GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G45448.1

Manuscript received 3 August 2018
Revised manuscript received 27 October 2018
Manuscript accepted 4 December 2018

# Genesis of chromite deposits by dynamic upgrading of Fe ± Ti oxide xenocrysts

C.M. Lesher[1]*, H.J.E. Carson[1], and M.G. Houlé[2]

[1]Mineral Exploration Research Centre, Harquail School of Earth Sciences, Goodman School of Mines, Laurentian University, Sudbury, Ontario P3E 2C6, Canada

[2]Geological Survey of Canada, Lands and Minerals Sector, Natural Resources Canada, 490 rue de la Couronne, Québec, Québec G1K 9A9, Canada

## ABSTRACT

**Most magmatic chromite deposits, particularly those in stratiform layered ultramafic-mafic intrusions, are interpreted to have formed by processes that decrease the solubility of chromite. However, such models have difficulty in explaining the great thicknesses (up to 10 m) of chromite mineralization at Inyala and Railway Block (Zimbabwe), Ipueira-Medrado (Brazil), Uitkomst (South Africa), and Sukinda (India), and the very great (up to 100 m) thicknesses of chromitite at Kemi (Finland) and in the Black Thor Intrusive Complex (Canada). We propose a new process that involves partial melting of Fe ± Ti oxide–rich rocks (oxide-facies iron formation or ferrogabbro) and conversion of fine-grained oxide to chromite by reaction with Cr-rich komatiitic magma in a dynamic magma conduit. This process is analogous to the widely accepted model for the upgrading of barren iron-sulfide xenomelts to form magmatic nickel–copper–platinum group element deposits. We demonstrate that this process is geologically, physically, and chemically feasible, that it probably occurred in the Black Thor Intrusive Complex, and that it may have applications elsewhere.**

## INTRODUCTION

Chromite deposits have traditionally been subdivided into stratiform (type I) and podiform (type II) types (e.g., Stowe, 1994). However, it has become clear that type I stratiform deposits can be subdivided (Prendergast, 2008) into those hosted by large, differentiated layered intrusions (periodically replenished magma chambers) (type IA), and small, less-differentiated magmatic conduits (flow-through feeder conduits and /or sills) (type IB) (Table DR1 in the GSA Data Repository[1]). Type IB deposits are normally laterally less extensive but thicker than type IA deposits, are typically hosted by more ultramafic rocks, are ordinarily derived from more magnesian—commonly komatiitic—magmas, and usually have higher Mg and lower Al contents (Table DR1).

A fundamental problem in the genesis of all stratiform chromite deposits is how layers of massive to semi-massive chromite that are commonly up to 1 m thick (e.g., Bushveld [South Africa], Stillwater [Montana, USA]), less commonly up to 10 m thick (e.g., Inyala and Railway Block [Zimbabwe], Ipueira-Medrado [Brazil], Uitkomst [South Africa], Sukinda [India]), but in some cases up to 100 m thick (e.g., Kemi [Finland], Black Thor Intrusive Complex [Canada]) (Table DR1) are generated from magmas that typically contain <0.35% Cr and crystallize very small amounts of chromite (normally <1% of the cumulus assemblage). Many models have been suggested, including (1) liquid immiscibility (e.g., McDonald, 1965), (2) oxidation (e.g., Ulmer, 1969; Ferreira Filho and Araujo, 2009), (3) felsification (e.g., Irvine, 1975; Spandler et al., 2005), (4) magma mixing (e.g., Irvine, 1977; Campbell and Murck, 1993), (5) pressure increase (e.g., Cameron, 1980; Lipin, 1993) or decrease (Latypov et al., 2018), (6) assimilation of iron formation (e.g., Rollinson, 1997), (7) hydration (e.g., Azar, 2010; Prendergast, 2008), (8) dynamic crystallization (Yudovskaya et al., 2015), and (9) cumulate-melt interaction (e.g., O'Driscoll et al., 2010), with or without upward transport (e.g., Eales, 2000; Mondal and Mathez, 2007) and/or downward slumping (e.g., Maier et al., 2013).

These processes are not mutually exclusive and may have operated to varying degrees in different deposits, yet all have problems. Upward-transport models simply relocate the problem, add a major degree of fluid dynamic complexity in terms of requiring re-entrainment of previously segregated chromite, and do not explain why chromite does not occur in economic concentrations in volcanic rocks. Magma mixing, contamination, oxidation, hydration, and pressure changes all are feasible to varying degrees, but require the amount of magma to greatly exceed the thickness of the host intrusion (e.g., Campbell and Murck, 1993; Eales, 2000; Carson et al., 2013). Layered intrusions likely inflated during crystallization and never contained melt zones of the thicknesses required at the lower (more realistic) efficiencies of extraction. Phase-equilibria studies (e.g., Irvine, 1977; Murck and Campbell, 1986) indicate that the most popular model—mixing of parental (new influx) and fractionated (resident) magmas across the convex olivine-chromite cotectic to drive it into the volume of chromite-only crystallization—can generate only ~0.1 wt% chromite as the magma is driven back to the cotectic. The interval over which chromite alone can crystallize after a pressure decrease (Latypov et al., 2018) has not been established, however it is limited within this context by the low solubility of Cr in silicate magmas.

Crystallization and deposition of chromite in a flow-through system, analogous to the lava channels and magma conduits that host magmatic Ni–Cu–platinum group element (PGE) deposits (e.g., Lesher et al., 1984; Lesher, 1989; Arndt et al., 2008), which are inferred to

---

*E-mail: mlesher@laurentian.ca

[1]GSA Data Repository item 2019075, Table DR1 (classification of Type I stratiform magmatic chromite deposits) and Table DR2 (key characteristics of Type IB conduit-hosted chromite deposits), is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

CITATION: Lesher, C.M., Carson, H.J.E., and Houlé, M.G., 2019, Genesis of chromite deposits by dynamic upgrading of Fe ± Ti oxide xenocrysts: Geology, https://doi.org/10.1130/G45448.1.

have processed two to three orders of magnitude more magma than the amount of sulfide presently preserved in the channels, would solve the mass-balance problem. However, the process(es) required to drive the magma into the field of chromite-only crystallization would need to occur continuously over very long periods of time to generate the vast amounts of chromite in type IB deposits.

Wholesale assimilation of iron formation (Rollinson, 1997) explains the close association of many type IB deposits with iron formation (Table DR2), however there are several problems with such a process:

(1) The presence of cotectic olivine(-chromite) cumulate rocks in the lower parts of the host intrusions (e.g., Kemi: Alapieti et al., 1989; Black Thor: Carson et al., 2013) indicates that the magmas were already saturated in chromite, so they should not have been able to assimilate another oxide phase.

(2) Adding an assimilant containing >20% FeO to a komatiitic magma that would normally contain ~10%–12% FeO would increase the Fe/Mg ratios of olivine, orthopyroxene, and clinopyroxene, which does not appear to be observed (e.g., Azar, 2010).

(3) Assimilation-crystallization models indicate that the modal proportion of chromite generated by such a process would be <0.3% (Azar, 2010).

## PARTIAL MELTING AND UPGRADING

A solution to this problem would be for the parental magma to partially melt an oxide-rich lithology such as oxide-facies iron formation or ferrogabbro. A high-Mg komatiitic magma with ~30% MgO would be undersaturated in chromite (Murck and Campbell, 1986) and would be able to completely assimilate significant amounts of either lithology; however, a low-Mg komatiitic magma with ~20% MgO would be saturated in chromite and would be able to dissolve the silicate phases but not the oxide phases. Addition of silica would account for the abundance of orthopyroxene in magmas that normally crystallize clinopyroxene (Arndt et al., 2008).

Converting xenocrystic magnetite and/or ilmenite to chromite requires magnetite to incorporate Cr-Al-Mg-V-Ni from the magma and release Fe and/or Ti into the magma. Magnetite and chromite are both isometric, so the conversion from magnetite would be topotactic, whereas ilmenite is trigonal, so the conversion from ilmenite would require a structural inversion, however that is unlikely to be a barrier at such high temperatures.

Whether this process is completely diffusional or whether it involves crystallization of additional chromite around the xenocryst depends on the enthalpy of the system, which depends on the relative rates of thermomechanical erosion, assimilation, and crystallization (see, e.g., Williams et al. 1998); however, the amount of magma required can be calculated from mass balance (Lesher and Burnham, 2001):

$$Y_i^f = \frac{\left(X_i^o R + Y_i^o\right)}{R + D_i^{\text{oxide/melt}}}, \qquad (1)$$

where $X_i^o$ is the concentration of element *i* in the initial silicate magma, $Y_i^o$ is the concentration of *i* in the initial oxide (magnetite or ilmenite), $Y_i^f$ is the concentration of *i* in the final oxide (chromite), $D_i^{\text{oxide/melt}}$ is the oxide–silicate melt partition coefficient for element *i*, and *R* is the magma/oxide mass ratio. Using conservative abundances of Cr in the magma and reasonable partition coefficients for Cr and Ti, the results (Fig. 1) indicate that magma/oxide ratios as low as 100 can produce Cr-rich chromites. These values are on the low end of estimates of *R* for many komatiitic Ni-Cu-(PGE) systems (e.g., 100–500 for Kambalda [Western Australia]: Lesher and Campbell, 1993; 300–1100 for Raglan [Canada]: Barnes and Picard, 1993; 50–200 for Thompson [Canada]: Layton-Matthews et al., 2011), so should be achievable in the dynamic systems envisioned for type IB chromite deposits.

This process is also limited by the diffusion rates of Cr-Al into magnetite/ilmenite and Ti out of ilmenite. The chromite grains in the best-preserved deposits are typically 0.1–0.2 mm, the magnetite grains in ferrogabbros are typically similar, and the magnetite grains in weakly metamorphosed iron formations are ~0.002 mm.

We have estimated the amount of time required to diffuse Cr-Al-Ti from a magma kept at constant composition (through advective flow) to the core of a 0.1 mm magnetite grain initially containing no Cr-Al-Ti using a one-dimensional (1-D) analytical solution to Fick's second law of diffusion (equation 2.45 in Crank, 1975), modified to allow for the preferential partitioning of Cr-Ti-Al from the melt into the oxide phase:

$$C_{(x,t)} = C_o D^{\text{oxide/magma}} \, erfc \frac{x}{2\sqrt{Dt}}, \qquad (2)$$

Where $C_{(x,t)}$ is the concentration of Cr in the magnetite at distance *x* from the rim at time *t*, $C_o$ is the concentration of Cr in the magma (assumed to be 3500 ppm in this case), $D^{\text{oxide/magma}}$ is the oxide-magma partition coefficient, *erfc* is the complementary error function, and *D* is the diffusion constant at 1440 °C, a temperature appropriate for a 22% MgO komatiitic magma. There are more sophisticated 2-D and 3-D solutions, but given all of the uncertainties in parameterization and the isometric structures of magnetite and chromite, the 1-D calculation is sufficient to demonstrate the feasibility of the process. The results (Fig. 2) indicate that 0.1 mm magnetite or ilmenite grains could be completely converted to chromite in 1–10 days, much less than the weeks to years duration of single magmatic events and the thousands to millions of years duration of most magmatic systems. This is consistent with the observation that individual chromite grains

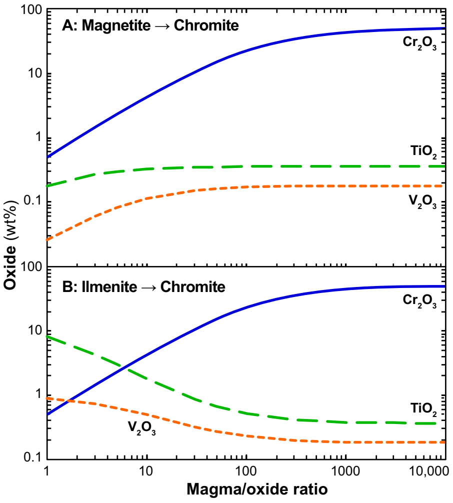

**Figure 1. Variations in the abundances of Cr, Ti, and V in oxide composition as function of magma/oxide mass ratio. Calculation method is described in text. A: Model for converting magnetite to chromite, assuming 0.5% $Cr_2O_3$, 0.36% $TiO_2$, and 0.03% $V_2O_3$ in initial magma, and $D^{\text{oxide/magma}}$ (partition coefficient) of 100 for Cr, 1 for Ti, and 6 for V (estimated from observed compositions), and no Cr, Ti, or V in initial oxide (typical magnetite in iron formation). B: Model for converting ilmenite to chromite. Same as A except assumes 16% $TiO_2$ and 1% $V_2O_3$ in initial oxide (typical titanomagnetite in ferrogabbro).**

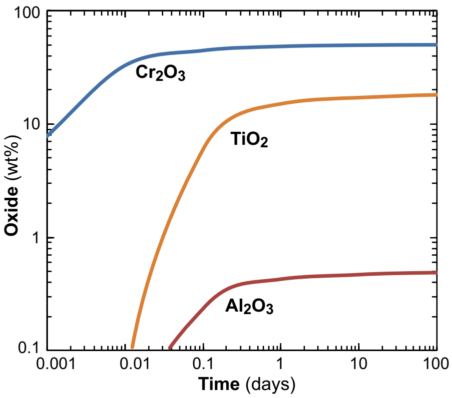

**Figure 2. Calculated abundances of Cr-Al-Ti diffused into core of 0.1-mm-diameter magnetite grain. Calculation method is described in text. Cr exchange is essentially complete after 1 day, and Al and Ti after 10 days. Calculation assumes 0.5% $Cr_2O_3$, 9% $Al_2O_3$, and 0.5% $TiO_2$ in magma (estimated based on observed compositions); $D^{\text{oxide/magma}}$ (partition coefficient) of 100 for Cr, 2 for Al, and 1 for Ti (based on observed compositions); $D_o$ (pre-exponential diffusion factor) of 7.17 × $10^{-4}$ $m^2$ $s^{-1}$ for Cr, 1.46 × $10^{-5}$ for Al, and 2.77 × $10^{-5}$ (Dieckmann et al., 1978; Aggarwal and Dieckmann, 2002); *Q* (activation energy for diffusion) of 335 kJ $mol^{-1}$ for Cr, 265 kJ $mol^{-1}$ for Al, and 267 kJ $mol^{-1}$ for Ti (Dieckmann et al., 1978; Aggarwal and Dieckmann, 2002); and *T* (temperature) of 1440 °C (appropriate for a 22% MgO magma).**

in most deposits are unzoned or normally zoned (reflecting equilibration with trapped liquid and/or modification during serpentinization).

## DISCUSSION

The Black Thor and Double Eagle Intrusive Complexes in the Ring of Fire Intrusive Suite of northern Ontario (Canada) appear to have had the best opportunity to generate chromite mineralization by the proposed mechanism. There are oxide-silicate–facies iron formations and Fe-Ti oxide-bearing gabbros in underlying rocks, the intrusions contain iron-formation and gabbro xenoliths, the parental magma was a chromite-saturated low-Mg komatiite (Mungall et al., 2010), and the chromite-bearing intrusions are dominated by cumulates and interpreted to represent flow-through magma conduits (Carson et al., 2013). The chromites in the Black Thor Intrusive Complex exhibit a wide range of textures including (1) massive, (2) inclusion-bearing (predominantly serpentine-actinolite-chlorite interpreted to represent altered komatiitic melt inclusions), and (3) pitted with fine Fe ± Cu sulfides (Fig. 3A). The first and third are similar to the textures of magnetite-silicate±sulfide iron-formations below the Black Thor Intrusive Complex (Fig. 3B), consistent with them being the source of the oxide in this deposit.

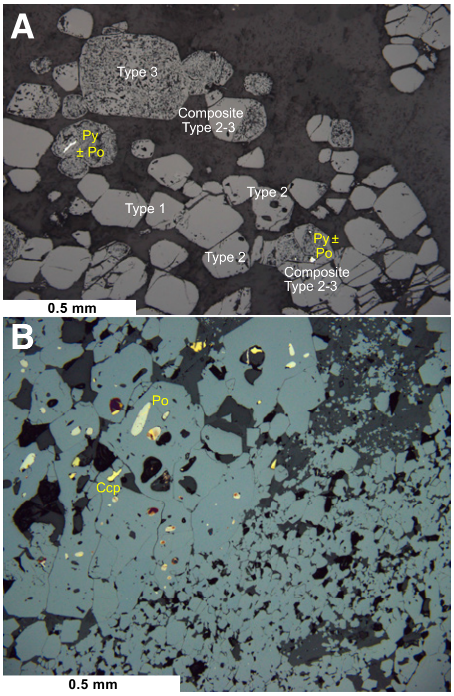

**Figure 3. A: Backscattered electron image of chromites (gray) in Black Thor Intrusive Complex (Canada: Universal Transverse Mercator coordinates 551333 m E, 5845928 m N, Zone 16, NAD83 datum) showing type I (massive), type II (inclusion-bearing), and type III (pitted) textures, including some composites of those types. Sample 1331337, DDH BT-09-76, 186 m. B: Photomicrograph of magnetite-silicate ±sulfide–facies iron-formation within the footwall of Black Thor showing similar textures. Sample 1331691, DDH FN-09-01, 152.15 m. Py—pyrite; Po—pyrrhotite; Ccp—chalcopyrite.**

There are examples where magmas have thermomechanically eroded oxide-facies iron formation (e.g., Duluth [Minnesota, USA]: Ripley, 1986; Digger's Rock [Western Australia]: Perring et al., 1996; Hunters Road [Zimbabwe]: Prendergast, 2003); however, none of these systems contain anomalous chromite. In the case of Duluth, the magma may have been too poor in Cr, whereas the magma at Digger's Rock and Hunters Road may have been undersaturated in chromite. Unfortunately, none of these studies reported the Cr contents of the oxide xenoliths. The country rocks of the Sukinda and the Inyala intrusions include iron formation, but no iron-formation xenoliths were reported by Chakraborty and Chakraborty (1984), Mondal et al. (2006), or Rollinson (1997). The Kemi intrusion contains Na-rich gneissic xenoliths; however, no iron-formation xenoliths were reported by Alapieti et al. (1989).

There are <2-cm-thick chromite layers in strongly differentiated komatiite flows where chromite has reached saturation after significant degrees of fractional crystallization (e.g., Kambalda: Lesher, 1989) and rare occurrences of Cr-rich lavas (e.g., Halkoaho et al., 2000), but the amount of chromite is very small and it is clear that it formed via fractional crystallization. The absence of thick chromite seams in komatiitic, picritic, or basalt lavas suggest that despite its fine grain size and theoretical high transportability (see Lesher, 2017), chromite is normally trapped at the same stratigraphic levels where it forms and is not normally transported significant distances vertically, likely because it forms larger untransportable "pseudoslugs".

The proposed process (Fig. 4) requires further testing; however, it explains a major paradox in the genesis of conduit-hosted, if not all, stratiform chromite deposits. It may also have applications in the genesis of some intrusions containing anomalous amounts of Fe-Ti-V oxides associated with high-Ti, low-Cr basaltic magmas.

## ACKNOWLEDGMENTS

The Natural Sciences and Engineering Council of Canada (DG 203171-2012) and Cliffs Natural Resources (CRD 446109-2012) provided financial support; the Ontario Geological Survey and the Geological Survey of Canada Targeted Geosciences Initiative program provided in-kind analytical support; and Cliffs Natural Resources and Noront Resources provided in-kind logistical support. We are grateful to Bronwyn Azar, Pedro Jugo, Riku Metsaranta, Ryan Weston, Jesse Robertson, Edward Ripley, and Roger Scoon for helpful discussions, and to Steve Barnes and an anonymous reviewer for insightful comments on the manuscript. This is Mineral Exploration Research Centre Metal Earth Contribution MERC-ME-2018-100.

## REFERENCES CITED

Aggarwal, S., and Dieckmann, R., 2002, Point defects and cation tracer diffusion in $(\text{Ti}_x\text{Fe}_{1-x})_{3-\delta}\text{O}_4$: II. Cation tracer diffusion: Physics and Chemistry of Minerals, v. 29, p. 707–718, https://doi.org/10.1007/s00269-002-0284-0.

Alapieti, T.T., Kujanpaa, J., Lahtinen, J.J., and Papunen, H., 1989, The Kemi stratiform chromitite deposit, northern Finland: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 84, p. 1057–1077, https://doi.org/10.2113/gsecongeo.84.5.1057.

Arndt, N.T., Lesher, C.M., and Barnes, S.J., 2008, Komatiite: Cambridge, UK, Cambridge University Press, 465 p., https://doi.org/10.1017/CBO9780511535550.

Azar, B., 2010, The Blackbird chromite deposit, James Bay lowlands of Ontario, Canada: Implications for chromitite genesis in ultramafic conduits and open magmatic systems [M.S. thesis]: Toronto, Canada, University of Toronto, 154 p.

Barnes, S.-J., and Picard, C.P., 1993, The behavior of platinum-group elements during partial melting, crystal fractionation, and sulphide segregation: An example from the Cape Smith fold belt, northern Quebec: Geochimica et Cosmochimica Acta, v. 57, p. 79–87, https://doi.org/10.1016/0016-7037(93)90470-H.

Cameron, E.N., 1980, Evolution of the Lower Critical Zone, central sector, eastern Bushveld Complex, and its chromite deposits: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 75, p. 845–871, https://doi.org/10.2113/gsecongeo.75.6.845.

Campbell, I.H., and Murck, B.W., 1993, Petrology of the G and H chromitite zones in the Mountain View area of the Stillwater Complex, Montana: Journal of Petrology, v. 34, p. 291–316, https://doi.org/10.1093/petrology/34.2.291.

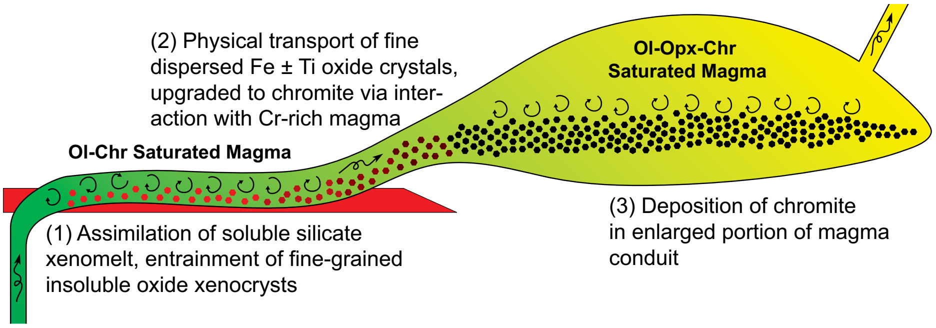

**Figure 4. Model for dynamic upgrading of Fe ± Ti oxides derived from oxide-facies iron formation or ferrogabbro via interaction with Cr-rich komatiitic magma. Ol—olivine; Chr—chromite; Opx—orthopyroxene.**

Carson, H.J.E., Lesher, C.M., Houlé, M.G., Weston, R.J., and Shinkle, D.A., 2013, Project Unit 13-002: Stratigraphy, geochemistry and petrogenesis of the Black Thor intrusive complex and associated chromium and nickel-copper-platinum group element mineralization, McFaulds Lake greenstone belt, Ontario, *in* Summary of Field Work and Other Activities 2013: Ontario Geological Survey Open File Report 6290, p. 52.1–52.15.

Chakraborty, K.L., and Chakraborty, T.L., 1984, Geological features and origin of the chromite deposits of Sukinda Valley, Orissa, India: Mineralium Deposita, v. 19, p. 256–265, https://doi.org/10.1007/BF00204378.

Crank, J., 1975, The Mathematics of Diffusion: Oxford, UK, Oxford University Press, 421 p.

Dieckmann, R., Mason, T.O., Hodge, J.D., and Schmalzried, H., 1978, Defects and cation diffusion in magnetite (III): Tracer diffusion of foreign tracer cations as a function of temperature and oxygen potential: Berichte der Bunsengesellschaft fur Physikalische Chemie, v. 82, p. 778–783, https://doi.org/10.1002/bbpc.19780820803.

Eales, H.V., 2000, Implications of the chromium budget of the Western Limb of the Bushveld Complex: South African Journal of Geology, v. 103, p. 141–150, https://doi.org/10.2113/103.2.141.

Ferreira Filho, C.F., and Araujo, S.M., 2009, Review of Brazilian chromite deposits associated with layered intrusions: Geological and petrological constraints for the origin of stratiform chromitites: Transactions of the Institution of Mining and Metallurgy, Section B: Applied Earth Science, v. 118, p. 86–100.

Halkoaho, T., Liimatainen, J., Papunen, H., and Välimaa, J., 2000, Exceptionally Cr-rich basalts in the komatiitic volcanic association of the Archaean Kuhmo greenstone belt, eastern Finland: Mineralogy and Petrology, v. 70, p. 105–120, https://doi.org/10.1007/s007100070016.

Irvine, T.N., 1975, Crystallization sequences in the Muskox intrusion and other layered intrusions—II. Origin of chromitite layers and similar deposits of other magmatic ores: Geochimica et Cosmochimica Acta, v. 39, p. 991–1020, https://doi.org/10.1016/0016-7037(75)90043-5.

Irvine, T.N., 1977, Origin of chromitite layers in the Muskox intrusion and other stratiform intrusions: A new interpretation: Geology, v. 5, p. 273–277, https://doi.org/10.1130/0091-7613(1977)5<273:OOCLIT>2.0.CO;2.

Latypov, R., Costin, G., Chistyakova, S., Hunt, E.J., Mukherjee, R., and Naldrett, T., 2018, Platinum-bearing chromite layers are caused by pressure reduction during magma ascent: Nature Communications, v. 9, p. 1–7, https://doi.org/10.1038/s41467-017-02773-w.

Layton-Matthews, D., Lesher, C.M., Liwanag, J., Halden, N., Burnham, O.M., Hulbert, L., Peck, D.C., and Keays, R.R., 2011, Mineralogy, geochemistry, and genesis of komatiite-associated Ni-Cu-PGE mineralization in the Thompson nickel belt, Manitoba: Reviews in Economic Geology, v. 17, p. 123–143.

Lesher, C.M., 1989, Komatiite-associated nickel sulfide deposits, *in* Whitney, J.A., and Naldrett, A.J., eds., Ore Deposition Associated with Magmas: Reviews in Economic Geology, v. 4, p. 44–101.

Lesher, C.M., 2017, Roles of xenomelts, xenoliths, xenocrysts, xenovolatiles, residues, and skarns in the genesis, transport, and localization of magmatic Fe-Ni-Cu-PGE sulfides and chromite: Ore Geology Reviews, v. 90, p. 465–484, https://doi.org/10.1016/j.oregeorev.2017.08.008.

Lesher, C.M., and Burnham, O.M., 2001, Multicomponent elemental and isotopic mixing in Ni-Cu-(PGE) ores at Kambalda, Western Australia: Canadian Mineralogist, v. 39, p. 421–446, https://doi.org/10.2113/gscanmin.39.2.421.

Lesher, C.M., and Campbell, I.H., 1993, Geochemical and fluid dynamic modelling of compositional variations in Archean komatiite-hosted nickel sulfide ores in Western Australia: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 88, p. 804–816, https://doi.org/10.2113/gsecongeo.88.4.804.

Lesher, C.M., Arndt, N.T., and Groves, D.I., 1984, Genesis of komatiite-associated nickel sulphide deposits at Kambalda, Western Australia: A distal volcanic model, *in* Buchanan, D.L., and Jones, M.J., eds., Sulphide Deposits in Mafic and Ultramafic Rocks: London, Institute of Mining and Metallurgy, p. 70–80.

Lipin, B.R., 1993, Pressure increases, the formation of chromite seams, and the development of the Ultramafic series in the Stillwater Complex, Montana: Journal of Petrology, v. 34, p. 955–976, https://doi.org/10.1093/petrology/34.5.955.

Maier, W.D., Barnes, S.-J., and Groves, D.I., 2013, The Bushveld Complex, South Africa: Formation of platinum-palladium, chrome- and vanadium-rich layers via hydrodynamic sorting of a mobilized cumulate slurry in a large, relatively slowly cooling, subsiding magma chamber: Mineralium Deposita, v. 48, p. 1–56, https://doi.org/10.1007/s00126-012-0436-1.

McDonald, J.A., 1965, Liquid immiscibility as one factor in chromite seam formation in the Bushveld igneous complex: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 60, p. 1674–1685, https://doi.org/10.2113/gsecongeo.60.8.1674.

Mondal, S.K., and Mathez, E.A., 2007, Origin of the UG2 chromitite layer, Bushveld Complex: Journal of Petrology, v. 48, p. 495–510, https://doi.org/10.1093/petrology/egl069.

Mondal, S.K., Ripley, E.M., Li, C., and Frei, R., 2006, The genesis of Archaean chromitites from the Nuasahi and Sukinda massifs in the Singhbhum Craton, India: Precambrian Research, v. 148, p. 45–66, https://doi.org/10.1016/j.precamres.2006.04.001.

Mungall, J.E., Harvey, J.D., Balch, S.J., Atkinson, J., and Hamilton, M.A., 2010, Eagle's Nest: A magmatic Ni-sulfide deposit in the James Bay Lowlands, Ontario, Canada, *in* Goldfarb, R.J., et al., eds., The Challenge of Finding New Mineral Resources: Global Metallogeny, Innovative Exploration, and New Discoveries—Volume II: Zinc-Lead, Nickel-Copper-PGE, and Uranium: Society of Economic Geologists Special Publication 15, p. 539–557.

Murck, B.W., and Campbell, I.H., 1986, The effects of temperature, oxygen fugacity and melt composition on the behaviour of chromium in basic and ultrabasic melts: Geochimica et Cosmochimica Acta, v. 50, p. 1871–1887, https://doi.org/10.1016/0016-7037(86)90245-0.

O'Driscoll, B., Emeleus, C.H., Donaldson, C.H., and Daly, J.S., 2010, Cr-spinel seam petrogenesis in the Rum Layered Suite, NW Scotland: Cumulate assimilation and *in situ* crystallization in a deforming crystal mush: Journal of Petrology, v. 51, p. 1171–1201, https://doi.org/10.1093/petrology/egq013.

Perring, C.S., Barnes, S.J., and Hill, R.E.T., 1996, Geochemistry of komatiites from Forrestania, Southern Cross Province, Western Australia: Evidence for crustal contamination: Lithos, v. 37, p. 181–197, https://doi.org/10.1016/0024-4937(95)00036-4.

Prendergast, M.D., 2003, The nickeliferous late Archean Reliance komatiitic event in the Zimbabwe craton—Magmatic architecture, physical volcanology, and ore genesis: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 98, p. 865–891, https://doi.org/10.2113/gsecongeo.98.5.865.

Prendergast, M.D., 2008, Archean komatiitic sill-hosted chromite deposits in the Zimbabwe craton: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 103, p. 981–1004, https://doi.org/10.2113/gsecongeo.103.5.981.

Ripley, E.M., 1986, Applications of stable isotope studies to problems of magmatic sulfide ore genesis with special reference to the Duluth Complex, Minnesota, *in* Friedrich, G.H., et al., eds, Geology and Metallogeny of Copper Deposits: Heidelberg Berlin, Springer-Verlag, p. 25–42, https://doi.org/10.1007/978-3-642-70902-9_3.

Rollinson, H., 1997, The Archean komatiite-related Inyala Chromitite, southern Zimbabwe: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 92, p. 98–107, https://doi.org/10.2113/gsecongeo.92.1.98.

Spandler, C., Mavrogenes, J., and Arculus, R., 2005, Origin of chromitites in layered intrusions: Evidence from chromite-hosted melt inclusions from the Stillwater Complex: Geology, v. 33, p. 893–896, https://doi.org/10.1130/G21912.1.

Stowe, C.W., 1994, Compositions and tectonic settings of chromite deposits through time: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 89, p. 528–546, https://doi.org/10.2113/gsecongeo.89.3.528.

Ulmer, G.C., 1969, Experimental investigations of chromite spinels, *in* Wilson, H.D.B., ed., Magmatic Ore Deposits: Society of Exploration Geophysicists Geophysical Monograph 4, p. 114–131.

Williams, D.A., Kerr, R.C., and Lesher, C.M., 1998, Emplacement and erosion by Archean komatiite lava flows at Kambalda: Revisited: Journal of Geophysical Research, v. 103, p. 27,533–27,549, https://doi.org/10.1029/97JB03538.

Yudovskaya, M.A., Naldrett, A.J., Woolfe, J.A.S., Costin, G., and Kinnaird, J.A., 2015, Reverse compositional zoning in the Uitkomst chromitites as an indication of crystallization in a magmatic conduit: Journal of Petrology, v. 56, p. 2373–2394, https://doi.org/10.1093/petrology/egv062.

Printed in USA