

Platinum-group elements mineralization in the cumulate gabbro of Phenai Mata Complex, Deccan Large Igneous Province, India

Platinum-group elements (PGE) are strongly siderophile elements, which provide valuable information on the petrogenesis of mantle-derived igneous rocks¹⁻³. The PGE abundances in the continental flood basalts (CFBs) are much lower compared to lithophile elements, usually at parts per billion (ppb) or even parts per trillion (ppt) level. Nevertheless, they are potential markers of the magmatic process and source nature of the basalts⁴⁻⁹. Recent search for PGE mineralization in the continental flood basalts¹⁰, especially the Deccan Traps^{5,6,9,11,12}, has been fruitful and has brought forth wealth of information on the PGE concentration of Western and Eastern Deccan basalts (lava flows and dykes).

Shukla *et al.*¹³ reported unusually high concentration of iridium in alkali basalts and alkaline rocks of Anjar and Amba Dongar region (Chhota Udaipur Subprovince). More recently, Crocket *et al.*⁵ studied spinels from Western and Eastern Deccan Traps and observed that the Western Deccan Trap spinels are rich in Ni–Ir–Ru–Pt, whereas Eastern Deccan Trap spinels show Pd–Au–Cu enrichment trends. Rao *et al.*¹⁴ studied PGE concentration of Behradih and Kodomali orangeite intrusions in the Mainpur field, Bastar craton, central India, which are emplaced synchronously with the Deccan flood basalts, and concluded that the anomalous iridium enrichment reported at the K–Pg boundary sections was not sourced from the mantle and likely originated from an extraterrestrial source. Occurrence of anomalous concentration of PGE in the basic–ultrabasic rocks of the Lower Narmada Valley was also previously studied¹⁵⁻¹⁷. Lamprophyres and microbasalts occurring in the Bakhatgarh–Phulmal area, which is a part of Chhota Udaipur alkaline–carbonatite complex, were found to contain good concentration of PGE, especially platinum¹⁷. Despite these continuous efforts, no PGE mineral was ever recorded from the Deccan Volcanic Province. Here we report the occurrence of PGE minerals in the cumulate gabbros of the Phenai Mata area, Deccan Large Igneous Province.

The Phenai Mata Igneous Complex (PMIC) is a plug-like body whose em-

placement is controlled by the Narmada rift (Figure 1). It is a bi-modal complex comprising tholeiitic and alkaline magmatism represented by plutonic and volcanic rocks. About two-thirds of PMIC is occupied by tholeiitic basalts and one-third by tholeiitic and alkaline plutonic series comprising gabbros, dykelets of intrusive basalts, lamprophyres, microsyenite, granite and granophyres¹⁸⁻²⁵. Gabbros have been grouped into two categories, viz. (1) tholeiitic gabbro and (2) alkali gabbro²¹. The former is intimately associated with tholeiitic basalt and acid differentiates, whereas the latter is in close association with syenitic rocks occurring in the northeastern part of Phenai Mata hill. Rhythmic layering is a prominent feature in these gabbros. Cumulates of pyroxene and olivine in the gabbros strongly impart cumulate texture to these rocks^{18,19,26,27}. Tholeiitic gabbro shows variations from gabbro (*sensu stricto*) to olivine gabbro, leuco-olivine gabbro, mela-olivine gabbro, anorthosite and troctolite. The alkali gabbros vary

between mela-olivine gabbro and plagioclase-bearing pyroxenite. A large plug of anorthosite is exposed on the southern bank of the Heran river. Traversing the basaltic country rock, a few dykes of dolerite, lamprophyre, basalt and breccia are also present^{21,23,28,29}.

The cumulate gabbros of Phenai Mata have been investigated earlier with a view to study possible Au–Cu–Ni–PGE mineralization³⁰. The result of this study has indicated presence of a suite of minerals, including chalcopyrite, pyrite, pyrrhotite, galena, sphalerite and notably pentlandite and Co–Ni–sulphide phase. Presence of latter phases, prompted us to look more intensively for PGE minerals in this rock. For this, we collected gabbro samples from different locations (Figure 1). Those samples containing sulphides were primarily targeted. The thin polished sections were carbon-coated and studied using CAMECA SX 100 electron microprobe, at the National Centre of Excellence in Geoscience Research, Geological Survey of India,

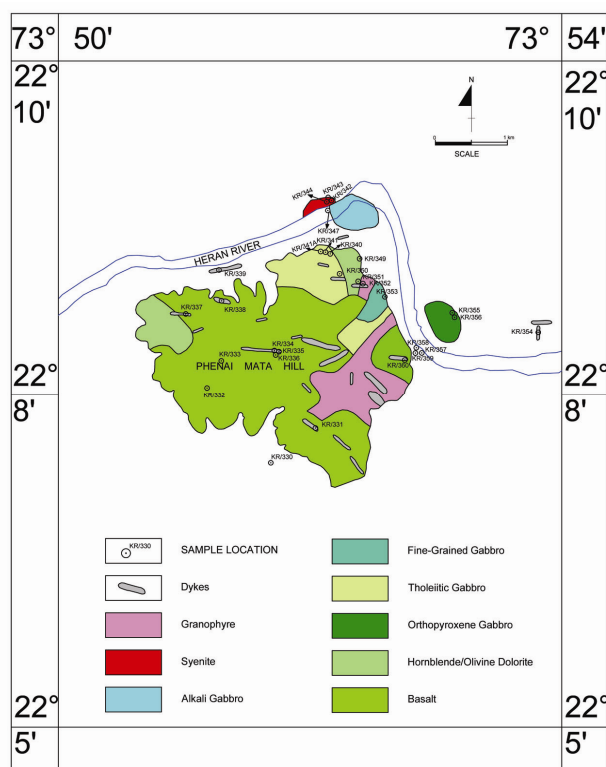


Figure 1. Geological map of the Phenai Mata area.

Table 1. EPMA point analyses of two mineral phases, daomanite and michenerite. Both minerals tend to show some deviation from the ideal composition, such as, daomanite shows higher Fe, whereas michenerite shows higher Fe and S. Analyses from all the three runs for daomanite are included. Run-1 and run-2 yielded higher totals (see text for more details)

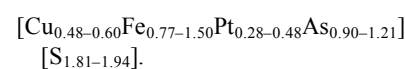
Mineral	Daomanite				Michenerite		
	Run-1	Run-1	Run-2	Run-3	Run-3	Run-3	Run-3
Point	1/1	2/1	1/1	1/1	2/1	5/1	6/1
Analyte	Weight (%)						
As	30.01	23.04	28.66	27.5	25.34	1.2	0.83
Ag	0	0	0	0	0	0.3	0.31
Bi	0.21	0.2	0.77	0.7	0.15	28.4	29.4
Fe	14.2	21.78	15.67	16.87	18.72	20.22	17.28
Cu	11.81	11.9	10.18	10.21	12.31	0	0.04
Au	0	0	0	0	0	0	0
Sb	0.04	0	0.07	0.04	0.05	0.13	0.05
Co	2.45	3.16	1.72	1.71	3.54	0	0.04
Ni	0.28	0.59	0.29	0.32	0.46	0.75	0.65
S	19.23	21.13	19.05	20.15	19.38	15.45	12.7
Pt	29.49	16.42	30.48	28.53	17.75	2.99	2.19
Pd	0.29	0.19	0.82	0.79	0.2	21.06	24.23
Ru	0	0	0	0	0	0	0
Rh	0.94	0.16	0.39	0.41	0.37	0	0
Os	0	0	0.03	0	0	0	0
Ir	0	0	0.02	0.1	0.41	0	0
Te	0.11	0.14	0.52	0.58	0.04	10.21	10.88
Total	107.43	114.47	108.35	107.91	98.72	100.71	98.6
Cations calculated assuming ideal site occupancy							
As	0.242	0.181	0.235	0.221	0.206	0.012	0.009
Ag	0.000	0.000	0.000	0.000	0.000	0.002	0.002
Bi	0.001	0.001	0.002	0.002	0.000	0.104	0.118
Fe	0.154	0.230	0.172	0.182	0.204	0.277	0.258
Cu	0.112	0.110	0.098	0.097	0.118	0.000	0.001
Au	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sb	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Co	0.025	0.032	0.018	0.017	0.037	0.000	0.001
Ni	0.003	0.006	0.003	0.003	0.005	0.010	0.009
S	0.363	0.388	0.365	0.379	0.369	0.369	0.331
Pt	0.092	0.050	0.096	0.088	0.055	0.012	0.009
Pd	0.002	0.001	0.005	0.004	0.001	0.152	0.190
Ru	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Rh	0.006	0.001	0.002	0.002	0.002	0.000	0.000
Os	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ir	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Te	0.001	0.001	0.003	0.003	0.000	0.061	0.071
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Bengaluru. Current intensity was 20 keV and 20 nA current was used. Beam diameter was 1 μm and signals used were S : Ka, Ag : Lb, Fe : Ka, Cu : Ka, Co : Ka, Pt : La, Ni : Ka, As : La, Pd : La, Ru : La, Rh : La, Sb : La, Te : La, Os : Lb, Ir : La, Au : La and Bi : Ma. Standardization was done using default samples. The following internal standards were used: S and Fe on pyrite, Ag on Ag, Co on Co, Pt on Pt, Ni on Ni, As on GaAs, Pd on Pd, Ru on Ru, Rh on Rh, Sb on Sb, Te on Te, Os on Os, Ir on Ir, Au on Au and Bi on Bi. Three consecu-

tive runs were performed for obtaining a better total in daomanite analyses (Table 1). Intensive search for PGE minerals has resulted in the discovery of two grains having the following description:

(1) Grain I: Within an amphibole crystal, a small sulphide phase comprising of chalcopyrite–pyrrhotite is hosted. A tiny PGE mineral phase of $\sim 1 \mu\text{m}$ diameter is included at the corner of this sulphide phase (Figure 2a). The EPMA data indicate a composition Pt–Cu–Fe–As–S, which resembles closely, though

not completely, with daomanite (CuPtAsS_2). Daomanite is considered to be a sulphide mineral having ideal site formula AmBnXp , with $(m+n):p = 3:2$ (refs 31–33). On recalculation assuming ideal site occupancy, we obtained the following formula for PMIC daomanite:



Excess Fe is attributed to the matrix effect, which probably masked counts for Cu and Pt during analyses.

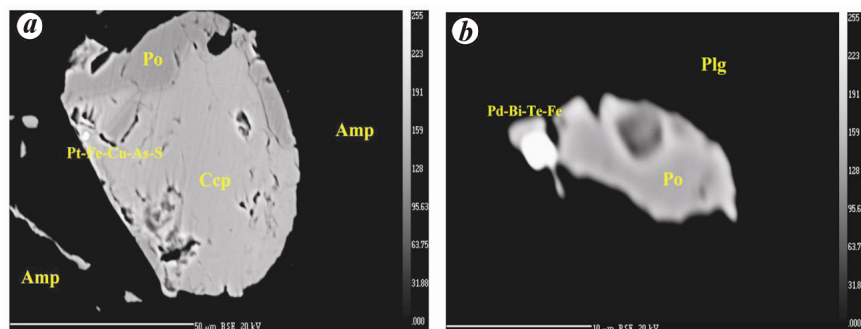
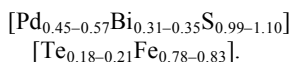


Figure 2. *a*, Grain I showing platinum mineral (Pt–Cu–Fe–As–S) hosted by chalcopyrite–pyrrhotite within an amphibole crystal. Grain diameter is $\sim 1 \mu\text{m}$; *b*, Grain II of palladium mineral (Pd–Fe–Bi–Te) is included within pyrrhotite, which is hosted by plagioclase. Grain diameter is $\sim 2 \mu\text{m}$.

(2) Grain II: Within the plagioclase crystal, a small grain of pyrrhotite is present, which hosts a PGE mineral phase of about $\sim 2 \mu\text{m}$ diameter (Figure 2 *b*). The EPMA analysis indicates presence of Pd–Fe–Bi–Te, which resembles, but again, not completely matches with michenerite (PdBiTe). Michenerite is considered to be a member of the cobaltite group of the minerals having the formula $AmBnXp$ with $(m+n):p = 1:2$. Ideal formula is PdBiTe with common impurities being Pt, Ag, Ni and Sb (refs 33–36). After recalculating the data assuming ideal site occupancy, we obtained the following formula



The above formula clearly indicates excess of Fe and S, which could be due to matrix effect, probably shielding Pd, Bi and Te, and/or little substitution as well.

The two PGE minerals described above contain Pt and Pd. However, Ir does not seem to be present in significant concentration. Therefore, we argue here that the Deccan Igneous Province is not completely ‘barren’ of PGE minerals has been thought earlier^{5,10}. The PGE contribution is not entirely extraterrestrial, but at least some of it is sourced from the mantle. More intensive search for PGE mineralization in the Deccan Igneous Province is necessary.

1. Li, Y. *et al.*, *Chem. Geol.*, 2012, **328**, 278–289; doi:10.1016/j.chemgeo.2012.03.007.
2. Rehkämper, M., Halliday, A. N., Fitton, J. G., Lee, D.-C., Wieneke, M. and Arndt, N. T., *Geochim. Cosmochim. Acta*, 1999, **63**(22), 3915–3934.

3. Momme, P., Óskarsson, N. and Keays, R. R., *Chem. Geol.*, 2003, **196**(1–4), 209–234.
4. Momme, P., Tegner, C., Brooks, C. K. and Keays, R. R., *Contrib. Mineral. Petrol.*, 2006, **151**(1), 88–100.
5. Crocket, J., Paul, D. and Lala, T., *J. Earth Syst. Sci.*, 2013, **122**(4), 1035–1044.
6. Crocket, J. H. and Paul, D. K., *Chem. Geol.*, 2004, **208**(1–4), 273–291; doi:10.1016/j.chemgeo.2004.04.017.
7. Qi, L. and Zhou, M. F., *Chem. Geol.*, 2008, **248**(1–2), 83–103.
8. Song, X. Y., Keays, R. R., Xiao, L., Qi, H. W. and Ihlenfeld, C., *Chem. Geol.*, 2009, **262**(3–4), 246–261.
9. Keays, R. R. and Lightfoot, P. C., *Miner. Deposita*, 2010, **45**(3), 241–257.
10. Zhang, M., O’Reilly, S., Wang, K.-L., Hronsky, J. and Griffin, W. L., *Earth Sci. Rev.*, 2008, **86**, 145–174.
11. Crocket, J. H. and Paul, D. K., *Chem. Geol.*, 2008, **248**(3–4), 239–255; doi:10.1016/j.chemgeo.2007.06.006.
12. Melluso, L., De, G. R. and Rocco, I., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 2010, **119**, 343–363.
13. Shukla, P. N., Bhandari, N., Das, A., Shukla, A. D. and Ray, J. S., *Earth Planet. Sci.*, 2001, **110**(2), 103–110.
14. Rao, N. V. C., Lehmann, B. and Balaram, V., *J. Asian Earth Sci.*, 2013; doi:10.1016/j.jseas.2013.06.009.
15. Chawade, M. P., *Geol. Surv. India Spec. Publ.*, 2001, **64**, 579–583.
16. Randive, K. R., In National Workshop on Mineral Deposit Modeling, Abstr. vol., South Asian Association of Economic Geologists, 2005, p. 52.
17. Randive, K. R., *J. Econ., Geol. Georesour. Manage.*, 2005, **2**(1), 1–25.
18. Sukheswala, R. N., *J. Geol. Soc. India*, 1969, **10**, 177–187.
19. Sukheswala, R. N., *Neues Jahrb. Mineral. Abh.*, 1973, **118**, 159–176.
20. Basu, A. R., Renne, P. R., Das Gupta, D. K., Teichman, F. and Poreda, R. J., *Science*, 1993, **261**, 902–906.

21. Kumar, S., *J. Geol. Soc. India*, 1996, **48**, 547–558.
22. Kumar, S., *J. Appl. Geochem.*, 2002, **4**(2), 93–102.
23. Gwalani, L. G., Rock, N. M. S., Chang, W.-J., Fernandez, S., Allegre, C.-J. and Prinzhofer, A., *Mineral. Petrol.*, 1993; **47**, 219–253.
24. Hari, K. R., Rao, N. V. C. and Swarnkar, V., *J. Geol. Soc. India*, 2011, **78**, 501–509.
25. Hari, K. R., Chalapatih Rao, N. V., Swarnkar, V. and Hou, G., *Geosci. Front.*, 2013; doi:10.1016/j.gsf.2013.06.007.
26. Sukheswala, R. N., *Bull. Geol. Soc. India*, 1964, **1**(2), 6–9.
27. Sethna, S. F., *Mem. Geol. Soc. India*, 1989, **15**, 47–61.
28. Durgadmath, M. B., *Geol. Surv. India Spec. Publ.*, 1984, **12**, 3–7.
29. Gwalani, L. G., Fernandez, S., Karanth, R. V., Demeny, A., Chang, W.-J. and Avasia, R. K., *Mem. Geol. Soc. India*, 1995, **33**, 391–423.
30. Randive, K. R., Project Report, DST, New Delhi, 2012, p. 127, unpublished.
31. Zuxiang, Y., *Acta Geol. Sin.*, 2001, **75**(3), 396–399.
32. Zuxiang, Y., Kuishou, D. and Jiangxiong, Z., *Am. Mineral.*, 1979, **65**, 408.
33. www.mindat.org.
34. Hawley, J. E. and Berry, L. G., *Can. Mineral.*, 1958, **6**, 200–209.
35. Cabri, L. J., Harris, D. C. and Gait, R. I., *Can. Mineral.*, 1973, **11**, 903–912.
36. Childs, J. D. and Hall, S. R., *Can. Mineral.*, 1973, **12**, 61–65.

ACKNOWLEDGEMENTS. We thank the Department of Science and Technology, New Delhi for research grant No. ESS/16/301/2006 under the ‘Deep Continental Studies Program’. We also thank Dr J. N. Das and C. S. Gundewar for providing the necessary facilities. K.R.R. thanks G. M. Manapure, M. G. Manapure, Chetana and Raghav for their assistance.

Received 5 December 2014; revised accepted 5 March 2015

KIRTIKUMAR RANDIVE^{1,*}
J. VIJAYA KUMAR^{1,2}
MAHESH KORAKOPPA³

¹Department of Geology,
RTM Nagpur University,
Nagpur 440 001, India

²Ore Dressing Laboratory,
Indian Bureau of Mines,
Ajmer 305 002, India

³Petrology,
Petrochemistry and Ore Dressing
Laboratory,
Geological Survey of India,
Bengaluru 560 078, India

*For correspondence.
e-mail: randive101@yahoo.co.in