14. *Lesnov F.P.* Petrochemistry of polygenic mafic-ultramafic plutons of folded regions. Novosibirsk: Nauka, 1986. 136 p. [in Russian].

15. *Balykin, P.A., Krivenko, A.P., Konnikov, E.G., Lesnov, F.P. et al.* Petrology of postharzburgite intrusives of Kempirsay- Khabarninsky ophiolite association (South Urals). Sverdlovsk, 1991. 160 p. [in Russian].

16. *Lesnov, F.P., Stepashko, A.A., Rechkin, A.N., Galvarsen, V.G.* Structural position, composition and content of mafic-ultramafic massifs in East-Sakhalin ophiolite association // Tectonics and subsurface structure of Asian East. Khabarovsk, 2009. P. 202-205. [in Russian].

17. *Lesnov F.P.* Multistage formation of mafic-ultramafic plutonic complexes of ophiolite association // Fourth international symposium on geodynamic evolution of paleoasian ocean. Novosibirsk, 1993. P. 97-99. [in Russian].

18. *Irvin W.P., Coleman R.G.* Preliminary map showing global distribution of alpine-type ultramafic rocks and blueschists. 1972.

U-PB AGE CONSTRAINTS ON TEMPORAL EVOLUTION OF THE ORE-BEARING NORIL'SK-1 INTRUSION: EVIDENCE FROM ZIRCON AND BADDELEYITE

Malitch K.N.*, Badanina I.Yu.*, Belousova E.A., Griffin W.L.**, Petrov O.V.*, Tuganova E.V.*, Distler V.V.***, Sluzhenikin S.F.***, Presnyakov S.L.*, Rodionov N.V.***

**All-Russian Geological Research Institute (VSEGEI), St. Petersburg, Russia*
e-mail: dunite@yandex.ru
***GEMOC ARC National Key Centre, Macquarie University, Sydney, Australia*
e-mail: wgriffin@els.mq.edu.au
****Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry RAS, Moscow, Russia*
e-mail: distler@igem.ru

INTRODUCTION

World-class PGE-Cu-Ni sulphide deposits occur in the Noril'sk-1, Talnakh and Kharaelakh areas in the northwestern part of the Eastern Siberia, Russia. They are associated with sill-like ultramafic-mafic intrusions, which are controlled by a long-lived intracontinental paleorift [16]. The first U-Pb data for the Noril'sk-1 intrusion have been restricted to zircon and baddeleyite from pegmatitic leucogabbro of the Noril'sk-1 intrusion (i.e., 248.0 ± 3.7 Ma [1] and 251.1 ± 3.6 Ma [5]). More recent preliminary attempts, based on U-Pb SHRIMP study of zircon from the main lithological units of the Noril'sk-1 intrusion [12], identified two distinct zircon ages (250.7 ± 1.5 Ma and 228 ± 1.4 Ma), indicative of a prolonged temporal evolution of their host rocks. New U-Pb data for about one hundred grains of zircon and baddeleyite shed new light on magmatic evolution of the Noril'sk-1 ore-bearing intrusion.

SAMPLES AND TECHNIQUES

The rocks in the investigated drill core MN-2 comprise (from top to bottom) gabbro-diorite (sample N1-1), leucogabbro (N1-3), olivine-free gabbro (N1-2, N1-4), olivine-bearing gabbro (N1-5), olivine gabbro (N1-6), plagiowehrlite and plagiodunite (N1-7), taxitic-textured rocks comprising melanotroctolite, olivine gabbro with relics of ultramafic rocks (N1-8, N1-9) and contact fine-grained gabbro (N1-10). PGE-Cu-Ni ores are represented by disseminated and low-sulphide types. Disseminated PGE-Cu-Ni ores occur in ultramafic (N1-7) and taxitic-textured (N1-8 and N1-9) rocks, which have thickness of about 17 m, whereas the low-sulphide horizon is about 1 m thick and occurs in the upper part of intrusion (N1-3).

243 grains of zircon and baddeleyite were concentrated using a *ppm-mineralogy* technique at NATI Research JSC (St. Petersburg, Russia). Grains of zircons and baddeleyite from each concentrate were hand picked, imaged by SEM and subsequently mounted in epoxy blocks together with the TEMORA and 91500 reference zircons. Transmitted and reflected light photomicrographs and CL images were made in order to select grains and choose sites for analyses omitting cracks and inclusions. The Sensitive High-Resolution Ion Microprobe (SHRIMP-II) at the Centre of Isotopic Research of the

VSEGEI was used to perform 129 *in-situ* U-Pb analyses by applying a secondary electron multiplier in a peak-jumping mode following the procedure described by *Williams* [17]. Age calculations use the routines of *Ludwig* [8]. Eight U-Pb analyses of baddeleyite were performed at GEMOC using an Agilent 7500s quadrupole ICP-MS instruments, attached to a New Wave/Merchantek UP-213 laser ablation system, following the analytical procedures reported by *Jackson* et al. [4]. The data have been reduced using the GLITTER software [3].

MORPHOLOGY AND INTERNAL STRUCTURE

Zircon has been observed in thin sections as single or polyphase grains enclosed in clinopyroxene, amphibole or mica, frequently intergrown with apatite. Rare examples show overgrowths of zircon on baddeleyite, implying that baddeleyite is likely a first mineral to crystallise in this assemblage. Separated zircon grains are commonly represented by idiomorphic and subidiomorphic transparent and semitransparent, sometimes fissured prism-shaped brown crystals; length to width ratios varies from 1:1 to 3:1 (rarely up to 6-7:1). Observations under petrographic microscope revealed at least two groups of zircon grains according to their internal structure. First group (about half of studied grains) is represented by polyphase zircon assemblages. They are composed of different zircon domains, with up to two distinct cores (i.e., zircon type 1, *ZR-1* and zircon type 2, *ZR-2*), which in turn may be mantled by one or two differently zoned overgrowths (i.e., zircon type 3, *ZR-3* and zircon type 4, *ZR-4*). Both cores and overgrowths from polyphase grains preserve distinct solid mineral inclusions. The second group of zircons includes solitary zoned euhedral to subhedral crystals or their fragments with inclusions dominated by glass, interpreted as zircon types 3 and/or 4. Both groups are characterized by similar fuzzy (smoky) cathodoluminescence, commonly with total absence of the growth zoning characteristic of zircons from magmatic rocks.

U-Pb AGES

Ninety eight zircon grains used for the U-Pb determination yielded four groups of concordant U-Pb ages irrespective of the lithology. Cores from polyphase grains, (*ZR-1* and *ZR-2*), produced $^{206}Pb/^{238}U$ ages of 261.3 ± 1.6 Ma (mean square of weighted deviates (MSWD) = 0.70) and 245.7 ± 1.1 Ma (MSWD=1.7), respectively. These ages are older than those found in other types (e.g., rims from polyphase grains and solitary zircon grains). Indeed, two clusters of younger concordant U-Pb ages, typical of *ZR-3* and *ZR-4*, gave $^{206}Pb/^{238}U$ ages of 236.5 ± 1.8 Ma (MSWD = 0.19) and 226.7 ± 0.92 Ma (MSWD=0.34), respectively. Close similarity of calculated U-Pb concordia ages and main fraction of U-Pb ages in relative probability plots within each zircon population is noteworthy. Eight baddeleyite grains from olivine-bearing gabbro (sample N1-4) yielded the fifth $^{206}Pb/^{238}U$ age cluster, with a mean of 290 ± 2.8 Ma. This is consistent with observed relationship between baddeleyite and zircon in thin sections. The oldest concordant $^{206}Pb/^{238}U$ age of 1914 ± 92 Ma has been calculated for a zircon grain from the gabbro-diorite (sample N1-1). This age suggests that zircon has been inherited from 1.9 Ga basement rocks, which may indicate the location of a deep-seated chamber for the magmatic protolith.

Th AND U CONTENTS

Th and U concentrations in baddeleyite vary in the range 4-25 and 235-542 ppm, respectively, with a mean Th/U of 0.025. All types of zircon are characterized by relatively high concentrations of thorium and uranium. Mean Th and U contents increase from zircon «cores» (*ZR-1* and *ZR-2*) to zircon «rims» (*ZR-3* and *ZR-4*) (e.g., *ZR-1,* Th=1386 ppm and U=589 ppm; *ZR-2*, Th=2159 and U=890 ppm; *ZR-3*, Th=7012 and U=2308 ppm; *ZR-4*, Th=3801 and U=1919 ppm), resulting in a clear negative correlation of Th and U values with age. Unusually high thorium and uranium contents in the zircons (up to 1.7 and 0.6 wt. %, respectively) in combination with increased Th/U ratios (up to 6) might indicate either a significant role of metasomatic processes or crystallization from late-stage residual liquids. On a Th-U diagram the zircons from the Noril'sk area clearly overlap the field of mantle metasomatic minerals (MARID*,* [6]), and partly match the field of glimmerite [14]. The inherited zircon, characterized by relatively low contents of U and Th, with Th/U ratio of 0.66, is clearly distinct from most of the other zircons. Th and U concentrations decrease from mafic (olivine-free gabbro, olivine-containng gabbro, olivine gabbro) to ultramafic rocks (e.g., plagiodunite, plagiowehrlite and melanotroctolite).

Geochemical and mineralogical evidence (e.g. distinctly different Th and U concentrations, presence of different solid inclusions) suggest that the younger zircons may have crystallized more rapidly than the older populations.

U-Pb CONSTRAINTS ON THE TEMPORAL EVOLUTION OF THE NORIL'SK-1 INTRUSION

Zircon and baddeleyite dated previously both by SHRIMP (*Campbell* et al., 1992) and ID-TIMS (*Kamo* et al., 1996) have been restricted to one lithology (e.g. leucogabbro) of the Noril'sk-1 intrusion. The U-Pb data presented by *Campbell* et al. [1] gave a range of $^{206}Pb/^{238}U$ ages from 243.8±4.9 to 251.6±5.0 Ma, with a mean of 248±3.7 Ma. U-Pb results presented by *Kamo* et al. [5] gave an even broader range of $^{206}Pb/^{238}U$ ages. These authors show (see Fig. 2, p. 3508) that all the analyses (n=10) gave a maximum $^{206}Pb/^{238}U$ age of 256.5±2.6 Ma, whereas nine tightly clustered analyses of zircon and baddeleyite produced an average $^{206}Pb/^{238}U$ age of 251.2±0.3 Ma. The variability of the U-Pb ages obtained by both techniques on the same lithology is striking and may be due to the polyphase nature of the zircon studied.

To better constrain the age of igneous event our study utilized ten rock samples characteristic of unmineralized and mineralized lithological units of the Noril'sk-1 intrusion. The $^{206}Pb/^{238}U$ ages of baddeleyite and the four zircon populations cover a significant time span, from Late Paleozoic to Early Mesozoic (e.g., 290±2 Ma; 261.3±1.6 Ma; 245.7±1.1 Ma; 236.5±1.2 Ma and 226.7±0.92 Ma), suggesting a prolonged evolution of the magmatic system. This magmatic activity is broadly consistent with a recognised stage of active tectonism in the development of the Siberian Craton [10]. The crystallisation of zircon populations 1 to 4 matches the known duration of the Early Mesozoic (P_2-T_2) tectonic cycle, while the formation of baddeleyite slightly preceeds these events. Similar results [9, submitted], with the majority of concordant U-Pb ages lying in the range 230-270 Ma, have been documented for zircons from the rocks of two other economic intrusions of the Noril'sk region (e.g. Talnakh and Kharaelakh).

It is commonly assumed that the ore-bearing Noril'sk-type intrusions represent one small component of a major episode of mafic activity at ~250 Ma, which included formation of the most extensive flood-basalt province on Earth. If the formation of the basalts was indeed restricted to the Permian-Triassic boundary as advocated most recently by *Reichow* et al. [13 and references cited therein], our data provide very little supporting evidence for a genetic link between the chalcophile element-depleted basalts and the sulphide-rich «Noril'sk-type» intrusions, and imply that their relationship could have been coincidental. Similar conclusions, arising from different lines of reasoning, have been reached previously by, among others, *Godlevsky* [3], *Tuganova* [15] and *Latypov* [7], and are in conflict with the conduit model proposed by *Naldrett* et al. [11].

On the basis of results reported here we propose that mafic-ultramafic magmas parental to the Noril'sk-1 intrusion were emplaced in the lithospheric mantle or deep crust ca 10-40 Ma before the flood basalts, and that the magmas generated in Early Mesozoic time (around 230-250 Ma) picked up baddeleyite and the *ZR-1* zircon population from these intrusive formations. The concordia age of zircon population *ZR-2* (e.g., 245.7±1.1 Ma) is slightly younger than that suggested for the flood basalts (248.7±0.6 – 250.3.2±1.1 Ma [13]). The timing of the magmatic episode exemplified by *ZR-2* might be possibly interpreted as either coeval with tholeiitic basalts or immediately postdating the main flood-basalt volcanism (in either case likely still remaining in the deep-seated magma chamber). *ZR-3* and *ZR-4* can be attributed to prolonged cooling and thermal recrystallisation after the emplacement of the intrusion, clearly postdating the eruption of the basalts.

CONCLUSIONS

The zircons from the Noril'sk-1 intrusion show mineralogical and isotope-geochemical features that are not usually expected for mafic and ultramafic rocks. Our new results demonstrate a prolonged period of magmatic activity (290-227 Ma), from Late Paleozoic to Early Mesozoic, consistent with ideas on the prolonged duration of fractionation in magmatic systems. These processes could have led to high degrees of separation and concentration of ore elements and the formation of specific ore-forming magmas of unique scales and concentrations.

The two oldest age groups represent previously unknown stages of magmatic activity, which preceed the 250 Ma Siberian flood-basalt volcanism. We further suggest that baddeleyite and zircons of population 1 and 2 (*ZR-1* and *ZR-2*) crystallized in a deep-seated chamber, whereas zircons of population 3 and 4 (*ZR-3* and *ZR-4*) can be attributed to prolonged cooling and thermal recrystallisation before and after the emplacement of the intrusion. Finally, our new findings imply that economic intrusions hosting PGE-Cu-Ni deposits of the Noril'sk region have a far more prolonged and complex magmatic history than is commonly assumed.

This investigation forms part of a larger project focused on the isotope-geochemical speciation of ultramafic-mafic intrusions of the northern Siberia. Financial support through contract 7F-TAO/2005 from the Agency of Natural Resources of the Russian Federation is gratefully acknowledged. The analytical work at GEOMOC was supported by ARC Discovery grant.

REFERENCES

1. *Campbell I.H., Czamanske G.K., Fedorenko V.A., Hill R.I., Stepanov V.* Synchronism of the Siberian traps and the Permian-Triassic boundary // Science. 1992. V. 255. P. 1760-1763.

2. *Godlevsky M.N.* Traps and ore-bearing intrusions of the Noril'sk region. Moscow: Gostekhmetizdat, 1958. 68 pp [in Russian].

3. *Griffin W.L., Powell W.J., Pearson N.J., O'Reilly S.Y.* Appendix 2. GLITTER: data reduction software for laser ablation ICP-MS // In: Sylvester P. (ed.) Laser Ablation–ICP–MS in the Earth Sciences, Mineralogical Association of Canada Short Course Series. 2008. V.40. P. 204-207.

4. *Jackson S.E., Pearson N.J., Griffin W.L., Belousova E.A.* The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geochronology // Chemical Geology. 2004. V. 211. P. 47-69.

5. *Kamo S.L., Czamanske G.K., Krough T.E.* A minimum U-Pb age for Siberian flood-basalt volcanism // Geochimica et Cosmochimica Acta. 1996. V. 60. P. 3505-3511.

6. *Kinny P.D., Dawson J.B.* A mantle metasomatic injection event linked to late Cretaceous kimberlite magmatism // Nature. 1992. V. 360. P. 726-728.

7. *Latypov R.M.* Phase equilibria constraints on relations of ore-bearing intrusions with flood basalts in the Noril'sk region, Russia // Contributions to Mineralogy and Petrology. 2002. V. 143. P. 438-449.

8. *Ludwig K.R.* User's Manual for ISOPLOT/Ex 3.00. A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication. 2003. No. 4. 70 pp.

9. *Malich K.N., Petrov O.V., Badanina I.Yu., Presnyakov S.L.* Zircons from ultramafic-mafic intrusions at Noril'sk area (Russia): a compositional and U-Pb study // Geochimica et Cosmochimica Acta. 2007. V. 71. № 15S. P. A616-A616.

10. *Malitch N.S.* Tectonic development of the cover of the Siberian Craton. Moscow: Nedra Press, 1975. 215 pp (in Russian).

11. *Naldrett A.J., Fedorenko V.A., Lightfoot P.C., Kunilov V.I., Gorbachev N.S., Doherty W., Johan Z.* Ni-Cu-PGE deposits of Noril'sk region, Siberia: their formation in conduits for flood basalt volcanism // Transactions of the Institution of Mining and Metallurgy. 1995. V. 104. P. B18-B36.

12. *Petrov O.V., Malitch K.N., Distler V.V., Sluzhenikin S.F., Shevchenko S.S., Matukov D.I., Presnyakov S.L., Knauf V.V., Lepekhina E.N., Khalenev V.O., Sergeev S.A.* Isotopic and geochemical characteristics of zircons from rocks of the Noril'sk-1 intrusion (Siberian Craton, Russia): preliminary results // Geophysical Research Absracts 2006. V. 8. European Geosciences Union (CD-ROM).

13. *Reichow M.K., Pringle M.S., Al'mukhamedov A.I., Allen M.B., Andreichev V.L., Buslov M.M., Davies C.E., Fedoseev G.S., Fitton J.G., Inger S., Medvedev A.Ya., Mitchell C., Puchkov V.N., Safonova I.Yu., Scott R.A., Saunders A.D.* The timing and extent of the eruption of the Siberian Traps large igneous province: Implications for the end-Permian environmental crisis // Earth and Planetary Science Letters. 2009. V. 277. P. 9-20.

14. *Rudnick R.L., Ireland T.R., Gehrrels G., Irving A.J., Chesley J.T., Hanchar J.M.* Dating mantle metasomatism: U-Pb geochronology of zircons in cratonic mantle xenoliths from Montana and Tanzania // Ext. Abstr. 7th Int. Kimberlite Conference, Cape Town. 1998. P. 754-756.

15. *Tuganova E.V.* Petrological geodynamical model of formation of sulfide copper-nickel deposits // Soviet Geology and Geophysics. 1991. V. 32. № 6. P. 1-7.

16. *Tuganova E.V.* Petrographic types, genesis and regularities of distribution of PGE-Cu-Ni sulfide deposits. St. Petersburg: VSEGEI Press, 2000. 102 pp [in Russian].

17. *Williams I.S.* U-Th-Pb Geochronology by Ion Microprobe // Applications of microanalytical techniques to understanding mineralizing processes, Reviews in Economic Geology. 1998. V. 7. P. 1-35.