

Lalchand Govindram Gwalani*, Ken Rogers, Francesco Stoppa, Peter J. Downes, Kirtikumar Randive, K.R. Hari, and Michał Bucha

A Special Issue (Part-II): mafic-ultramafic rocks and alkaline-carbonatitic magmatism and associated hydrothermal mineralization – dedication to Lia N. Kogarko

DOI 10.1515/geo-2015-0026

Introduction

The papers presented in this special issue of Open Geosciences (also see [1]) cover a diverse range of topics from the graphite-diamond association in carbonatites, to platinum-group element (PGE; including platinum, palladium, rhodium, ruthenium, iridium and osmium) mineralization and many aspects of the petrogenesis of mafic-ultramafic rocks, in keeping with the research interests of Professor Kogarko. Studies of PGE mineralization in mafic-ultramafic rocks are of great interest to exploration geologists due to the fact that PGEs offer the dual attraction of rare, high-value precious metals as well as major industrial applications. Platinum has aesthetic qualities, combined with a permanent lustre, which encourage its use in the manufacture of jewellery and, like gold, it also finds an investment role. Platinum, rhodium, and palladium have important applications as catalysts, enabling petroleum

and fuels and chemicals to be produced efficiently from crude oil. At present, most of the world's reserves of PGEs occur in South Africa, with virtually all the South African production being derived from the Bushveld Complex.

PGEs are strongly siderophile and chalcophile elements and have similar geochemical behaviors during magmatic processes. Traditionally, the PGEs are subdivided into two groups, the compatible IPGEs (Os, Ir, and Ru) and the incompatible PPGEs (Rh, Pd, and Pt). IPGEs are refractory and tend to be retained in mantle peridotites during partial melting, whereas the PPGEs are concentrated in the base metal sulphides (e.g. pentlandite, chalcopyrite) and fractionated into the magma. Due to their unique geochemical characteristics, the PGEs can be used to identify magma sources and unravel complex petrogenetic processes, such as partial melting, melt percolation and metasomatism (e.g. [2–4])

PGE-rich magmas are most often high-Mg intraplate magmas, including komatiites and picritic flood basalts, produced by high degrees of melting of their mantle source regions. High degrees of melting allowed all of the sulfur in the mantle source to be dissolved in the silicate melt, thus maximizing the PGE content prior to magma ascent [5]. Ultramafic complexes that are potential targets for PGE exploration broadly fall into two categories: (i) Kambalda-type deposits [6, 7]; and (ii) PGE reef-type deposits [8–11], and in both cases PGEs are produced as a by-product of Ni–Cu extraction.

***Corresponding Author: Lalchand Govindram Gwalani:** Copper-Gold-Fluorite Research Project, KRCL-Uni.WA, c/o Ms. Shradha L. Gwalani, Boronia 26 Mounts Bay Village, 122 Mounts Bay Road, Perth WA 6000, Australia

Ken Rogers: Speewah Research Project, King River Copper Limited, 7 Norton Ridge, Winthrop (Perth) WA 6150, Australia

Francesco Stoppa: Petrography and Petrology, G. d'Annunzio University, Department of Psychological Sciences, Humanities and Territory, 66100 Chieti, Italy

Peter J. Downes: Department of Earth and Planetary Sciences, Western Australian Museum, Locked Bag 49, Welshpool DC, WA 6986, Australia

Kirtikumar Randive: Department of Geology, Rashtrasant Tukadoji Maharaj Nagpur University, Nagpur – 440 001 (MH), India

K.R. Hari: School of Studies in Geology and Water Resource Management, Pt. Ravishankar Shukla University, Raipur 492 010 (CG) India

Michał Bucha: University of Wrocław, Institute of Geological Sciences, Max Born Square 9, 50-210 Wrocław, Poland

 © 2015 L.G. Gwalani *et al.*, licensee De Gruyter Open.

This work is licensed under the Creative Commons Attribution-NonCommercial-NoDerivs 3.0 License. The article is published with open access at www.degruyter.com.

Papers presented

Professor Kogarko leads the volume in her honour with an important study with her colleague, Dr Igor D. Ryabchikov, on the physiochemical conditions of graphite and diamond formation in carbonate-rich melts. Based on their study on the mineral relationships and compositions in carbonatites from the Chernigovka Massif, Ukraine and

the Chagatai carbonatite complex, Uzbekistan, they estimate the graphite crystallization temperature and the composition of the fluids involved providing vital information about the formation of diamond in the Earth's mantle [12].

Three papers examine PGE mineralization and geochemistry in mafic-ultramafic complexes in India. Meshram *et al.* [13] describe, PGE mineralization in chromitite cumulates within the Kondapalli Layered Complex (KLC), Krishna District (Andhra Pradesh). The KLC is a dismembered mafic-ultramafic layered intrusion that is mainly composed of gabbroic and anorthositic rocks with subordinate ultramafics and chromitite. The PGE mineralization is orthomagmatic, comprising laurite (RuS₂), irarsite (Ir, As, S), iridosmine (Os, Ir), Os-Ir sulphide and Ru-Os-Ir-Zn alloys (grains $\leq 10 \mu\text{m}$ wide), and formed in a supra-subduction zone.

The Madawara Igneous Complex in the southern part of the Bundelkhand Craton in Central India is bounded by two major shear zones and comprises ultramafic rocks enriched in MgO, Ni, Cr and PGEs. Satyanarayanan *et al.* [14] describe the geochemical evolution of an ultramafic suite, that includes lherzolite, olivine websterite, orthopyroxene and harzburgite, where pyroxenite, websterite and olivine websterite may be relatively enriched in PGEs. They suggest the presence of a PGE-enriched source magma, which formed at moderate to greater depths by a high degree of partial melting of the mantle.

Subramanyam *et al.* [15] examine the petrology and geochemistry of the Pedda Cherlo Palle (PCP) gabbrodiorite pluton from the Prakasam Igneous Province in Andhra Pradesh. They identify cumulate textures in sub-alkaline tholeiitic gabbros that have undergone fractional crystallization and were derived by partial melting of a depleted mantle source. Geochemical signatures, including a low abundance of PGEs, suggest that the tectonic setting of the PCP gabbros may have been a subduction-related intra-oceanic island arc that had accreted to the SE margin of India during Ur to Rodinia amalgamations.

Another contribution from India is an examination of unusual mafic igneous dykes from the Kawant area near the Amba Dungar Carbonatite Complex in Chhota Udaipur district of Gujarat, India. They contain a dense population of quartz xenocrysts within a basaltic groundmass. Randive and Hurai [16] describe fluid inclusions in the quartz xenocrysts and explore the possible links with fluids exsolved during the final stages of evolution of the Amba Dungar carbonatites.

Downes *et al.* [17] use the U-Pb ages of zircons derived from a lower crustal granulite-facies xenolith in alkaline intra-plate volcanics to reveal Neogene metamorphism be-

neath the Pannonian Basin in Hungary. Most of the zircons were younger than 30 Ma, and ranged in age to ~ 5.1 – 4.2 Ma, coinciding with the age of eruptions of the host alkali basalts. These young zircons that are close to the eruption age of the host basalt suggest that the heat flow in the base of the Pannonian Basin was sufficiently high to keep many of them close to their blocking temperature. This implies that metamorphism is continuing in the lower crust of the region at the present day.

Siani *et al.* [18] provide age constraints on Eocene epithermal gold mineralization at the Glojeh deposit in NW Iran using Ar-Ar geochronology. This mineralization overlaps in timing with the emplacement of associated granite and high-K calc-alkaline to shoshonitic volcano-plutonic rocks in the Tarom-Hashtjin metallogenic province. Siani *et al.* [18] suggest that these magmas were derived from the partial melting of a depleted mantle source during Neotethyan subduction.

In three other papers various aspects of alkaline and mafic-ultramafic magmatism in South America have been described. Giovannardi *et al.* [19] establish a Neoproterozoic age (800–780 Ma) for the Cana Brava Layered Complex (CBLC) in Northern Goias, Brazil, by SHRIMP U-Pb analyses of zircon. This study indicates that the age of the CBLC is the same as that of the Niquelandia Complex, another mafic-ultramafic massif within the Brasilia Belt, and resolves previous uncertainty over its emplacement age.

Ernesto *et al.* [20] investigate the palaeomagnetic characteristics of alkaline igneous complexes in the Alto Paraguay Province (APP) at the border of Paraguay and Brazil. The age of the APP is well constrained within the range 240–250 Ma (preferred age 241 Ma). The calculated palaeomagnetic pole of 319° E 78° S is in agreement with other South American poles of Permo-Triassic age.

Finally, Ponce *et al.* [21] describe suites of spinel-facies ultramafic xenoliths from Cenozoic basalts in the Paso de Indios region in Argentina, providing an insight into mantle processes related to this magmatism. Variations in the degree of partial melting were observed in the mantle column beneath the Matilde and León Hills ($>22\%$) in comparison to the peridotites from the Chenque suite ($\sim 10\%$). They also documented two main mineralogical reaction schemes due to channeled and/or pervasive melt extraction/migration. These are: i) pyroxene dissolution and segregation of new olivine in olivine-rich peridotites, and ii) replacement of primary olivine by orthopyroxene \pm clinopyroxene in orthopyroxene-rich peridotites. Enhanced pyroxene dissolution is attributed to channeling of silica-undersaturated melts, whereas replacement of primary olivine by orthopyroxene \pm clinopyroxene points to reaction with silica-saturated melts.



Figure 1: Friendly meeting of the Prime Ministers of Australia and India at the G20 summit.

Acknowledgement: Encouragement from a confident India and Australia at the G20 summit (2014) with PM Narendra Modi (India) and PM Tony Abbott (Australia) supporting cooperative research programmes and greater friendship.

We sincerely thank and greatly welcome the encouragement recently given to scientists, engineers and graduate students by the Honorable Prime Ministers Narendra Modi of India and Tony Abbott of Australia (Figure 1) to become rigorously involved in more erudite science and technology collaborations in natural resource management and investment within India and Australia. This is indeed the intention of this volume, and in our opinion we are right on target as editors and authors. The encouragement is indispensable to all those like us who are actively involved in mineral exploration and generate new approaches in problem solving and building up more friendly ties.

Publication of this special issue would not have been possible without the help of many individuals and the organizations where we work. We gratefully thank De Gruyter Open publisher. We also wish to thank authors for their contributions. We are indebted to the following individuals for reviewing the papers included in this volume (arranged alphabetically): Bell, Keith; Bjerg, Ernesto Alfredo; Buhn, Bernhard; Comin-Chiaramonti, Piero; Corfu, Fernando; Chinnasamy, Sakthi S.; D'Agrella-Filho, Manoel; Devaraju, T.C.; Dora, M.L.; Downes, Peter; Gerel,

Okir; Giovanardi, Tommaso ; Gwalani, L.G.; Hari, K.R.; Hurai, Vratislav; Irene, Maria; Jaques, Lynton; Malviya, Vivek; Mohan, Ram; Neubauer, Franz; Nguyen, Thuy Thi; Ramachandra, H.M.; Randive, K.R.; Raposo, Bartolomeu; Scandolara, Jaime E.; Sethna, Sam; Sinigoi, Silvano; Viladkar, S.G. and Vlach, Silvio Roberto Farias.

L.G. Gwalani would like to thank, Indira, Jyoti and Shradha Gwalani and Veenu and Lalchand Dayalani for the generous help, support and cooperation extended while working on this volume. K.R. Randive thanks Chetana and Raghav for their support and cooperation.

References

- [1] Gwalani, L.G., Rogers, K., Stoppa, F., Downes, P., Randive, K.R., Hari, K.R., Bucha, M. (2015) Editorial – A special issue (Part-II): Mafic-ultramafic rocks and alkaline-carbonatitic magmatism and associated hydrothermal mineralization – dedication to Lia N. Kogarko, *Open Geosci.* 7, DOI: 10.1515/geo-2015-0025.
- [2] Green, D.H., Experimental melting studies on a model upper mantle composition at high pressure under water-saturated conditions. *Earth Planet. Sci. Lett.*, 1973, 19(1), 37–63.
- [3] Navon, O., Stolper, E., Geochemical consequences of melt percolation: The upper mantle as a chromatographic column. *Jour. Geol.*, 1987, 95(3), 285–307.
- [4] Prouteau, G., Scaillet, B., Pichavant, M., Maury, R., Evidence for mantle metasomatism by hydrous silicic melts derived from saturated oceanic crust. *Nature*, 2001, 410, 197–200.

- [5] Mungall, J.E., Naldrett, A.J., Ore deposits of the platinum-group elements. *Elements*, 2008, 4, 253–258.
- [6] Hudson, D.R.; Robinson, B.W., Vigers, R.B.W, Travis, G.A, Zoned michenerite–testibiopalladite from Kambalda, Western Australia. *Can. Mineral.*, 1978, 16, 121–126.
- [7] Leshner, C.M., Barnes, S.J., Komatiite-associated Ni-Cu-(PGE) Deposits, In: *Magmatic Ni-Cu-PGE deposits: Genetic models and exploration*, Li, C., Ripley E.M. (Eds.), Geological Publishing House of China, 2009, 27–101.
- [8] Maier, W.D., Barnes S.J., Deklerk W.J., Teigler B., Mitchell A., Cu/Pd and Cu/Pt of silicate rocks in the Bushveld complex: Implications for platinum-group element exploration, *Econ. Geol.*, 1996, 91, 1151–1158.
- [9] Crocket, J.H., Paul, D.K., Platinum-group elements in Deccan mafic rocks: a comparison of suites differentiated by Ir content, *Chem. Geol.*, 2004, 208, 273–291.
- [10] Maier, W.D., Platinum-group element deposits and occurrences: Mineralisation styles, genetic concepts, and exploration criteria, *J. Afr. Earth Sci.*, 2005, 41, 165–191.
- [11] Naldrett, A.J., Wilson, A, Kinnaird, J., Chunnett, G., PGE tenor and metal ratios within and below the Merensky Reef, Bushveld Complex: Implications for its genesis, *J. Petrol.*, 2009, 50, 625–659.
- [12] Kogarko, L., Ryabchikov, I.D. (2015) Regime of volatiles in graphite-bearing carbonatites, CEJG-D-14-00057.
- [13] Meshram, T.M. (2015) Occurrence of PGE mineralization in Chromite bearing ultramafic of the Kondapalli Layered Complex, Krishna District, AP, India, *Open Geosci.* 7, DOI: 10.1515/geo-2015-0018.
- [14] Satyanarayanan, M., Singh, S.P., Balaram, V., Mohanty, N. (2015) Geochemistry of Madawara Igneous Complex, Bundelkhand Craton, Central India: Implications for PGE Metallogeny, *Open Geosci.* 7, DOI: 10.1515/geo-2015-0016.
- [15] Subramanyam, K.S.V. (2015) Petrography and geochemistry (trace, REE and PGE) of Pedda Cherlo Palle gabbro-diorite pluton, Prakasam igneous province, A.P., India, *Open Geosci.* 7, DOI: 10.1515/geo-2015-0014.
- [16] Randive, K.R., Hurai, V. (2015) Fluid inclusion study of quartz xenocrysts in mafic dykes from Kawant area, Chhota Udaipur district, Gujarat, India, *Open Geosci.* 7, DOI: 10.1515/geo-2015-0019.
- [17] Downes, H., Carter, A., Armstrong, R., Dobosi, G., Embey Isztin, A. (2015) Lower crustal zircons reveal Neogene metamorphism beneath the Pannonian Basin (Hungary), *Open Geosci.* 7, DOI: 10.1515/geo-2015-0028.
- [18] Siani, M.G., Mehrabi, B., Azizi, H., Wilkinson, C.M., Ganr, M. (2015) Geochemistry and geochronology of the volcano-plutonic rocks associated with the Glojeh epithermal gold mineralization, NW Iran, *Open Geosci.* 7, DOI: 10.1515/geo-2015-0024.
- [19] Giovanardi, T., Girardi, V.A.V., Correia, C.T., Sinigoi, S., Tassinari, C.C.G., Mazzucchelli, M. (2015) U-Pb zircons SHRIMP data from the Cana Brava layered complex: new constraints for the mafic-ultramafic intrusions of Northern Goiás, Brazil, *Open Geosci.* 7, DOI: 10.1515/geo-2015-0015.
- [20] Ernesto, M., Comin-Chiaramonti, P., Gomes, C.B. (2015) The Early Triassic magmatism of the Alto Paraguay Province, Central South America: Paleomagnetic and ASM data, *Open Geosci.* 7, DOI: 10.1515/geo-2015-0022.
- [21] Ponce, A.D., Bertotto, G.W., Zanetti, A., Brunelli, D., Giovanardi, T., Aragón, E., Bernardi, M.I., Hémond, C., Mazzucchelli, M. (2015) Short-scale variability of the SCLM beneath the extra-Andean back-arc (Paso de Indios, Argentina): Evidences from spinel-facies mantle xenoliths, *Open Geosci.* 7, DOI: 10.1515/geo-2015-0023.