An experiment on thermal modelling of the Paleoproterozoic Fedorova layered intrusion, Kola Region, Russia: implications for the origin of contact-style PGE mineralisation

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Summary This contribution presents the results of thermal modelling of the Paleoproterozoic Fedorova intrusion located in the central part of the Kola Peninsula, NW Russia. The intrusion hosts a large contact-style platinum-group elements (PGE) deposit in its basal 300-m-thick unit (Fedorova Tundra). This basal unit is composed of varied-textured gabbronorite and is believed to be an additional injection of sulphide-saturated magma, representing a second intrusive phase. The irregular distribution of sulphides across the entire basal unit and the absence of sulphide liquid migration into the underlying basement rocks suggest that this second injection exploited the cooled down contact between the first intrusive phase and the basement. The hiatus between the first and the second intrusive event allowed for some cooling of the former, however, the duration of the hiatus remains unknown. Assuming an average geothermal gradient of 30°C/km and a basement temperature of approx. 400°C due to preheating, thermal modelling indicates that the hiatus may have lasted for some 600–700 thousand years. These results are in agreement with a classic contact-style PGE mineralisation model for Fedorova Tundra and suggest an out-of-sequence formation of the layered succession.

1. Introduction

A critical factor in the formation of contact-style low-sulphide platinum group elements (PGE) mineralisation in layered mafic-ultramafic intrusions is the preheating of host rocks due to magmatic activity, preceding the emplacement of sulphide-saturated magma (Karykowski et al. 2018). Preheating of the basement to 400 °C by the intrusion of, for example, a series of dikes or sills that precede the main intrusion, creates conditions for the effective accumulation of sulphide droplets at the bottom of the magma chamber as well as for the percolation of sulphide droplets into the partially molten basement rocks. The Paleoproterozoic Portimo and Monchegorsk layered complexes on the Fennoscandian Shield are typical examples of intrusions where this factor played a crucial role (Iljina 1994; Karykowski et al. 2018).

The Fedorova intrusion represents the western block of the Paleoproterozoic Fedorova-Pana Complex located in the central part of the Kola Peninsula, NW Russia. The intrusion forms a 4-km-thick lens-like body that is steeply dipping to the southwest (Fig. 1a). Three zones are distinguished in the sequence of the Fedorova intrusion (from the bottom upwards): a Norite-Gabbronorite Zone (or ‘basal unit’), a Leucogabbro-Gabbronorite Zone, and a Leucogabbro Zone (Staritsina 1978). It is suggested that the Leucogabbro-Gabbronorite and the Leucogabbro zones comprise an early magmatic phase (2526–2515 Ma) with reef-style PGE mineralization, whereas the contact-style PGE mineralisation-hosting basal unit belongs to a later intrusive phase (2493–2485 Ma) (Schissel et al. 2002; Groshev et al. 2009; Groshev et al. 2019). The 300-m-thick basal unit is composed of varied-textured melanorite and gabbronorite containing abundant orthopyroxenitic autoliths and irregular patches of disseminated sulphide enriched in PGE (2–5 vol. %) (Fig. 1, b). Evenly disseminated sulphide accumulations (20–30 vol. %) are generally rare, whereas massive sulphides are absent. The PGE mineralisation is only hosted

by the basal unit of the intrusion, showing no evidence for sulphide liquid percolation into the basement rocks. These sulphides form the Fedorova Tundra deposit with a total resources of more than 400 t of PGE (Rasilainen et al. 2010).

Figure 1. Simplified geologic map of the Fedorova Tundra intrusion (a) and schematic geologic cross section through the deposit (b). Purple dotted lines show a position of PGE reefs (FT-1 and FT-2) on the map; red rectangles on the cross section indicate mineralized intervals of the FT-1 Reef. Proterozoic structures of the predominantly Archean Kola Region (inset): Imandra-Varzuga (IV), Kuolajarvi (K), and Pechenga (P) paleorift structures; Lapland (L) and Umba (U) granulite belts. Modified after (Groshev et al. 2019).

It is believed that the first intrusive phase of the Fedorova intrusion preheated the basement before the second phase intruded along the lower contact of the first intrusive phase (Fig. 1). A thermal contact aureole of the first phase reaches several hundred meters as evidenced by partially molten two-pyroxene diorites observed in some drill holes (Groshev et al. 2009). In spite of this the second intrusive phase does not practically show features of sulphide accumulation within the basal unit or sulphide percolation into the basement rocks. Consequently the time gap between the intrusive phases was long enough for cooling of the basement below 400 °C (temperature supporting sulphide migration and accumulation). The purpose of this study is to estimate the time gap between the two intrusive phases comprising the Fedorova intrusion using thermal modelling and to discuss the results in the context of the crystallization duration of layered intrusions as well as the formation of a contact-style PGE mineralisation.

2. Methods

The cooling of the first intrusive phase of the Fedorova massif can be modelled by heat exchange between the magmatic succession with a temperature of 1200 °C, which has intruded the Archean basement at a depth of 5 km (Dubrovskiy and Rundkvist 2008). The thickness of the body is assumed to be 4 km (Groshev et al. 2019). Discretisation of the one-dimensional heat equation gives the following recurrence formula:

$$T_i^{n+1} = T_i^n + k\Delta t \left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta x)^2} \right),$$

where k – thermal diffusivity ($k = 2 \cdot 10^{-6} \text{ m}^2\text{s}^{-1}$), and T_i^n – temperature at a depth of $i \cdot \Delta x$ m in $n \cdot \Delta t$ years. A detailed derivation of the equation is given in (Karykowski et al. 2018). To eliminate boundary effects, the depth of modelling was increased to 20 km. The thermal modelling was carried out using a FPC-based software (Stepenshchikov and Groshev 2019). Intrusive bodies are defined by four parameters: the boundary of the roof (m), thickness (m), temperature (°C) and the point in time of intrusion (years).

3. Thermal modelling results

The simulation shows that the emplacement of the Fedorova first phase will lead to a significant heating of the underlying rocks (Fig. 2 a–c; Table 1). The partial melting temperature of the basement (≈ 700 °C) will be reached approx. 250 m away from the lower intrusion contact after some 25 thousand years (Fig. 2 c, blue circle). This is in agreement with the thickness of two-pyroxene diorite below the intrusion (Fig. 1 b).

Figure 2. Temperature-depth graphs showing changes in temperature (red line) near the lower contact of the first intrusive phase of the Fedorova intrusion for different time moments (a–f). Note that an intrusion of the second phase could occur only after a contact cooling to 400 °C (green circle).

Since the magma of the second intrusive phase was sulphide-saturated, as a result of its emplacement in the preheated by the first phase contact with the basement the sulphides would have been concentrated near the bottom of the intrusion forming sulphide-rich layers and locally

percolating into the Archean gneissic basement. Fig. 1 b shows that sulphides distributed unevenly and the migration of sulphide liquid is not observed at the Fedorova Tundra deposit. Consequently, the basal unit consisting of varied-textured gabbro-norite that postdate the first intrusive phase were emplaced after the temperature at the lower contact of the first phase reached less than 400 °C. Under these boundary conditions, the minimum time separating the different intrusive phases is some 600–700 thousand years, as can be seen in Fig. 2 e–f (green circle) and Table 1.

Table 1. Thermal modelling results for the first phase of the Fedorova intrusion.

t (years)	Temperature, T (°C)		t (years)	Temperature, T (°C)	
	d=5 km	d=9 km		d=5 km	d=9 km
1	839	880	400000	306	462
10	732	787	500000	276	431
100	692	753	600000	254	407
1000	677	744	700000	236	386
10000	663	750	800000	223	369
100000	517	635	900000	211	355
200000	415	551	1000000	202	342
300000	350	500	–	–	–

4. Discussion

4.1. Duration of the Fedorova intrusion crystallization

The example of the Fedorova intrusion shows that the duration of crystallization under open-system conditions can be hundreds of thousands of years (Fig. 2). At the same time, the latest data on systematic isotope dating of open-system layered intrusions, show that the duration of their crystallization ranges from 1 to 3 Ma with an error of individual age determinations of up to 0.26 Ma modulo (Scoates and Wall 2015; Zeh et al. 2015; Wall et al. 2018). In this regard, it is worth noting that the currently available geochronological data on the Fedorova intrusion suggest a duration of crystallisation spanning some 40 Ma (Groshev et al. 2009), which appears to be greatly overestimated due to the likely inclusion of secondary zircon in the calculation of U-Pb ages (Groshev and Karykowski 2019).

Thus, the Fedorova Tundra deposit most likely represents a separate ‘out-of-sequence’-type of contact-style PGE mineralization. The advancement of the isotope age determination on the intrusive phases of the Fedorova intrusion is possibly one of the most important unresolved problems in the petrology of layered intrusions on the Fennoscandian Shield.

4.2. Similar contact-style PGE mineralization in other layered intrusions

The presence or absence of sulphide liquid migration from the basal mineralised zones into the basement rocks is an important genetic feature of contact-style PGE deposits, revealing their thermal history. Except the Fedorova intrusion it can be shown by thermal modeling for the Nyud-Poaz massif (Monchegorsk Complex), which has two ore-bearing intrusive phases both containing disseminated sulfides, extending beyond the intrusion in the basement (Karykowski et al. 2018; Groshev and Pripachkin 2018). An additional phase (Gabbro-10), emplaced along the basal contact of the Nyud-Poaz intrusion hosts PGE mineralisation that percolates into the Archean basement for 30 m. Consequently, the additional injection of sulphide-saturated magma occurred at a time when the basal contact of the Nyud-Poaz massif was characterised

by elevated temperatures. The time gap between these two phases, according to the thermal modelling of the Nyud-Poaz massif, is no more than 150 thousand years. The accuracy of isotope dating cannot resolve such small time differences at the moment (Scoates and Wall 2015). This is also shown by the isotope dating of the Gabbro-10 intrusion whose age coincides with the age of the Nyud-Poaz massif within the error limits (Amelin et al. 1995; Groshev et al. 2018).

The South Sopcha intrusion of the Monchegorsk Complex is another example of contact-style PGE mineralisation that was likely formed out-of-sequence (Chashchin and Mitrofanov 2015; Pripachkin et al. 2015). The South Sopcha intrusion has an orthopyroxenitic lower unit, which is extensively intruded and brecciated by sill-like gabbro-pegmatites and coarse-grained gabbro-norites containing PGE-rich disseminated sulphide. The issues of sulphide migration from the gabbro-norites into the basement rocks as well as the duration of the South Sopcha crystallisation are to be solved in future research.

Acknowledgements

The research was supported by the Ministry of Science and Higher Education of the Russian Federation (project 0226-2019-0053).

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