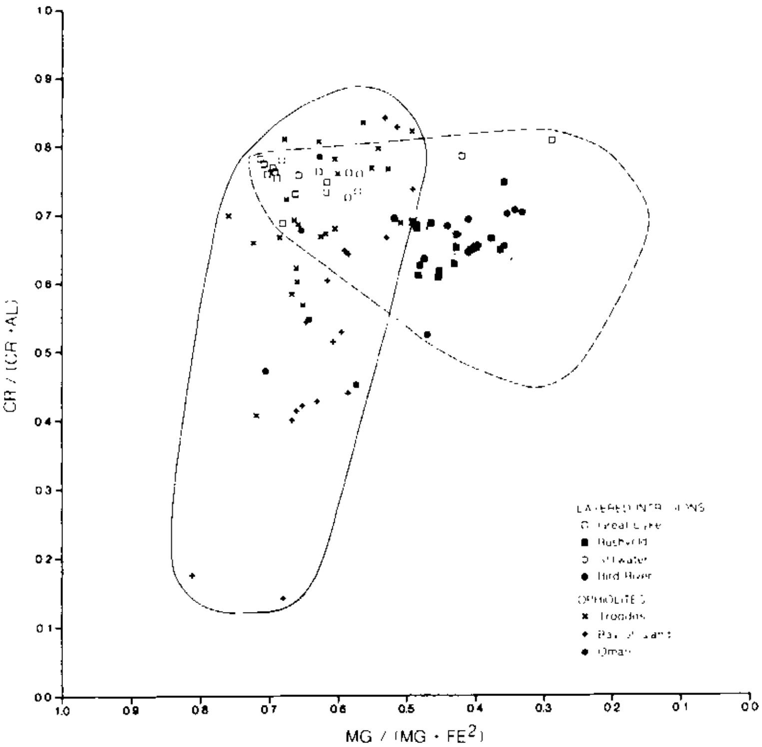

Figure 6: *Variation of Mg (Mg + Fe²⁺) and Cr (Cr + Al) ratios in chromite from certain stratiform and podiform deposits. Data from same sources as Figure 5.*

Chemical Composition of Chromite

Chrome spinel is a solid solution having the general formula (Mg, Fe^{2+}) (Cr, Al, $Fe^{3+})_2O_4$ and natural chromites are characterized by a wide range of chemical composition. Chromite composition is to a large extent indicative of the deposit type. The variation of trivalent cations is depicted in Figure 5. In podiform deposits, the proportion of Fe^{3+} in chromite is very low and the main differences in composition reflect the $Cr \rightleftharpoons Al$ substitution. The chromite in stratiform ores generally contains more Fe^{3+} than does podiform chromite, and both Fe^{3+} and Al tend to increase with decreasing Cr. The $Mg/Mg + Fe^{2+}$ ratio of chromite in podiform deposits does not vary greatly but does show a slight negative correlation with $Cr/Cr + Al$, whereas the $Mg/Mg + Fe^2$ ratio in stratiform chromite varies over a comparatively wide range (Figure 6). A further compositional distinction between podiform and stratiform chromites is the TiO_2 content, which is generally less than 0.3 wt. % in the former but greater in the latter (Dickey, 1975).

The composition of chromite varies systematically within individual stratiform deposits, although the variation is not in the same sense in every deposit that has been studied. Cameron (1977) has documented a systematic cryptic variation of chromite composition across 26 chromitite layers in the Bushveld critical zone whereby the Mg/Mg + Fe^{2+}, Cr/Cr + Al, and Cr/Fe ratios decrease upward through the sequence. Similar trends are suggested by Worst's (1958) data for the Great Dyke. Jackson (1968) reported that the Cr/Fe ratio increases upward toward the middle of the sequence of chromitites in the Stillwater and then decreases toward the top. However, the ratio decreases upward from the base in individual chromitite layers, and there is also a significant lateral variation in the relative proportions of Fe^{2+} and Fe^{3+} along many of the layers.

Systematic compositional variation has also been documented within some podiform chromite deposits. Neary and Brown (1979) reported a small upward decrease in the Cr/Fe ratio of chromite within a single chromitite lens in the Al'Ays ophiolite complex in Saudi Arabia. Brown (1980) has shown that both the Cr/Fe and Cr/Cr + Al ratios of chromite increase significantly as a function of the depth of the chromitite body beneath the petrologic Moho across a thickness of 6.5 km of ultramafic tectonite in the Oman ophiolite.

ORIGIN OF CHROMITE DEPOSITS

Stratiform Deposits

The chromite-rich layers that constitute stratiform ores are igneous cumulates, and their formation is simply a special case of the larger problem of the origin of layered igneous rocks. For many years, cumulate rocks were widely believed to represent accumulations formed by the settling of crystals to the floor of a magma chamber under the influence of gravity, and igneous layering was largely explained by processes analogous to those responsible for the layered sedimentary rocks. Thus, mechanical sorting through the action of magmatic currents, or differential settling of minerals of different density or grain size, was invoked by various workers as being at least partly responsible for stratiform chromite accumulations (e.g., Cameron and Emerson, 1959; Irvine and Smith, 1969).

Jackson (1961) observed that certain features of the layering of the Ultramafic Zone of the Stillwater complex are not consistent with crystal settling, and proposed that crystal nucleation and growth occurred in a stagnant zone very close to the floor of the magma chamber. A dramatic change in the perception of igneous layering has occurred in recent years, and it is now believed that, although crystal settling and deposition from magmatic currents are important in certain circumstances, layering is probably more often the result of crystallization *in situ* at the floor, roof or walls of the magma chamber (Campbell, 1978; McBirney and Noyes, 1979; Rice, 1981).

Irvine (1970) demonstrated that the sequence of appearance of the principal cumulus minerals in layered mafic rocks, that is, olivine, plagioclase and the pyroxenes, is largely in accord with experimentally determined phase relationships and the magma compositions inferred for the various intrusions. The occurrence of chromitite layers in which chromite is the only cumulus mineral is problematical in this context because, as pointed out by Irvine and Smith (1969), chromite is not expected to be alone on the liquidus during the normal course of fractional crystallization. Most of the stratiform chromite ores occur in sequences involving olivine, orthopyroxene, and chromite as cumulus minerals, and the problem is elucidated by reference to the schematic phase diagram devised by Irvine (1975) and presented here as Figure 7.

Although chromite is commonly an early crystallization product of mafic and ultramafic magmas, it is seldom the earliest phase. The intrusions of interest typically have abundant olivine cumulates in their lowermost parts, and it follows that the compositions of their parent magmas would plot in the olivine liquidus field in Figure 7, at a point such as A. Fractional crystallization of olivine from such a magma would drive the liquid composition towards the olivine-chromite cotectic at B, at which point the two phases would coprecipitate and the liquid composition would move along the cotectic towards the distribution point D. At the distribution point both olivine and chromite disappear and orthopyroxene appears as the sole crystalline phase. The proportions of olivine and chromite separating at any point along the olivine-chromite cotectic are given by the intersection of the tangent to the cotectic with the olivine-chromite join. For realistic magma compositions, in which the solubility of chromite is very low, the chromite will comprise at most a few percent of the solid

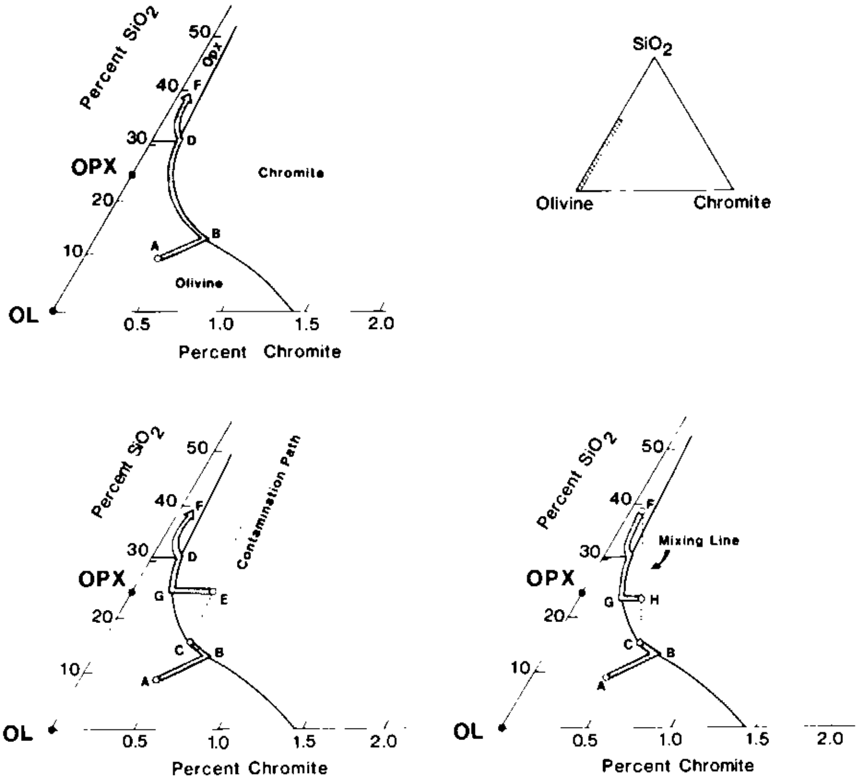

Figure 7: *Schematic phase diagram of the system olivine-chromite-silica after Irvine (1975, 1977), with modifications. Point D is a distribution point and the normal crystallization path (heavy arrow) of a magma of initial composition A leads to the cumulate sequence olivine, olivine + chromite, orthopyroxene (upper left). Contamination of a liquid on the olivine-chromite cotectic (e.g., at C) with salic material results in the sequence olivine, olivine + chromite, chromite, olivine + chromite, orthopyroxene (lower left). A similar modification of the cumulate sequence arises if a liquid on the cotectic mixes with a more evolved liquid (e.g., at F). Note that the proportions are weight percentages and that the horizontal scale is greatly expanded.*

fraction. This is in accord with the typical proportions of disseminated chromite that are observed in dunites and peridotites.

In order to form a chromitite, the magma composition must lie in the chromite field, and one of two things must happen: either the magma composition must change such that it enters the primary liquidus field of chromite, or the position of the olivine-chromite (or orthopyroxene-chromite) boundary must shift towards the olivine-silica join. Exactly how the shift in magma composition or phase boundary is accomplished is the key to the origin of stratiform chromite deposits, and a number of possible mechanisms have been proposed.

Ulmer (1969) reviewed the abundant experimenal data that demonstrated that increasing the oxygen fugacity greatly enlarged the liquidus field of the Mg-Fe-Al spinel minerals in mafic melts and suggested that the liquidus of chrome spinel would be similarly affected. Cameron and Desborough (1969) and Ulmer (1969) proposed that the "chromitic intervals" in the critical zone of the Bushveld complex represented periodic increases in the ambient oxygen fugacity which caused chromite to precipitate alone or with various proportions of cumulus silicates. The experiments of Hill and Roeder (1974) confirmed that oxygen fugacity had an important effect on the liquidus relations of chromite in basaltic systems, but also led Cameron (1977) to conclude that the cryptic variation of chromite composition in theBushveld complex is inconsistent with the hypothesis that increasing oxygen fugacity led to the precipitation of chromite. Moreover, in a broader context, it seems likely that the oxygen fugacity which prevails in a large body of magma is to a large extent internally buffered and is not subject to the rapid but spatially uniform fluctuations implied by the rhythmically layered chromitites.

Cameron (1977, 1980) proposed that the formation of the Bushveld chromitites could reflect changes in the total pressure under which crystallization occurred. Osborn (1978) demonstrated that the liquidus field of Mg-Fe-Al spinel in a simplified basalt system expanded with increasing pressure, and Cameron inferred that the effect on the stability of chromite would be qualitatively similar. Thus Cameron suggested that the Bushveld magma composition was in the bronzite field, but close to the chromite-bronzite cotectic or the chromite-bronzite-olivine triple point during the accumulation of the lower subzone of the critical zone, and that the intermittent appearance of chromite represents shifts in the phase boundaries in response to changes in total pressure. Slight changes in total pressure might occur as a result of tectonic activity or the addition or removal of batches of magma to or from the magma chamber. This model is appealing from the standpoint that the pressure variations would be laterally uniform.

Irvine (1975) proposed that salic contamination of a magma by, for example, assimilation of the roof rocks of an intrusion could bring about chromite saturation. This derives from the curvature of the olivine-chromite cotectic (Figure 7), which means that addition of silica-rich material to a liquid on the cotectic at, for example, C would move its composition toward the SiO_2 apex and into the liquidus field of chromite to a point such as E. The liquid would then crystallize chromite alone, and its composition would move back towards the cotectic at G, at which point the normal crystallization path would be resumed. Such a sequence of events could result in a crystallization order such as that observed in the cyclic units in the Stillwater complex (Figure 3). Assimilation of a larger proportion of salic material, such that the liquid composition was driven towards the chromite-orthopyroxene boundary rather than the chromite-olivine boundary, could lead to cyclic units of the Muskox type.

Irvine (1977) subsequently concluded that although the salic contamination model was sound in principle, it would be very difficult to achieve the necessary amount and uniformity of contamination in nature. He proposed an alternative hypothesis, based on the same phase relationships, which he considered more likely to occur in nature. Accordingly, suppose a magma chamber contained a liquid that had an initial composition on or close to the olivine-chromite cotectic at C and that the liquid had followed a normal fractionation path with the result that it evolved to composition F in the orthopyroxene field. If an influx of primitive magma of composition C then entered the chamber and mixed with the evolved liquid, the resulting mixture could lie within the liquidus field of chromite at H and bring about the precipitation of chromite alone. I consider this to be one of the more satisfying models of chromite genesis, since multiple injections of magma are very plausible in many intrusions, and differences in the proportions and compositions of the liquids that are mixed would allow a variety of crystallization sequences.

Podiform Deposits

Although many characteristics of podiform chromite deposits may be attributed to deformation, the common occurrence of cumulate textures in the ores suggests that they formed initially by magmatic segregation processes fundamentally similar to those that produced stratiform deposits. The analogy seems particularly appropriate for podiform deposits within the ultramafic cumulate rocks of ophiolite successions which have been generated by fractional crystallization of basaltic magma in chambers at the base of the oceanic crust. The precipitation of chromite from such magmas is subject to the same phase equilibria constraints as those outlined above for stratiform deposits, but the environment of crystal accumulation is undoubtedly rather different. It is unlikely that the chromitites once formed layers that were continuous over many kilometres as in the stratiform deposits which were subsequently broken up by tectonic activity. The discontinuous nature of the podiform deposits is regarded as a reflection of the magmatic environment. Greenbaum (1977), noting the occurrence of chromite in isolated deposits of limited lateral extent, suggested that the conditions necessary for the precipitation of massive chromitite (i.e., a chromite cumulate rather than an olivine-chromite cumulate) prevailed only locally within the magma chamber. Thayer (1969) interpreted various structural and textural features of podiform ores as indicative of deformation at magmatic temperatures. Because ophiolitic magmatism occurs at active spreading centres, the magma chamber is subject to tectonic disturbance throughout its evolution, and it is likely that the partially consolidated cumulate pile would undergo slumping, flowage and other processes which would disrupt primary cumulate features.

Diverse explanations have been offered for the occurrence of chromite deposits within the ultramafic tectonite which represents the refractory residua of partial melting. It might be argued that the dunite and chromitite bodies within the residual harzburgite are simply pockets of more advanced partial melting. Dickey *et al.*(1971) found that chrome diopside melts incongruently to chromite + liquid, and Dickey and Yoder (1972) suggested that chromite formed in this way could be aggregated into pods by winnowing as magma percolates through the partially molten rock. However, such an origin is not in accord with the presence of cumulate textures. As noted above, the chromitites are typically enveloped by dunite, and are most abundant near the contact of the harzburgite with the overlying cumulates. Accordingly, it has been suggested that they are outliers of the cumulate succession that were emplaced in the tectonite either by gravitational sinking of dense autoliths (Dickey, 1975) or by infolding of the lowermost cumulate layers (Greenbaum, 1977). Thayer and Lipin (as quoted in Anon., 1979, p. 9) report that neither hypothesis is consistent with field relations or the composition of chromite in some ophiolites which they have studied, and conclude that the chromite deposits are indigenous to the harzburgite. Similarly, the systematic variation of chromite composition with depth below the petrologic Moho and spatial distribution of chromitite bodies documented by Brown (1980) in the Oman ophiolite are not consistent with an origin either involving introduction from the overlying cumulates or as a refractory residuum from partial melting. On balance, the evidence supports the view that the chromitites and associated dunites within the ultramafic tectonite are magma chambers in which olivine and chromite accumulated during fractional crystallization of ascending basaltic liquids. Neary and Brown (1979) described these as "mini-chambers" on the order of 0.5 to 1 km in extent that are transitional between "grain boundary partial melting" below and the "well defined" magma chamber within the overlying oceanic crust. They clearly do not represent chambers where the ascending magmas came to rest and crystallized as a closed system: if this were the case, significant volumes of gabbroic rocks would be present. Rather, these small magma chambers were stopover points *en route* to the crust. Lago *et al.*, (1982) have taken a somewhat similar view in suggesting that the precipitation and accumulation of chromite took place in small, steeply inclined cavities that were essentially widenings of the conduits through which the magmas ascended. However, it would not appear that this hypothesis is consistent with textures and cryptic variation which suggest accumulation of chromite in horizontal layers in many occurrences.

Conclusion

The chromite deposits that I have described are undoubtedly magmatic segregation deposits that have formed through the precipitation and accumulation of chromite from mafic or ultramafic magmas. Moreover, the geological settings in which chromite deposits occur are reasonably well defined, albeit in rather broad terms. Because geophysical and geochemical methods have enjoyed only limited success in chromite prospecting, rational exploration should depend heavily upon a good understanding of the origin of chromite ores. However, in my opinion, we do not yet understand the details of the ore-forming processes sufficiently well to allow formulation of a definitive genetic model. There is a critical need for theoretical and experimental studies of the factors that control the precipitation of chromite in a range of magma compositions. The many theories of the origin of layering in igneous rocks must be tested. Careful field and laboratory investigations of many known chromite deposits are needed. When such research has been carried out, we may be in a position to adopt a genetic model that will be of use in chromite exploration. In the meantime, exploration criteria will be empirical in nature and based in large part on analogy with known chromite deposits.

Acknowledgements

R.I. Thorpe and R.F. Emslie of the Geological Survey of Canada, and D.H.Watkinson of Carleton University provided constructive criticism of the manuscript. Brian Williamson assisted in the preparation of the diagrams. This review was undertaken as part of Geological Survey of Canada project 800025.

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MS received December 3, 1982.