

Magmatic and Hydrothermal Platinum-Group Element Mineralization in the Baula Area, Orissa, India

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Here we summarize the geological environment of the Baula Area, describe the mineralization and its unusual contexts, and suggest an emplacement model.

Geology and Structure of the Bangur Area

The Bangur Gabbro partly intrudes an ultramafic complex, the Baula Complex (Orissa, India; Fig. 1), that is ~3 km long by 0.5 km wide with an estimated thickness of 170-200 m. This Complex is hosted by the Gabbro-Anorthosite Unit of the Singhbhum Craton, and comprises a massive pyroxenite layer, about 50 m thick, overlain by a peridotite unit containing three layers of massive chromitite (currently being mined). Each chromitite layer is 2 to 5 m thick and has been partly dismembered by late tectonism. The peridotite unit locally contains ortho- and clinopyroxene that define a mineral layering parallel to the layering in the chromitite; it also shows a differentiation trend marked by an increase in the iron content of the olivine and pyroxenes. The relationship between the ultramafic complex and the host gabbro unit is not exposed.

The Bangur Gabbro, which is a gabbro norite with a porphyritic tendency, locally cuts and incorporates dunite and chromitite in the southern part of the ultramafic complex (Fig. 2). Metre- to centimetre-size blocks of dunite and chromitite are found near the contact between the ultramafic body and the gabbro intrusion, with the chromitite commonly being dismembered to the extent that the originally massive chromitite becomes disseminated. It is in this block-rich zone that the Type 1 (Pt-dominant) PGE mineralization is found, with the PGM included in the magmatic silicates. This first PGE mineralization is therefore considered as orthomagmatic.

At the top of the Bangur Gabbro, injection of the magma into a shear zone provoked brecciation of the host rock and its incorporation as a magmatic breccia (Fig. 2). The breccia system cuts obliquely across the ultramafic succession and,

in the north toward the upper part of the system, enters the host gabbro. The breccia zone is thus composed of a "Bangur Gabbro" matrix incorporating blocks of different lithology (mainly dunite and chromitite), shape and size torn from the host. Dismembering of the chromitite also provoked a dissemination of chromite grains into the matrix, locally giving rise to "chromitiferous" gabbro. This dissemination was also accompanied by a transformation of chromite into a magnetic mineral known as "ferritchromite" —the breccia matrix locally contains as much as 50% disseminated "ferritchromite".

The breccia matrix was also affected by intense hydrothermal alteration accompanied by transformation of the magmatic mineral assemblage into secondary hydrous phases, crystallization of hydrous minerals, transformation of chromite into ferritchromite, and local deposition of a base-metal-sulfide (BMS) and Type 2 PGE mineralization, considered as hydrothermal. We are able to distinguish three generations of amphibole, two generations of biotite, late chlorite replacing biotite, and septa-chlorite.

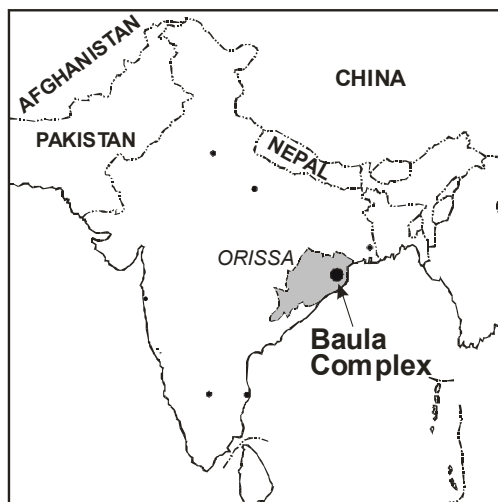


Figure 1. Location map.

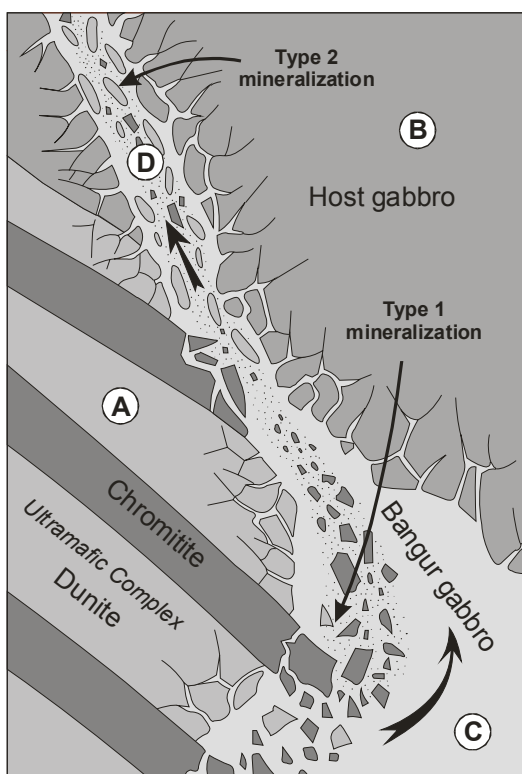


Figure 2. Sketch reconstruction of the Bangur Gabbro emplacement. A Baula ultramafic Complex with its three chromitite layers. B Host gabbro of the Gabbro-Anorthosite Unit. C Intrusion of the Bangur Gabbro with the Type 1 PGE mineralization near the Ultramafic-Gabbro contact. D Breccia Zone with the Type 2 PGE mineralization.

Geochronology

A zircon age of 3122 ± 5 Ma has been obtained for the main Bangur Gabbro intrusion, and similar ages (3123 ± 7 Ma and 3119 ± 6 Ma; U-Pb SHRIMP ages) have been obtained on the PGE-mineralized gabbro matrix of the breccia, thus confirming a genetic link between the Bangur Gabbro and the mineralized breccia. The mean weighted age of 3121 ± 3 Ma for the mineralization defines one of the (if not the) oldest recorded PGE mineralizing events. A similar age (3205 ± 280 Ma) has been obtained from Sm-Nd data on eight samples of the intrusive system.

PGE mineralization

The Type 1 PGE mineralization occurs within a sulfide-free magmatic environment within the Bangur Gabbro, near its contact with the ultramafic complex. The mineralized host rock contains relicts of dunite and chromitite extracted mechanically from the ultramafic formations by the intrusion. The PGE-rich zone has not yet been

traced in the field owing to the lack of outcrop, but it appears to be discontinuous. Its thickness varies between 50 cm and 1 m, and it is located within a maximum distance of 50 m from the contact—in spite of detailed study, no PGE anomaly has been detected in either the ultramafic units or the chromitite layers (except for a few hundred ppb Ru and Os).

The Type 1 mineralization is dominated by Pt (Pt/Pd 8–9) and is anomalous in Ru and Rh, with the PGM assemblage being dominated by isoferroplatinum, braggite and malanite, plus sperrylite and laurite, included in pyroxene and plagioclase (Table 1). Hydrothermal alteration is very weak to nil.

The Type 2 PGE mineralization (divided into 2A and 2B) is restricted to the hydrothermally altered matrix of the breccia zone. In Type 2A, which is associated with a BMS mineralization, the PGE assemblages are characterized by Pd (Pt/Pd 0.5)—the PGE minerals are mainly sudburyite, Pd-Bi-Te-Sb system minerals, and sperrylite (Table 1). The BMS are disseminated, locally massive, and include chalcopyrite (main sulfide), pyrrhotite, pentlandite, violarite, millerite, pyrite, minerals of the cobaltite-gersdorffite solid solution series (as reported by Mondal et al., 2001), and rare maucherite ($\text{Ni}_{11}\text{As}_8$), nickeline (NiAs), heazlewoodite (Ni_3S_2), cubanite, bornite, mackinawite, electrum, ullmannite (NiSbS), galena, and orcelite ($\text{Ni}_{5-x}\text{As}_2$).

In Type 2B, which is not associated with BMS, the PGE are characterized by Pt (Pt/Pd 2–3). PGE mineral phases from the Pt-Sb-As system (geversite, sperrylite) coexist with Pd antimony (mertieite-II, Table 1).

The Type 2 PGE minerals form discrete grains a) within the hydrosilicate matrix (commonly as clusters) without BMS, or within the silicate matrix accompanying BMS trails where locally adjacent to disseminated BMS, b) within ferritchromite, c) within BMS in silicates, and d) within or adjacent to BMS in ferritchromite.

Stable Isotopes

In order to characterize the hydrothermal and mineralizing fluids in the breccia zone, a sulfur-oxygen-hydrogen isotope study was made on biotite 2, amphibole 3 and chlorite from selected ferritchromite-rich samples showing extensive hydrothermal alteration and mineralization.

Sulfur: The $\delta^{34}\text{S}$ of the sulfides (mainly chalcopyrite) is homogeneous, ranging from -0.8 to $+1.4\text{‰}$. This range, relatively close to 0‰ , is consistent with a magmatic origin of the sulfur in the fluids (Taylor, 1987). The negative pyrrhotite-

chalcopyrite fractionation shows that the sulfides are not at the isotopic equilibrium.

Oxygen: The $\delta^{18}\text{O}$ of the biotite 2 and amphibole 3 is respectively $+3.7 \pm 0.1\text{‰}$ and $+5.5\text{‰}$, which is comparable to magmatic values found in the literature for this type of system. The $\delta^{18}\text{O}$ of the diffuse chlorite, resulting essentially from the breakdown of the hydrothermal biotite, is $+3.8\text{‰}$, quite close to that of the biotite. The ferritchromite $\delta^{18}\text{O}$ ranges from -0.3 to $+1.2\text{‰}$, with the highest values being measured in biotite-rich samples and the lowest values in chlorite-rich samples. The values are significantly lower than for magmatic chromite, which strongly suggests that the chromite transformation to ferritchromite favored isotopic exchanges during hydrothermal alteration —this is contrary to the known generally resistant behavior of chromite to alteration.

Table 1. Characteristics of the Type 1 (magmatic) and Type 2 (hydrothermal) PGE mineralization and their PGM assemblages.

Mineralization type	1	2A	2B
Ferritchromite	•	•	●
Chromite	•		
Sulphide		•	
Pt (ppm)	1.1 - 9.7	0.3 - 1.7	1.0 - 4.4
Pd (ppm)	0.1 - 1.7	1.5 - 25.8	1.0 - 3.0
Rh (ppm)	1.8 - 3.8	0.01 - 1.2	0.1 - 0.3
Ru (ppm)	1.2 - 3.6	0.01 - 0.3	0.1 - 0.4
Au (ppm)	<0.02	0.07 - 3.3	0.05 - 0.4
Pt/Pd	8 - 9	0.5	2 - 3
PGM			
Isoferroplatinum Pt ₃ Fe	•		
Braggite (Pt,Pd,Ni)S	•		•
Sperrylite PtAs ₂	•	•	•
Geversite Pt(Sb,Bi) ₂			•
Malanite Cu(Pt,Ir) ₂ S ₄	•		
Ni-cuprorhodsite Ni(Rh,Pt) ₂ S ₄	•		
Moncheite (Pt,Pd)(Te,Bi) ₂			•
Mertieite-II Pd ₈ (Sb,As) ₃		•	•
Sudburyite (Pd,Ni)Sb		•	
Merenskyite (Pd,Pt)(Te,Bi) ₂		•	
Laurite RuS ₂	•	•	•
Osmium * OsIr			
Hollingworthite (Rh,Pt,Pd)AsS	•	•	•
Sb-merenskyite Pd ₂ (Te,Sb,Bi) ₃		•	
Bi-merenskyite Pd(Te,Bi,Sb) ₂		•	
Bi-sudburyite Pd(Sb,Bi,Te)		•	
Unnamed 1 Pd(Sb,Te,Bi)		•	
Unnamed 2 (Pd,Ni) ₃ (Sb,Te) ₄		•	
Unnamed 3 Pd,Ag,Sb,Te,Bi		•	
Potarite PdHg	•		
Electrum AuAg		•	

Symbol size reflects the relative abundance of each mineral or element. * Present only as inclusion in chromite.

Hydrogen: The δD of the biotite 2 and amphibole 3 is respectively $-70 \pm 5\text{‰}$ and -76‰ . These values are similar to phases analyzed in other mineralized mafic-ultramafic systems and reputed to be due entirely to magmatic or late-magmatic processes (e.g. phlogopite of the Merensky Reef, Mathez et al., 1994). The δD of the diffuse chlorite is -44‰ .

Oxygen isotopic thermometry: Isotopic thermometry is not easy to use in these circumstances, being based on a complex mineralogy and the unknown isotopic behavior of chromite/ferritchromite. Temperatures were estimated assuming relative similar fractionations for ferritchromite, chromite and magnetite. The biotite 2 - ferritchromite pair ($\Delta^{18}\text{O} = +2.6\text{‰}$) gives equilibrium temperatures around 695 °C using the magnetite-H₂O and biotite-H₂O fractionations of Bottinga and Javoy (1973). The amphibole 3 - ferritchromite pair ($\Delta^{18}\text{O} = +5.4\text{‰}$) gives equilibrium temperatures around $490\text{--}525\text{ °C}$ using the magnetite-H₂O and amphibole-H₂O fractionations of Bottinga and Javoy (1973) and Zheng (1993).

Isotopic composition of the hydrothermal fluids: Oxygen and hydrogen isotope compositions of the fluids were calculated using isotopic temperatures and mineral-water fractionations from the literature. The $\delta^{18}\text{O}$ and δD values of water in equilibrium with biotite 2 are respectively $+6.5\text{‰}$ and -49‰ compared to SMOW, whereas those of water in equilibrium with amphibole 3 are respectively $+7.2\text{‰}$ and -56‰ . Thus the fluids in equilibrium with biotite and amphibole exhibit a magmatic signature.

Model

Both types of PGE mineralization are closely associated with the intrusion of the Bangur Gabbro (Fig. 2). The Type 1 mineralization was magmatic —inclusion of the PGM in pyroxene and plagioclase suggests that they crystallized early in the evolution of the magma. The PGE mineralization was closely related to the incorporation of chromitite as nodules and disseminations in the gabbro; an incorporation that occurred at very high temperatures (before plagioclase crystallization).

Two main possibilities can explain these observations: The PGE source was ultramafic rocks incorporated in the gabbro, or The PGE source was the gabbro itself, with a massive local precipitation of PGM being provoked by sudden changes in physico-chemical conditions due to the incorporation and part digestion of ultramafic material.

Considering the absence of any detectable Pt anomaly in the ultramafic units, the second possibility appears most favorable. The PGM mineralogy is characteristic of a high-temperature, sulfide-free magmatic PGE mineralization, and shows striking similarities to some Bushveld Complex occurrences, such as UG2 and Platreef with braggite, laurite and sperrylite, and to the orthomagmatic stage described by Coghill and Wilson (1993) for the Great Dyke, Zimbabwe.

The Type 2 mineralization can be divided into i) Type 2A associated with BMS mineralization – the PGE are dominated by Pd and the PGM are from the Pd-Bi-Te-Sb system, and ii) Type 2B where BMS are absent – the PGE are dominated by Pt and the PGM are from the Pt-Sb-As system and Pd antimonides. Types 2A and 2B are both restricted to the hydrothermally altered matrix of the breccia zone. They can occur together in the field, and can even be found in the same outcrop.

We have plentiful evidence to show that the Type 2 mineralization is related genetically to the hydrothermal event that affected the breccia matrix. The PGM and BMS are systematically associated with hydrosilicates and ferritchromite, and textural investigations indicate that all the base metals, gold and PGM are contemporaneous and related to the same hydrothermal mineralizing event.

Hydrous minerals were formed during the late magmatic evolution of the Baula Gabbro without significant introduction of external fluids into the system and testify to a volatile-rich magmatic system. We have found no evidence that the BMS assemblage could be magmatic in the sense of resulting from sulfide immiscibility in a mafic silicate magma —on the contrary, the data indicate that the BMS were related to a fluid-rich, hydrothermal stage, with crystallization temperatures in the 300-500 °C range.

No marked difference in terms of silicate and oxide assemblages is seen between the Types 2A and 2B mineralization, and both show evidence of the same hydrothermal processes. Differences in BMS-PGM assemblages are important (Table 1), but we have found no real spatial separation between the two. This can be interpreted as indicating crystallization from fluids of different compositions (at least in terms of minor and trace elements), or alternatively as marking an evolution in fluid composition. One possible scenario is a first stage with the crystallization of Pt-PGM, followed by a later stage with the formation of BMS and PGM from the Pd-Sb-Te-Bi system. This possible evolution in the nature of the fluid may also partly

explain the different base-metal sulfide assemblages observed in the breccia zone.

Conclusion

We have evidence of orthomagmatic PGE mineralization (Type 1) in the Archean Bangur Gabbro, but no evidence that this mineralization was remobilized. Similarly, we have evidence of hydrothermal BMS mineralization, but no evidence of sulfide remobilization. We can conclude, therefore, that the BMS and Type 2 PGE mineralization both crystallized from a fluid-rich phase during a late hydromagmatic stage. This fluid phase would have been generated by the crystallization of silicates at a magmatic stage in the gabbro and become concentrated in the breccia zone at the top of the magmatic system. The exsolved fluid phase would then have become progressively enriched in volatiles, Cu, S, semi-metals and PGE, accompanied by 'autohydrothermal' alteration of the gabbro mineral assemblages. Consequently, we can consider that two separate PGE mineralizing events occurred within a single, but complex, evolution of the magma.

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