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PETROLOGY OF MAFIC-ULTRAMAFIC LAYERED INTRUSIONS IN PRECAMBRIAN PLATFORMS: STATE OF THE ART AND NEW APPROACHES

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Phase layering in mafic and ultramafic intrusions cannot be explained in terms of convection and accumulation in magma chamber as convection of melt rich in cumulus crystals is impossible. Intrusion of heterogeneous magma with 40–50 vol.% crystal phase is rather associated with compaction whereby intercumulus liquid is squeezed out toward the roof of the chamber.

Layering, cumulus, intercumulus melt, convection, compaction, percolation

INTRODUCTION

Layered mafic-ultramafic intrusions, or *differentiated gabbro and norite intrusions* according to Kuznetsov [1], have always attracted interest of geologists as a clue to magma differentiation and natural diversity of igneous rocks, and as a source of economic Ni, Cu, Co, Cr, Ti, V, PGE, and Au mineralization.

Phase layering of mafic-ultramafic plutons has been commonly explained petrologically in terms of separation of crystals from silicate melt in a magma chamber. Within-chamber differentiation of these intrusions was associated with fractional crystallization of magma whereby cumulus crystals settle on the floor and thus fill the chamber from bottom to top. This hypothesis is supported by successive upward changes from high-temperature to lower-temperature phases in many stratified intrusions. Two most often invoked scenarios for the origin of layering imply that either (i) minerals crystallized near the roof of the intrusion precipitate on the floor by gravity or convection [2] or (ii) all minerals crystallize and solidify *in situ* [3]. The latter (Jackson's) scenario was originally less popular than the former one, suggested by Wager and Brown. The idea of *in situ* crystallization became more so doubted after diffusion coefficients of major elements had been obtained experimentally for melts of various compositions. Compared with the real cooling time of magma [4], the coefficients turned to be inconsistent with Jackson's differentiation by "directed crystallization". Both scenarios basically assumed an idealized magma chamber containing an originally superliquidus homogeneous silicate melt intruded in a single episode, which never occurs in real intrusions, as it became clear from later studies.

First, natural silicate melts are never or rarely superheated. Wager and Brown [2] needed superheating to avoid the formation of chilled selvages before the onset of convection of basaltic melt driven by a temperature gradient between the roof and the floor of the chamber. However, superheating of intruding basaltic magmas is disproved by geological evidence which indicates a range of 1050 to 1200 °C, based on direct temperature estimates in modern lavas and predicted homogenization temperatures of melt inclusions.

Second, layered plutons most often form by influx of successive batches of magma into the chamber. This idea was prompted by abrupt compositional trend changes discovered in minerals from stratified intrusions [5, 6]. Von Gruenewaldt et al. [7] reported evidence for the origin of the Bushveld pluton by intrusion of boninitic and tholeiitic magmas. They detected sills of 2.1 Ga pre-Bushveld amphibolites and sills varying in composition from

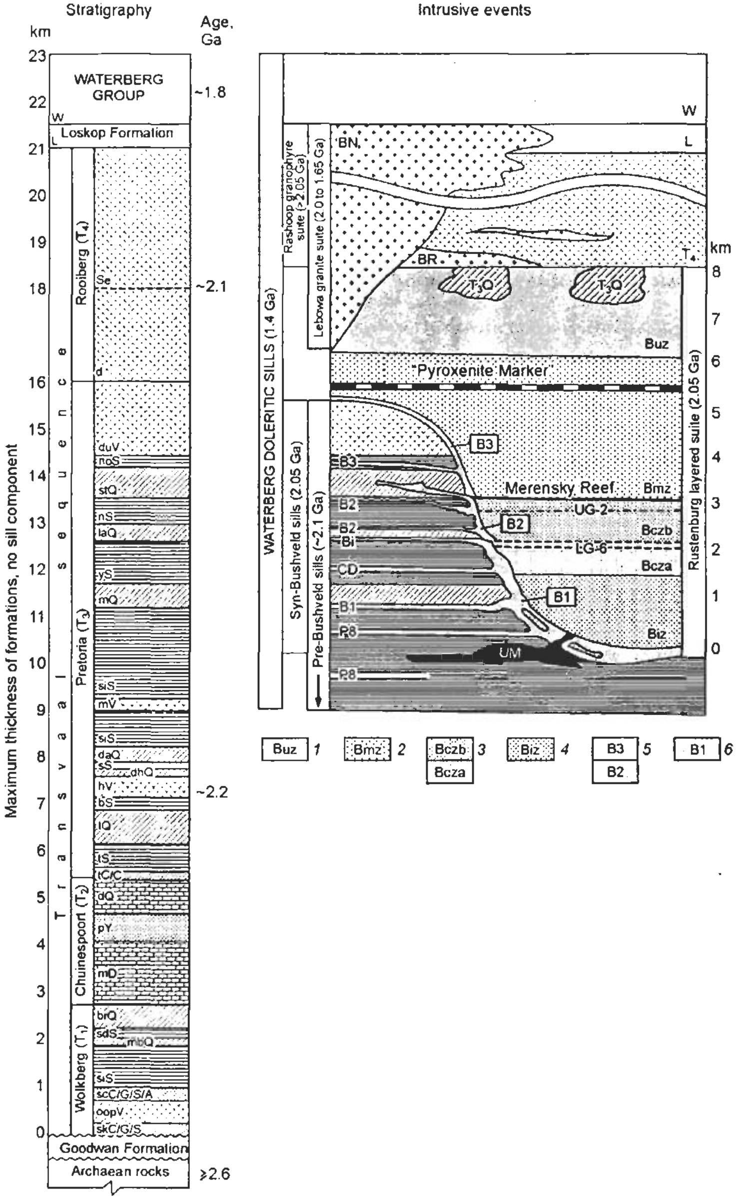

Fig. 1. Stratigraphy of eastern Transvaal showing relations of Transvaal sequence, Bushveld complex, and younger intrusions, after [7]. Zones of Bushveld complex: *1* — Upper, *2* — Main, *3* — Critical, *4* — Lower; Marginal rocks and sills: *5* — gabbroic, *6* — pyroxenitic; UG-2 and LG-6 — chromitite layers. Abbreviations stand for UM — ultramafic sills, CD — quench-textured sills, PB — pre-Bushveld sills. Lithologies: A — arkose, C — conglomerate, D — dolomites, G — graywacke, I — iron formation, Q — quartzite, S — shale, V — volcanics.

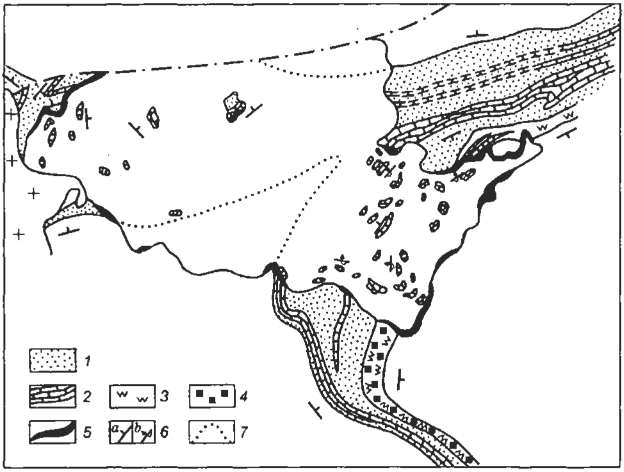

Fig. 2. Traceable textures of buried country rocks in Chinei gabbronorite pluton. ***1–3*** **— Early Proterozoic Butun Formation: terrigenous sediments (*1*), carbonates and their xenoliths in gabbronorites (*2*), black shales (*3*);** ***4*** **— disseminated sulfide;** ***5*** **— sulfide ores at base of pluton;** ***6*** **— normal (*a*) and reverse (*b*) bedding;** ***7*** **— predicted boundaries of Butun Formation beneath gabbronorite pluton.**

peridotites through pyroxenites with chilled textures to gabbros coeval to the Bushveld rocks (2.05 Ga). The peridotite and pyroxenite sills correlate in major- and trace-element compositions with rocks of the Lower zone and ultramafics of the Critical zone, and the gabbros are comparable with the Main and upper Critical zones of the complex (Fig. 1). Detailed studies furnish more evidence for magma heterogeneity in layered intrusions. Melt inclusion data from layered complexes [8, 9] and lavas [10, 11] indicate that parent melts are product of mixing of compositionally different magmas.

The Wager-Brown hypothesis used so far in models of layered mafic intrusions implies separation of material in convective flows of magma, especially thermal convection produced by temperature difference between the roof and the floor of the chamber. However, this convection is impossible [12], as a near-liquidus intruding magma would rapidly loose heat and crystallize once it contacts the colder country rocks, and chilled selvages would arise before the onset of thermal gradient and convection. Therefore, the idea of thermal convection as a mechanism of differentiation in the magma chamber gave way later to a more realistic idea of sedimentation mass transfer in phase and general convection. Phase convection arises as a response of liquid magma to precipitation of crystals that originate at the chamber roof and involves an additional upward melt flow. Phase convection periodically grades into general convection when the cold crystal-rich layer at the top of the intrusion reaches its critical density, becomes concentrated, then rapidly falls down and spreads out at the chamber floor [13]. The velocity of this descending plume, according to hydrodynamic estimates [14], is much above the Stokes' settling rate, and melt mixing is also much more efficient than in phase convection.

At the same time, there is increasing evidence that mantle magmas reaching shallow continental crust are already crystal-rich. Ariskin and Barmina [15] report phase compositions of parent magmas for a number of known intrusions back-calculated using melt-crystal equilibrium modeling and show that natural melts are as a rule heterogeneous consisting of crystals suspended in silicate liquid. The percentages of the two phases in the parent magmas of mafic melts vary broadly in different plutons, e.g., from 15–25 vol.% in the Talnakh and Kiglapeit plutons to 40–65 vol.% (!) in the Partridge and Dovyren plutons and the Kamenisty sill (East Kamchatka). These striking contrasts find a satisfactory explanation in terms of intrusion dynamics [16]. A basaltic melt filling a cone-shaped chamber in non-isothermal conditions crystallizes to 10–15% at a rate of 100–200 m^3/s, to 25–30%

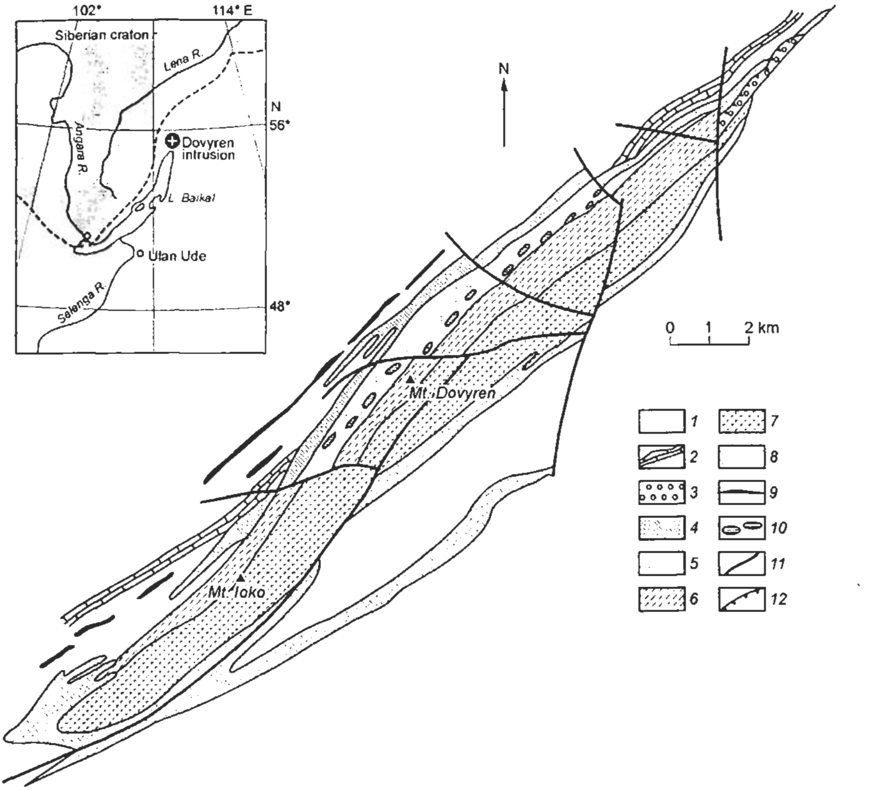

Fig. 3. Location map of Dovyren dunite-troctolite-gabbro layered pluton on periphery of Siberian craton (inset) and its geological framework, after [19]. ***1, 2*** **— Late Proterozoic terrigenous (*1*) and carbonate (*2*) host rocks;** ***3*** **— Early Precambrian conglomerates, sandstones, and shales;** ***4–9*** **— rocks of Dovyren pluton: plagioclase lherzolites at base of pluton (*4*), dunites (*5*), troctolites (*6*), olivine gabbro and gabbronorites (*7*), granophyre gabbronorites (*8*) and their sills in country rocks (*9*);** ***10*** **— xenoliths of apodolomite Mg skarns in dunites;** ***11*** **— faults;** ***12*** **— unconformities.**

at 10–100 m^3/s, and to 40% at 0.2–10 m^3/s. Thus, a melt, if not superheated, cannot fill the chamber without crystallizing and cannot remain homogeneous.

Note that even superheated basaltic melts, at far super-liquidus temperatures (1500 °C), retain a minor amount of microscopic crystals [12]. This heterogeneity is observed in small inclusions in olivine which is the primary liquidus mineral in basaltic melts. So, olivine grains from dunites and peridotites of the Dovyren pluton contain 20–100 μm inclusions of mafic plagioclase and clinopyroxene crystallized after separation of the greatest portion of olivine. It was apparently a fairly thick suspension of these crystal embryos in the magma as some olivine grains contained about a dozen plagioclase phenocrysts; clinopyroxene and orthopyroxene embryos are also present but much less often.

Besides the subliquidus crystal phases parental to the cooling magma, heterogeneity of some mafic-ultramafic intrusions is increased due to persisting xenoliths, such as high-alkali felsic glasses or feldspar and biotite crystals that exist as microinclusions in early liquidus minerals (olivine, pyroxene, and plagioclase). High-silica glasses (69–77 wt.% SiO_2) were found in Klyuchevsky lavas [17], in trappean intrusions in the Noril'sk region [8], and in the Dovyren dunite-troctolite-gabbro layered pluton in northern Transbaikalia [9]. The origin of these exotic

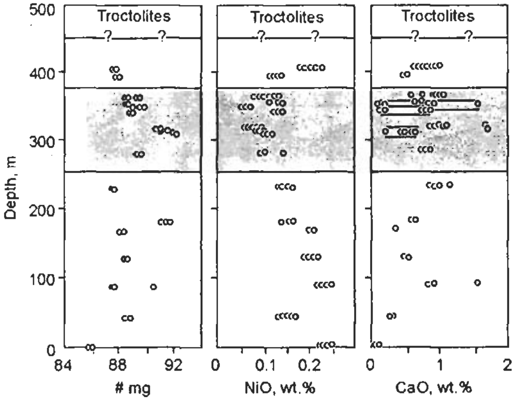

Fig. 4. Depth-dependent variations of mg number in olivine, and NiO and CaO contents in dunites of Dovyren pluton, after [20]. Gray fields indicate horizons rich in Mg skarn xenoliths.

phases in mafic magmas is currently being investigated, and is most likely associated with crust-mantle melt interaction.

Therefore, crystal-rich magma intruding into sialic crust must be much more viscous than crystal-free basaltic melts. Estimates using the Einstein-Rosko equation [18] show that the parent magma of the Dovyren pluton which contained about 50 vol.% olivine crystals [19] had a viscosity about $6 \cdot 10^4$ P, i.e., about ten times that of a homogeneous basaltic melt at $T = 1185$ °C and $P = 0.5$ kbar. Such a viscous magma hardly can have been involved in within-chamber convection.

There is no geological evidence for convective flow of melts during the formation of layered intrusions which would be recorded in their structure but there are arguments against magma flow inside the magma chamber. For instance, the buried texture of country rock clearly traceable in sediment-hosted plutons, such as the Chinei (Fig. 2) and Dovyren (Fig. 3) complexes. Rare carbonate layers of the country rocks are preserved as xenoliths in plutonic rocks, possibly because of their strong resistance to magma substitution. The Chinei layered pluton is attributed to an unconformity between the Kodar and Kemen subgroups of the Early Proterozoic Udokan Group. Its layering is generally conformable to its outer contours and the layers dip to the north at ~30°. The eastern part of the pluton truncates the hinge of the Katuga brachysynclinal fold and occurs among the Butun carbonates. This part of the pluton contains abundant skarn-bearing carbonate xenoliths of various sizes (from few meters to 400 m). The xenoliths are well exposed and deeply eroded and have no connection with the buried country rocks but hold almost the same position they had in the country rocks.

In the modern erosional section, the Dovyren dunite-troctolite-gabbro layered intrusion is a projection of a lens-shaped body conformably embedded into a carbonate-schist sequence and positioned almost vertically as a result of folding. The slightly warping base of the pluton crosscuts a 150 m thick section of dolomites among black shales but its pre-intrusion position is clearly traceable from numerous xenoliths of apodolomite Mg skarns. The stability of carbonate xenoliths in the Dovyren magma is also confirmed by CaO enrichment (up to 1 wt.% [2], Fig. 4) of olivine grains in the surrounding dunites and the presence of interstitial clinopyroxene crystals rich in Ca-Tchermak's component ($CaAl_2SiO_6$) instead of mafic plagioclase.

The impossibility of convection in crystal-rich intruding magmas prompted us to try a different approach to layering models, namely for the Dovyren pluton [19]. Figure 5 shows the vertical structure of the pluton and features of its mineralogy and chemistry. Modeling included computing phase equilibrium based on geothermometry, using the COMAGMAT-3.52 software [15]. The initial composition of the Dovyren magma was simulated for marginal rocks, plagioperidotites of the pluton base, and weighted mean bulk composition of the layered series. Phase equilibria were computed for $P = 0.5$ kbar and redox conditions of the WM buffer, according to the real emplacement history. The intruding magma was estimated to be 1180–1190 °C and contain 40–50% crystals (mostly

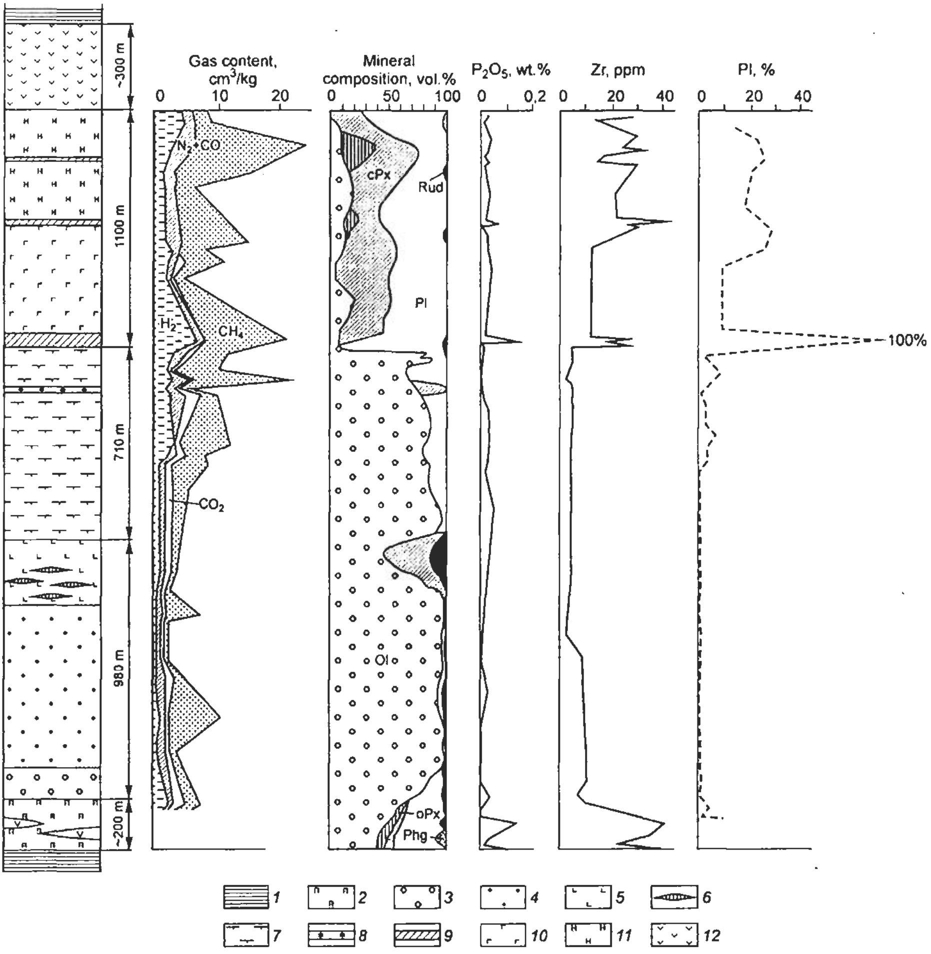

Fig. 5. Depth-dependent petrography of Dovyren pluton and distribution of gases, rock-forming minerals, P_2O_5, Zr, and plagioclase. *1* — marginal rocks, *2* — plagioclase lherzolites, *3* — plagioclase dunites, *4* — dunites, *5* — wehrlites, *6* — apodolomite Mg skarn xenoliths, *7* — troctolites, *8* — porphyraxeous poikilitic wehrlites, *9* — reefs with low-sulfide PGE mineralization, *10* — olivine gabbro, *11* — olivine gabbronorites, *12* — granophyre gabbronorites.

olivine) and liquid compositionally similar to olivine basalt (54 wt.% SiO_2) from the chilled zone. The predicted temperature was later confirmed by estimates for homogenization of melt inclusions [9]. Since fractionation of the intruding crystal-rich Dovyren magma is inconsistent with convection and accumulation, it is hypothesized that phase layering was most likely produced by compaction [21] of the crystal phase by Stokes' settling accompanied by upward percolation of interstitial liquid. The compaction mechanism agrees with the very low porosity of olivine-plagioclase cumulates in this part of the section, as is proved valid by the distribution of incompatible Zr (Fig. 5) and Ti (Fig. 6). Compaction is the least in dunites and troctolites (2–10% of the overlying section) in which adcumulus textures reveal additional isothermal overgrowth of olivine and plagioclase crystals according to

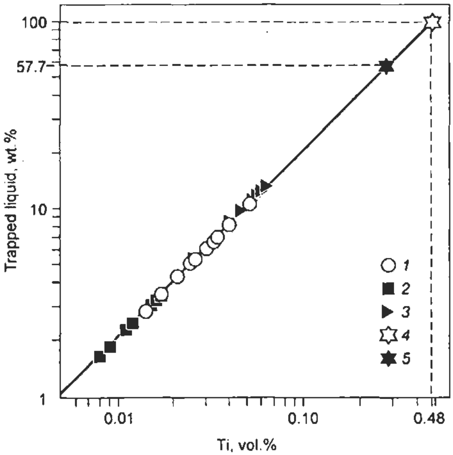

Fig. 6. Ti contents in Dovyren cumulates plotted against percentages of trapped intercumulus liquid, after [19]. Plot is based on assumption of ideal distribution of incompatible Ti. Point of Ti = 0.48 vol.% corresponds to its content in parent melt when it consisted of 100% liquid. *1* — dunites, *2* — troctolites, *3* — olivine gabbro, *4* — parent melt, *5* — chilled selvages.

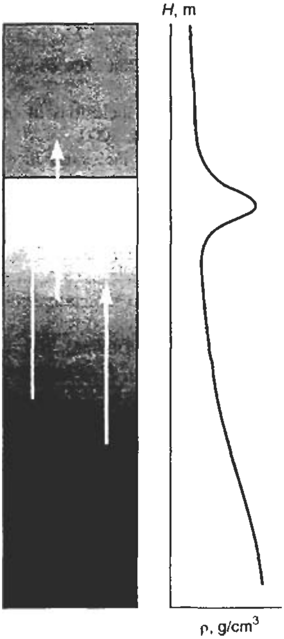

Fig. 7. Depth-dependent cumulus density in Dovyren pluton and migration of late PGE-rich magmatic fluid, after [24].

the theory of adcumulus growth [22]. The adcumulus growth is also evidenced by the stability of olivine and plagioclase compositions in the dunite-troctolite section (Fig. 5). Plagiodunites and plagioperidotites formed at base of the pluton, where intercumulus liquid was partly buried under cumulus olivine as is indicated by higher Zr abundances.

The formation of a Pt-rich reef in the Dovyren pluton is likewise well accounted for in terms of compaction of crystal mush. This specific layer with low-sulfide PGE mineralization occurs at the boundary between the dunite-troctolite and gabbro zones, more so because this is where starts the crystallization of plagioclase, main cumulus mineral in gabbros. A zone of low-density cumulus arose at the boundary between the dunite-troctolite and gabbro layers of the pluton (Fig. 7) because plagioclase, which crystallizes the first from gabbro melts, has a lower density than olivine (2.8 against 3.3 g/cm^3). Obviously, the PGE-bearing fluids that separated during crystallization at base of the intrusion flew to this zone where they deposited PGE metals [23]. The formation of intrusions from crystal-rich parent melts appears to be a more or less usual case, as similar position of main zones with low-sulfide PGE mineralization is known in many layered plutons (Great Dyke, Stillwater, Jimberlana, Mooney-Mooney, etc. [24]).

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REFERENCES

1. Kuznetsov, Yu.A., *Main types of igneous rocks* [in Russian], 385 pp., Nedra, Moscow, 1964.

2. Wager, L.R, and G.M. Brown, *Layered igneous rocks*, 588 pp., Freeman, San Francisco, 1967.

3. Jackson, E.D., Primary textures and mineral associations in the ultramafic zone of the Stillwater complex, Montana, *US Geol. Surv. Prof. Paper*, **358**, 1–106, 1961.

4. Frenkel, M.Ya., and A.A. Yaroshevsky, Fractional crystallization of an intrusive melt: A diffusion mechanism of heat and mass transfer, *Geokhimiya*, 8, 1197–1203, 1976.

5. Campbell, J.H., Physical and chemical processes in layered intrusions, *Episodes*, **12**, 289–293, 1989.

6. Gibb, F.G.F., and C.M.B. Henderson, Convection and crystal settling sills, *Contrib. Minerl. Petrol.*, **109**, 538–545, 1992.

7. Von Gruenewaldt, G., M.R. Sharpe, and C.J. Hatton, The Bushveld complex: Introduction and Review, *Econ. Geol.*, **80**, 803–812, 1985.

8. Krivolutskaya, N.A., and A.V. Sobolev, Magma inclusions in olivines from the Noril'sk intrusions: A message from parental melts, *Dokl. RAN*, **381**, 3, 393–398, 2000.

9. Konnikov, E.G., and S.V. Kovyazin, Felsic melt inclusions in olivine from peridotites of the Dovyren intrusion, *Dokl. RAN*, **385**, 5, 667–671, 2002.

10. Lassiter, J.C., E.H. Hauri, I.K. Nikogosian,and H.G. Barsczus, Chlorine-potassium variations in melt inclusions from Raivavae and Rapa, Austral Islands: Constraints on chlorine recycling in the mantle and evidence for brine-induced melting of oceanic crust, *Earth Planet. Sci. Lett.*, **202**, 525–540, 2002.

11. Kent, A.J.R., D.W. Peate, S. Newman, E.M. Stolper, and J.A. Pearce, Chlorine in submarine glasses from the Lau Basin: Seawater contamination and constraints on the composition of slab-derived fluids, *Earth Planet. Sci. Lett.*, **202**, 361–377, 2002.

12. Osipov, M.A., *Formation of layered plutons* [in Russian], 100 pp., Nauka, Moscow, 1982.

13. Hess, H.H., Stillwater igneous complex, Montana: A quantitative mineralogical study, *Geol. Soc. Amer. Miner.*, **80**, 230–254, 1960.

14. Trubitsyn, V.P., and E.V. Kharybin, Convection in magma chambers induced by reverse depth distribution of settling crystals, *Izv. RAN. Ser. Fizika Zemli*, 5, 47–52, 1997.

15. Ariskin, A.A., and G.S. Barmina, *Modeling phase equilibrium associated with crystallization of basaltic magmas* [in Russian], 364 pp., Nauka, Moscow, 2000.

16. Sharapov, V.N., A.N. Cherepanov, V.N. Popov, and A.G. Lobov, Cooling dynamics of a mafic melt filling a cone-shaped magma chamber, *Petrologiya*, **5**, 1, 10–22, 1997.

17. Plechov, P.Yu., N.L. Mironov, Plechov, A.A., and S.A. Khubunya, Chemistry and origin of melt inclusions in plagioclases of the Apakhonchich lava flow, Klyuchevsky volcano (Kamchatka), *Geokhimiya*, 1, 39–47, 2000.

18. Roscoe, R., The viscosity of suspensions of rigid spheres, *Br. J. Appl. Phys.*, **3**, 267–269, 1952.

19. Ariskin, A.A., E.G. Konnikov, and E.V. Kislov, Modeling equilibrium crystallization of ultramafics: Implications for the origin of phase layering in the Dovyren pluton, *Geokhimiya*, 2, 1–25, 2003.

20. Wenzel, Th., L.P. Baumgartner, G.E. Brugmann, E.G. Konnikov, and E.V. Kislov, Partial melting and

assimilation of dolomitic xenoliths by mafic magma: the Ioko-Dovyren intrusion (North Baikal region, Russia), *J. Petrol.*, **43**, 11, 2049–2074, 2002.

21. Boudreau, A.E., and A.R., McBirney, The Skaergaard layered series: Part III. Non-dynamic layering, *J. Petrol.*, **38**, 1003–1020, 1997.

22. Wager, L.R., The mechanism of adcumulus growth in the layered series of Skaergaard intrusion, *Miner. Soc. Am. Spec. Paper*, **1**, 1–9, 1963.

23. Konnikov, E.G., W.P. Meurer, S.S. Neruchev, E.M. Prasolov, E.V. Kislov, and D.A. Orsoev, Fluid regime of platinum group elements (PGE) and gold-bearing reef formation in the Dovyren mafic-ultramafic layered complex, eastern Siberia, Russia, *Miner. Dep.*, **35**, 6, 526–532, 2000.

24. Meurer, W.P., and A.E. Boudreau, Compaction of density-stratified cumulus: Effect on trapped-liquid distribution, *J. Petrol.*, **104**, 115–120, 1996.

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