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Open-File Report 2010–1232

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

Suggested citation:
Schulte, R.F., Taylor, R.D., Piatak, N.M., and Seal, R.R., II, 2010, Stratiform chromite deposit model: U.S. Geological Survey Open-File Report 2010–1232, 7 p., available at *http://pubs.usgs.gov/ofr/2010/1232*.

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Stratiform chromite deposits are of great economic importance, yet their origin and evolution remain highly debated. Layered igneous intrusions such as the Bushveld, Great Dyke, Kemi, and Stillwater Complexes, provide opportunities for studying magmatic differentiation processes and assimilation within the crust, as well as related ore-deposit formation. Chromite-rich seams within layered intrusions host the majority of the world's chromium reserves and may contain significant platinum-group-element (PGE) mineralization.

This model of stratiform chromite deposits is part of an effort by the U.S. Geological Survey's Mineral Resources Program to update existing models and develop new descriptive mineral deposit models to supplement previously published models for use in mineral-resource and mineral-environmental assessments. The model focuses on features that may be common to all stratiform chromite deposits as a way to gain insight into the processes that gave rise to their emplacement and to the significant economic resources contained in them.

Stratiform chromite deposits are expressed as massive chromitite (greater than 90 percent chromite) bodies or seams of disseminated chromite in large, unmetamorphosed, repetitively layered mafic-ultramafic intrusions that were emplaced in stable cratonic settings or during rift-related events (Lee, 1996; Naslund and McBirney, 1996; Cawthorn and others, 2005). The chromitite seams are usually found in the lower, ultramafic parts of the layered intrusions. In addition, chromitite seams are cyclic in nature as well as laterally contiguous throughout the entire intrusion.

The intrusions are typically funnel- or saucer-shaped, extend anywhere from 2 to 180 kilometers (km) in diameter, and can reach thicknesses of up to 15 km (table 1). The thicknesses of the individual chromitite seams are variable, ranging from less than 1 centimeter (cm) (for instance, the Rum intrusion of northwestern Scotland; O'Driscoll and others, 2009) to 5 to 8 meters (m) (for instance, the Ipueria-Medrado sill in Brazil; Marques and Ferreira-Filho, 2003).

Large stratiform chromite deposits, such as the Bushveld Complex (figure 1), are comagmatic with their host intrusions, and typically formed in mid-continent anorogenic provinces; however, there is considerable debate regarding the structural control related to stratiform chromite deposits as several intrusions (for instance, the Muskox, Great Dyke, and Burakovsky intrusions) record evidence that rifting may have been involved in their formation. Economic chromite deposits typically formed during three main periods: (1) the Stillwater Complex (Montana, United States) and Bird River Sill (southeastern Manitoba, Canada) approximately 2.7 billion years ago (Ga); (2) the Great Dyke (Zimbabwe), the Kemi intrusion (Finland), and the Burakovsky layered intrusion (Russia) at approximately 2.5 Ga; and (3) the Bushveld Complex (South Africa) and Ipueira-Medrado sill (Brazil) at approximately 2.0 Ga.

Chromium is the primary commodity associated with stratiform chromite deposits. The economic potential of chromite deposits depends mainly on the thickness, continuity, and grade of ore. The most important uses of chromium are in stainless steels, nonferrous alloys, and chromium plating. Chemical-grade chromium is widely used in chemicals and pigments. Chromium also is an important component in refractories. Many of the major stratiform chromite deposits such as the Bushveld Complex also contain economic levels of platinum, palladium, rhodium, osmium, iridium, and ruthenium, which are referred to as the PGEs.

Chromite ($FeCr_2O_4$) is black with a metallic to dull luster and yields a dark-brown streak. This streak distinguishes chromite from other black spinel-group minerals, such as magnetite, that typically have a white streak. Chromite is opaque to slightly translucent in thin section, depending on the amount of trivalent iron in the chromite. If it has very little Fe^{3+}, the mineral will be slightly translucent, but opaque if it contains more than a few percent Fe^{3+}. The hardness (using the Mohs hardness scale) is typically 5.5 to 6.5. Chromite does not show cleavage, but does exhibit a conchoidal to uneven fracture.

The mineralogy of the ore primarily includes the following mineral assemblage: chromite ± magnetite ± pyrrhotite ± pentlandite ± chalcopyrite ± platinum group minerals (dominantly laurite, cooperite, and braggite). The most common mineral assemblages in the chromitite seams are olivine + chromite, chromite ± bronzite + plagioclase, chromite + plagioclase, and chromite + clinopyroxene (augite). Rutile and ilmenite also are found in a few deposits. In many cases, the primary silicates have been altered to serpentine, chlorite, and talc. Other alteration phases include magnetite, kaemmererite, uvarovite, hornblende, and carbonate minerals (such as calcite and dolomite). It should be pointed out, however, that most of the chromitite seams in the Bushveld Complex, which contains the bulk of the world’s stratiform chromite, are associated with either bronzite and (or) plagioclase.

On the whole, chromitites from layered mafic-ultramafic igneous intrusions contain high concentrations of chromium and demonstrate strong associations with PGE. The rocks also are characterized by anomalously high magnesium concentrations and low sodium, potassium, and phosphorus concentrations. Variations in overall composition are attributed to competition between chromite and orthopyroxene for aluminum, iron, and magnesium during co-precipitation and subsolidus re-equilibration.

The grade of the chromite ore varies from a low of 21 weight percent Cr_2O_3 in the Rum intrusion up to 57 weight percent Cr_2O_3 in the Campo Formoso complex (table 1). In some cases, however, the contained chromite is not economic due to low grades or limited tonnage. Furthermore, the number of exploitable chromite deposits and occurrences available in a specific layered intrusion can vary from as little as six (Campo Formoso complex, Brazil; Cawthorn and others, 2005) to as many as 925 (from 20 major chromite mines in the western and eastern parts of the Bushveld Complex, South Africa; Cawthorn and others, 2005).

Host rocks may include alternating layers of norite, gabbronorite, dunite, harzburgite, lherzolite, pyroxenite, troctolite, anorthosite, orthopyroxenite, and gabbro, although not all will be found in each layered intrusion. There is considerable lithological variability between the different stratiform chromite deposits, as well as within the different parts of the same layered intrusion. The main host rocks for the chromite are generally cumulate pyroxenites, such as feldspathic pyroxenite in the Bushveld Complex, or harzburgites (olivine cumulates) in the Stillwater Complex and Muskox intrusion. Typically, a layered mafic-ultramafic intrusion consists of two main sections: an ultramafic series and a mafic series.

Overall, the presence of orthopyroxenite in many of the stratiform chromite deposits suggests high silica and high magnesium concentrations in the parental magma. High potassium, light rare earth elements (LREE), and zircon concentrations in the source magmas introduce questions about upper crustal contamination, either via assimilation during magma ascent or incorporation into the mantle by past subduction of sediments (Hatton and Von Gruenewaldt, 1990).

Weathering processes associated with mine wastes from processing ore are dominated by interactions with chromite; trace amounts of sulfide minerals such as pyrrhotite, chalcopyrite, and pentlandite; and associated gangue minerals, including olivine, orthopyroxene, clinopyroxene, and plagioclase. Chromite, the primary ore mineral, occurs in mine waste in minor amounts due to the imperfect grinding of the ore prior to producing a chromite concentrate. The processing of chromite concentrates produces a variety of chromium-bearing solid phases in the chromite ore-processing residue, which include brownmillerite, hydrocalumite, hydrogarnet, and ettringite, in addition to periclase, larnite, brucite, calcite, and aragonite (Hillier and others, 2003), all of which affect the geochemical behavior of chromium in the environment.

Stratiform chromite deposits are mined using predominantly underground mining methods, although some surface mining has occurred. Once mined, the chromite ore goes through various stages of processing. The first step usually involves hand sorting and screening. Fine and coarse materials, which have been crushed and ground, are separated either by gravity or electromagnetic methods. The concentrate is then sent to one of three types of beneficiation plants for processing. Chromite ore-processing facilities commonly are near or at the mine sites although some plants are fed by several mines.

Although there has been extensive study of the large, layered mafic-ultramafic intrusions in which the stratiform chromite deposits are located, few studies focus only on the magma chamber processes that are responsible for chromite crystallization and there is little consenus about them. Changes in pressure, oxygen fugacity, and country-rock assimilation all have been proposed to explain the occurrence of the chromitite seams (see Ulmer, 1969; Irvine, 1975; Cameron, 1980; Lipin, 1993; and references therein); however, some workers have argued that crystallization of chromite follows magma mixing at the roof of the magma chamber (for example, Alapieti and others, 1989; Spandler and others, 2005). Recently, the discovery that thin, subsidiary chromite-bearing seams in the Rum intrusion have different compositions than disseminated chromite from the surrounding peridotite and troctolite led O’Driscoll and others (2009) to propose that some of the layering of the intrusion formed by downward infiltration of a picritic melt. According to their model, the infiltrating melt would dissolve and assimilate cumulus olivine and plagioclase located in the residual troctolite crystal mush. The most widely accepted explanation for stratiform chromite deposit formation, however, involves the mixing of primitive and fractionated magmas (see Lee, 1996; Naslund and McBirney, 1996; Cawthorn and others, 2005; and references therein).

The value of numerous economic commodities in stratiform chromite deposits (such as PGEs, nickel, chromium, and vanadium) increases the likelihood of continued scientific investigation of these intrusions well into the foreseeable future. In fact, much of the current research on layered mafic-ultramafic intrusions focuses on PGE mineralization. Modern technological advances, both in terms of mining as well as commodity usage, will continue to drive the need for stratiform chromite ore as well as additional exploration.

Table 1. Physical dimensions of select stratiform chromite deposits.

[Abbreviations and symbols as follows: cm, centimeters; km, kilometers; km^2, square kilometers; m, meters; n.d., no data; ≈, approximately; >, greater than; <, less than]

Deposit	Shape	Areal extent	Intrusion thickness	Chromitite seam thickness	Cr_2O_3 content of ore (weight percent)	References (see footnotes below)
Bushveld Complex (South Africa)	Funnel-shaped; four peripheral limbs that may connect at depth (fifth limb hidden under sediment cover)	≈65,000 km^2	7–9 km	Tens of centimeters to ≈2 m	40–50	1, 2, 3, 18, 24
Stillwater Complex (Montana, United States)	Truncated top; upper parts lost to exhumation and erosion	180 km^2; maximum dimensions of 47 km × 8 km	Maximum exposed thickness of 6.5 km	More than 10 seams ranging centimeters to 8 m	35–47	3, 4, 17, 18, 20, 24
Great Dyke (Zimbabwe)	Highly elongate linear body; Y-shaped in cross section	550 km × 4–11 km	>3 km	Up to 1.8 m in upper pyroxenite; 10–20 cm in lower ultramafic part	40	3, 11, 18, 20, 24
Kemi intrusion (Finland)	Originally funnel-shaped, later tilted to current lenticular shape	15 km × 0.2–2 km	Extends downward at least 2 km	Main layer is 20 m, locally up to 90 m; as thin as 0.5 m	26.6	6, 20, 22
Rum intrusion (Scotland)	Mushroom-shaped; circular in plan view	10 km diameter	n.d.	Millimeters to <2 cm	21–45	7, 8, 14, 25
Burakovsky intrusion (Russia)	Lopolithic or funnel-shaped; irregular oval in plan view; majority of intrusion is covered by glacial sediments	≈700 km^2; 50 km × 13–17 km	4–6 km	0.5–4 m	49–52	5, 6, 26
Niquelândia complex (Brazil)	Fault-bounded on all sides	1,800 km^2	10–15 km	Two horizons, 5–30 cm thick, locally reaching 1 m	36	9, 15
Campo Formoso complex (Brazil)	Tabular, arch-shaped	40 km × 0.1–1.1 km	Unknown due to extensive erosion	At least seven layers, a few centimeters to several meters; max 12 m	30–57	10, 15, 21, 23
Ipueira-Medrado sill (Brazil)	Sill-shaped	7 km long	300 m	Main seam 5–8 m; others 0.3–1.1 m	30–40	13, 23
Bird River Sill (Canada)	Sill-shaped	700 km long	700 m	Five 5–10-cm-thick seams in lower series; three chromite members in 3.1–m–thick group in upper series	15, 19	12, 16, 18, 26

References: [1]Eales and others (1993); [2]Eales and Cawthorn (1996); [3]Cawthorn and others (2005); [4]McCallum (1996); [5]Higgins and others (1997); [6]Alapieti and others (1990); [7]Tepley and Davidson (2003); [8]Emeleus and others (1996); [9]Ferreira Filho and others (1995); [10]Garuti and others (2005); [11]Wilson (1996); [12]Ohnenstetter and others (1986); [13]Marques and Ferreira Filho (2003); [14]Power and others (2000); [15]Girardi and others (2006); [16]Theyer (1991); [17]Jackson (1968); [18]Stowe (1994) and references therein;[20]Lee (1996); [21]Garuti and others (2007); [22]Alapieti and others (1989); [23]Lord and others (2004); [24]Naldrett (2004) and references therein; [25]O'Driscoll and others (2009); [26]Sharkov and others (1995).

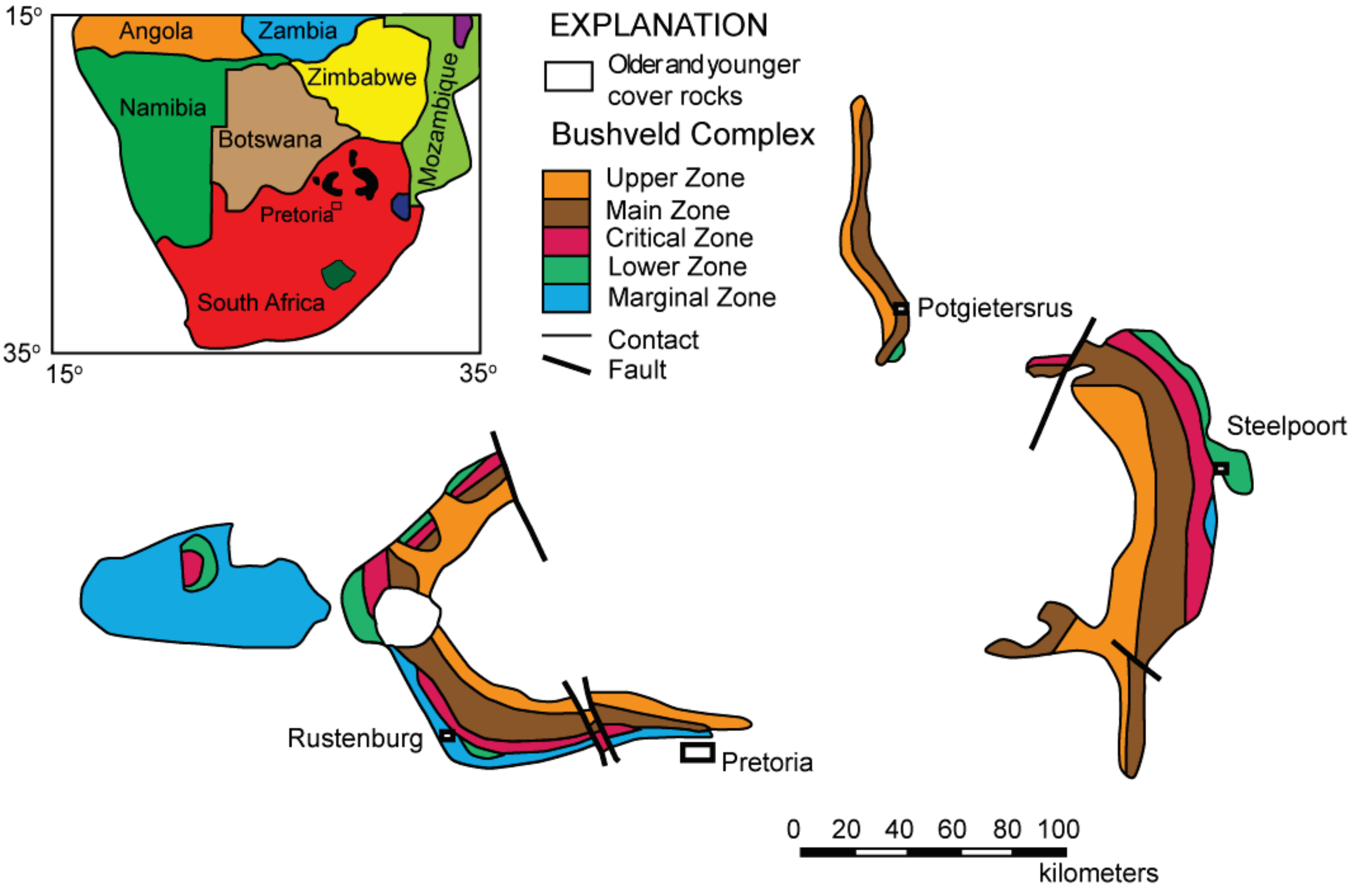

Figure 1. Simplified geological map of the Bushveld Complex modified from Cawthorn (2007). Inset map shows locations of enlarged bodies. City names shown for orientation.

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