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Review Article

Platinum Group of Metals (PGM) Occurrence and Future Prospective in Ultramafic and Associated Rocks from Madaura-Ikauna-Pindar Tract in Madaura Igneous Complex: Signature of Plume Activity During Evolution of Bundelkhand Craton, Central India

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Abstract

The major world Platinum Group of Metals (PGM) deposits are generally occurred in association with ultramafic/mafic complexes. Likewise, the serpentinized peridotite and talc actinolite schist from Madaura-Ikauna-Pindar tract, in Lalitpur district of Bundelkhand craton have been found enriched with PGM, Au and Ag. Ultramafic rocks comprising dunite, peridotites occur as intrusive in the form of hillocks as discrete and deformed lensoid body at this tract in to granite-gneisses of craton. The peridotites are dominated by olivine cumulates where chromite and precious metal-bearing sulphides crystallized along with pyroxenes, subsequent to crystallization of olivine into the interstitial spaces of cumulates during cooling. Ultramafic rocks have high MgO (up to 30.76wt.%), FeO (up to 5.8wt.%), and low SiO_2 (up to 48wt.%). The Ikauna ultramafic contain Platinum (up to 2.78ppm) along with significant amount of Au,Ag,Ni,Co and Cr. Precious metal bearing large scale ultramafic/mafic intrusive of Bijawar areas related with rifting phenomenon might have been caused by the plume/superplume during Paleoproterozoic period. This event might has been started in geological setting of Southern Bundelkhand Craton during Neoarchean period. The general trend of rocks from tract as well as major shear direction is E-W. The analyses of selected samples of boreholes from Ikauna area return with still higher value of PGM (up to 10ppm).These high values of PGM indicate that this tract has good potential for a PGM deposit of Northern India as well as strong indicators for plume/ superplume activity during crustal evolution of Bundelkhand Craton.

Keywords: Bundelkhand craton; PGM; Ultramafics; Ikauna complex

Introduction

Platinum Group of Metals (PGM) mineralization and related ore deposits are expected mainly in mafic igneous intrusions of different tectonic setting [1]. The ultramafic complexes for PGE exploration have been broadly divided into two categories on the basis of their occurrences, viz., PGM as by-product in massive deposit of Ni-Cu (Kambalda type deposit) [2,3] and PGM deposits with Ni-Cu as by-product (PGM reef type deposits, [4-6]). The PGM geochemistry is also used in understanding the mechanism responsible for the Ni-Cu and PGM deposits in different geological and tectonic settings [7,8]. The fundamental geochemical controls of platinum group of metals (PGM: Ru,Rh,Pd,Os,Ir,Pt) and their formation and distribution in Earth's crust and to understand the characteristics of primary mantle derived magmatic processes [9-16].

Exploration for PGM in India has been undertaken in several proposed prospective areas based on some fundamental genetic concepts of PGM mineralization in space and time. However, valuable occurrences of PGM in India are still very limited and have been reported from the plutonic to hypabyssal magmatic intrusions of Archean-Paleoproterozoic age, mostly emplaced into the Indian shield [17,18]. Sukinda and Baula-Nausahi areas of Orissa in Singhbhum Craton [19-21], Sittampundi area of Tamil Nadu in Southern Granulite Belt [22] and Hanumalapura area of Karnataka in Dharwar Craton [23,24] are the few important areas apart from some small locations [18,25,26]. The presence of PGM in Ultramafic terrain (Ikauna area) of Bundelkhand was reported by the Directorate of Geology and Mining, Uttar Pradesh [27]. This surface finding encouraged us to start a detailed work in Ikauna ultramafic/mafic suit and subsequent to this report we find presence of 10 g/ton of ΣPGM in the ultramafic rocks of Ikauna from boreholes [28].

PGM explorations in Madaura-Ikauna-Pindar tract reveal that mafic/ ultramafic intrusive of Bijawar are economically important for sulphide mineralization including Gold and PGM. The occurrence of high PGE values of Madaura-Ikauna-Pindar tract indicates the area may have potentiality to be a PGE deposit of Northern India. The high PGE bearing mafic/ultramafic intrusive of Bijawar indicate that the related rifting may have been caused by a plume/superplume activity from primitive mantle during Paleoproterozoic period [29].

Geological Setting

Bundelkhand Craton (BC) is not only an oldest part of the Indian shield area but also exist greenstone belts here. The systematic geochronological data of BC is lacking but whatever data available till now shows the oldest age reported as ~3590Ma [30]. BC covers an area of 29,000sq. km and consists of Archean (3.55-2.8Ga) sodium-rich Tonalite-Trondhjemite-Granodiorites (TTGs), Mesoarchean (ca. 2.84Ga) to Neoarchean (2.57-2.54Ga) Greenstone Complexes, and Neoarchean potassium-rich granitoids [31-35]. The regional stratigraphy of Bundelkhand area has been proposed by Poscoe [36] and coined the term for the crystalline and volcano-sedimentary sequences of Archaean age as Bundelkhand Granite, Mahroni Schist, Bijawar series and Vindhayan System. Thereafter several workers like Sarkar et al. [37], Mondal et al. [38,39] and Slabunov et al. [40,41] worked in Bundelkhand area and suggested several modifications for Bundelkhand stratigraphy (Table 1). The stratigraphy of south western part of Bundelkhand Craton have observed that the gneisses of Rajaula formation been the oldest formation then followed by Berwar and Madaura Formation ((Table 1) [42]) but Nath et al. [43] put the granite member (Vein quartz, Pegmatites and Granite) of Madaura formation younger to Bijawars and older to Kaimur Group (Vindhyan sediments) (Figure 1).

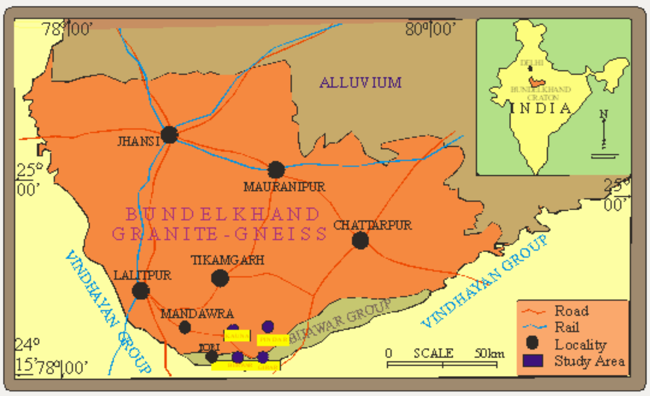

Figure 1: General Geological map of Bundelkhand Craton.

The Paleoproterozoic rocks (low metamorphosed sedimentary along with mafic flows and sills) of the Bijawar and Gwalior Groups are exposed in the southern and northern parts of BC. Saha et al. [30] estimate the chronological order to different tectonothermal events and described that first tectonothermal events (T1) happened to occur during 3590Ma followed by a second tectonothermal event (T2) at 3440Ma, leading to calc-alkaline magmatism and subsequent crustal growth. After these two events, there was acid magmatism of different episodes during 2500-2300Ma. BC have received two more thermal events in which mafic dyke (2200-2000Ma; [44]) and quartz reefs (~1800Ma; [45]) were emplaced. Paleoproterozoic (~2.15Ga) mafic dykes occur mostly along NNW-SSE to NW-SE trend. The hydrothermal silica rich fluids are dominant feature of the craton is the presence of NE-SW trending quartz veins. Moreover, correlations and dynamic reconstructions have been difficult to make since there are no isotopic age determinations on these rocks where Singh & Slabunov [46,47] have indicated that the BC contains two distinct supracrustal complexes i.e. Central Bundelkhand and South Bundelkhand. The Central Bundelkhand Supracrustal Complex includes Babina and Mauranipur greenstone belts. This complex essentially consists of two associations the early (Mesoarchean) sequence consisting of metamorphosed tholeiitic basalt and high Mg-basalt (basaltic association), meta-dacite-rhyolite and Banded Iron Formation (BIF) and the late (Neoarchean) felsic volcanics [32,47]. On the basis of geochemical and geochronological data, subductional setting has been proposed for the formation of volcano-sedimentary rocks from Central Bundelkhand greenstone Complex.

Slabunov et al. [40] suggest that the South Bundelkhand Supracrustal Complex lies unconformably under the gently dipping, undeformed, Paleoproterozoic rocks (conglomerates, cherts, carbonates and sandstone) of the Bijawar Group. This might be an indirect evidence for the older sequences, presumably Archean age for the rocks of Girar supracrustal belt. U-Pb zircon data from quartzite of Girar supracrustal belt, give an older age of 3.43Ga and younger age of 3.25Ga [48], suggesting 3.25Ga to be the minimum age of the source sediments. Whole-rock Sm-Nd analysis of quartzite gives a depleted mantle Nd (TDM) model age of 3.29Ga which is similar to the U-Pb age of the analysed zircons [48], thereby indicating that the continental crust of the southern part of BC formed during the Paleoarchean (3.4-3.3Ga). It can be summarized that the quartzites of Girar Supracrustal Belt (GSB) were produced by the reworking of granitoids, whose zircons clearly dominate in sediments. The nature and age obtained from quartzite of Girar supracrustal complex suggest that the continental crust in southern Bundelkhand formed during two Paleoarchean events (3.43Ga and 3.35Ga) due to reworking of the pre-existing continental crust. This reworking age is comparable to second tectonothermal event (T2) of BC [30]. The field relations shows that GSB overlay on Rajaula formation therefore the dates obtain from quartzite of GSB suggest that Rajaula Formation may have established prior to 3.43Ga or contemporaneous because basement of BC is not exposed in and around Girar area.

Mishra [29] has suggested based on the exposed dyke swarms and sills of mafic and ultramafic rocks that are exposed far apart and their extent to sub-surface based on geophysical data. It is suggested that a large plume/superplume existed during Paleoproterozoic (1.9Ga) under the Indian continent. It was responsible for the break up (rifting) of the Craton at margins and provided for depositions

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of the former older group of rocks with self-type of sediments and large scale mafic/ultramafic intrusives. Bijawars and intrusive mafic/ultramafic of Paleoproterozoic period formed during the rifting phase due to the plume/superplume activity at the southern hinge zone of BC [29].

Madaura-Ikauna-Pindar Ultramafic Tract

The ultramafic/mafic rocks of Madaura- Ikauna-Pindar tract is the eastern extension of Madaura Ultrabasic Complex. A series of E-W trending ultramafic rocks are randomly exposed as lensoidal intrusive discrete bodies in the form of isolated outcrops into the granite-gneisses around 20km stretched in Madaura-Ikauna-Pindar tract (Figure 2). The ultramafic/mafic rocks occur as E-W elongated enclaves of lenticular bodies of varying in size from east of Madaura to Dhasan river of 20km length. These outcrops are dislocated and elongated due to intense extension and shearing processes. The evidences are seen in the form of elongation of peridotite lenses in E-W and wrapping of intense deformed schistose rocks. The outcrop of the ultramafic rocks of this tract are found in Bhikhampur, Hanumatgarh, Rajaula, Purani Pindar, South of Gidwaha, Siron, Bamhauri Kalan, Dangli, Madaura, Gangchari areas among these largest outcrop is found in Madaura area. These ulframafic rocks comprise mainly Dunite, Harzburgite, Lherzolite, Olivine websterite, Orthpyroxenite, pyroxene-hornblende peridotite and Websterite. The Madaura Ultrabasic Complex found at the southern hinge zone of BC overlain by Bijawars in the south. The generalized litho-stratigraphical comparative sequence [42] is given in Table 1. Generalized sequence of litho-stratigraphy of Southwestern part of Craton belongs to Madaura-Ikauna-Pindar tract but some rocks are absent in the area. Ultramafics are found associated with medium-to-coarse grained diorite.

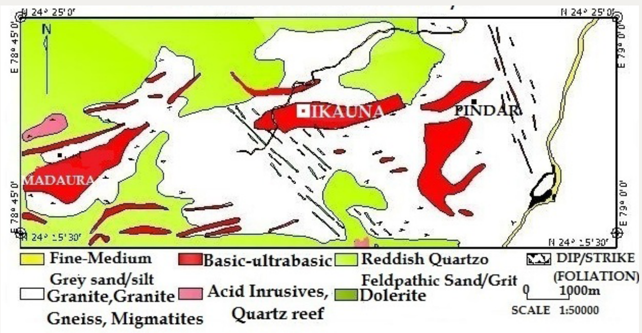

Figure 2: Geological map around Madaura-Ikauna-Pindar tract (after 1:50000 Map of Geological Survey of India, 2012-13).

At Ikauna, peridotite and associated rocks form a continuous E-W trending bodies with width varies 180m to 90m and extending to 3.5km strike length. The main body comprises lenticular exposure of peridotite (10-50m wide and 15-100m long), which are wrapped by sheared talc- actinolite schistose rocks. Chlorite schist bands (30cm to 1m wide) continuity has found out in talc actinolite schist zone of 1.5km in strike length with sometime containing chrome spinel. Peridotite lenses are fully or partially enveloped by associated talc-actinolite schistose rocks while peridotite contact with gneisses or diorites are marked by schistose rocks. The shear foliation of marker metamorphites is parallel. The contact between ultramafic rocks and granite-gneisses is sharp, but in many places, sheared and mylonitized. The ultramafic body of Ikauna complex is cross-cut by NW-SE trending dolerite dykes. An epidote rich fine grained ultramafic (100-150m wide) body also cut across the sequence of peridotite and associated rocks which traced in 2.0km strike length just east to the Ikauna village. The occurrence of epidote bearing rocks is discordant to normal sequences which imply that the development of epidote is possibly resulted by later dynamothermal event of the area. The quartz vein is also present in NW-SE which is also cutting the diorites and peridotite sequences [28].

Ultramafic rocks of Pindar area comprise mainly dunite, harzburgite, lherzolite, olivine websterite, orthopyroxenite and websterite. However, the ultramafic complex is dominated by peridotite rocks. They are associated with medium- to coarse grained gabbro and diorite. Sometimes, the lenses of ultramafic rocks are found in the diorites. Pindar area is about 15km east of Madaura town where ultramafic rocks are exposed in the small hillocks. The ultramafic rocks exposed here are E-W trending and lensoidal in shape that is about 800 m in length and 200-300m width. The contact between ultramafic rocks and granite-gneisses is sharp, but in many places, sheared and mylonitized. The gabbro and diorites are mainly confined to the southern part of Pindar. The E-W trending ultramafic rocks of Pindar region is displaced by NW-SE faults at several places. The olivine websterite is dark bluish grey coloured, hard and compact, characterized by coarse grained cumulates of olivine and often found as intrusions into peridotite. They occur as small to giant size lenses (up to 8-10m in length) and peridotites is usually altered, sometimes sheared and mylonitized. Talc-chlorite schist is seen along the sheared contact. The olivine websterite and websterite are sometimes found as a disseminated body within the peridotite and its orientation is also parallel to the main ultramafic complex [49].

The rock foliation of Madaura-Ikauna-Pindar tract is generally dipping towards north with moderate to steep angles. The whole sequence of ultramafic/mafic rocks has been cut across by dolerite dyke. The peridotite bodies are lenticular and are almost envelope by talc, actinolite chlorite schist. This rock is found all along the 20Km strike length in the east as well as west of Madaura-Ikauna-Pindar but some time it pinches and reappears at different place (Figure 2). This sheared contact implies that emplacement of peridotite was not contemporaneous to the associated other rock unit. A series of E-W trending ultramafic rocks are randomly exposed as lensoidal intrusive discrete bodies in the form of isolated outcrops into the granite-gneisses stretched in E-W direction implies that this area suffered E-W extension. Slabunov et al. [41] revealed that Ikauna complex is Archean because Neoarchean Bundelkhand orthoclase granite (~2500Ma) cut the ultramafic body near Ikauna village. The tentative age of the rocks of the Ikauna area may be in

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between 3430Ma to 2000Ma as per field relationships of the rocks and correlation of regional dates (Table 1).

Table 1: The stratigraphy of south western part of Bundelkhand Craton and its correlation with geochronological data [42].

Formation Lithology (Madaura- Ikauna-Pindar area)
Madaura Fm. Dolerite Dykes (~2200-2000Ma)
Quartz vein, pegmatite, and graphic granite
Coarse to medium Diorite
Peridotite, Chlorite, Talc- actinolite Schist (PGE bearing)
...............Unconformity.........................
Berwar Fm. Missing or not exposed
.... Unconformity......................
Rajaula Fm. Biotite-feldspar Gneiss (~3430Ma)

Petrography

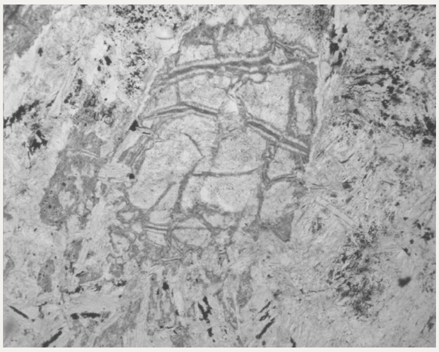

Figure 3a: Photomicrographs Altered Peridotite; (magnification 10x; Serpentinized Olivine)

The rocks of Ikauna area include diorites, dolerites, granites, massive peridotite, gneisses, talc-actinolite-schist, chlorite schist, epidote bearing ultramafic rocks. The serpentinized peridotite, talc-actinolite schist and chlorite schist are PGE bearing while others are devoid of PGE. The petrological study of Ikauna area has been carried out on microscope of Leica DMEP model coupled with computer. The peridotites are composed of serpentinized olivine, orthopyroxene, amphiboles, feldspars and accessory minerals such as clinopyroxene, biotite, opaques. Olivine is highly fractured and along the fracture serpentinization is found. This serpentinized olivine is mainly found in ground mass of aggregates of feldspar and amphiboles. Modal percentage of serpentinized olivine (Figure 3a) is ranging between 40-50%. In amphiboles, hornblende is dominant mineral phase while in orthopyroxene mainly hypersthene is present. According to IUGS scheme stated in sub-commission by Streckeisen [50,51], these peridotites can be sub grouped as harzburgite and pyroxene-hornblende peridotite. Harzburgite contains serpentinized olivine, hypersthene, feldspar as main mineral and amphiboles, clinopyroxene, biotite and opaques as accessory. Pyroxene-hornblende peridotite contains serpentinized olivine, hypersthene, hornblende and feldspar as main mineral, biotite and opaques as accessory. Talc-actinolite schistose rocks contain well developed schistosity defined by actinolite, talc. These talc schist rocks are showing similar kind of texture as reported by Nozaka [52] from Happo complex. Although mylonization was not as intense as Happo Belt but textural development is similar. Chlorite schist occasionally contains the chrome spinel (0.3-1m wide) along with well-developed schistosity defined by chlorite and other flaky minerals [28]. The Cr-spinel has also been reported by Mohanty and Sen [53] from Sukinda ultramafic Complex (Figure 3b).

Figure 3b: Talc-actinolite schist (magnification 10x) (after Farooqui and Singh, 2010).

The Pindar ultramafics are usually medium-to-coarse grained that consists of harzburgite, lherzolite, dunite and olivine websterite. However, the complex is dominated by peridotite rocks. The olivine websterite is dark bluish grey coloured, hard and compact, characterized by coarse grained cumulates of olivine and often found as intrusions into peridotite. Mineralogically, olivine is the primary mineral of these ultramafic rocks, which is medium-to-coarse grained, free from inclusions, rimmed by pyroxenes. The intergranular space of the olivine cumulates are either occupied by orthopyroxene or clinopyroxene with chromite [49]. The sulphide-bearing phases, viz., pentlandite, pyrrhotite, chalcopyrite, and platinum group minerals (PGM), which were identified by SEM-EDS, occur as accessory fine-grained crystal into intergranular spaces of olivine or along the cleavages of pyroxenes [49]. The alteration of olivine, pseudomorphic texture, appearance of talc-chlorite and serpentine is common. Plagioclase and amphiboles (hornblende) are nearly absent in the ultramafic rocks of Pindar. Mineralogically and petrographically the rocks of ultramafics of Pindar and Ikauna are broadly similar it shows they are genetically similar and part of a big magmatic episode. There alteration is also same mostly altered and metamorphosed as talc actinoloite schist and chlorite schist containing Cr-spinel.

Chemical Analyses

Whole rock PGM concentrations of Ikauna area were obtained from National Geophysical Research Institute NGRI), Hyderabad as well as from Indian Bureau of Mines (IBM) Nagpur. 25 samples (Surface & Subsurface) including host rock serpentinized peridotites & talc actinoliteschists analyzed from NGRI, Hyderabad by fire assay followed by tellurium coprecipitation technique in

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combination with ICP-MS (Perkin-Elmer, Elan DRC II make). The details of instrument and operating parameters are described by Balaram and Rao [54] and procedure followed is discussed by Mathuret al. [55] and Balaramet al. [56]. Surface & Subsurface samples including host rock as well as diorites, quartz vein and metamophitesetc. were analyzed from IBM Nagpur by ICP-AES after pre-concentration through Ni-S fire assay method. The analytical values of platinum varies from 0.05-2.78ppm, palladium varies from 0.005-2.02ppm, PGM (Σ Pt,Pd,Ir,Ru,Rh) varies from0,058-10.07ppm whereas gold varies from 0.013-1.05ppm, Silver varies from 0.03-3.61ppm. The values of Ni,Co & Cr are obtained from AAS Unit of Directorate of Geology & Mining, U.P. The maximum values obtained for Ni, Co & Cr are 3070ppm, 3200ppm & 751ppm respectively. Major oxide value obtained from wet lab of DGM, U.P. Such as MgO (up to 30.76wt%) and Fe2O3 (up to 8.76wt%); low SiO_2 (upto 42.14wt%).

Mineralization

The ultramafic/mafic rocks of Ikauna area contain Cr-spinels, sulphide minerals along with the serpentinized olivine which indicates the possibility of PGE enrichment because a relationship between PGM enrichment and olivine, chromite, sulphide minerals has been petrographically and geochemically established [57,58]. Ir,Os and Ru are compatible with chromite and olivine whereas, Pt and Pd are incompatible elements partitioned into sulphides [59,60]. These surface indications triggered us to start an exploration for PGE in this area. To delineate the mineralization at the surface, ten trenches were excavated across the peridotite lenses. Selected samples have been analyzed from trenches near boreholes which are 50m apart and each sample representing 1m width of the trench. These samples were selected from three rock type's viz. peridotite, talc-actinolite schist and chlorite schist. All samples gave anomalous value of PGM but 2-3 samples of peridotite and talc-actinolite schist showed the PGM values as high as 2.58ppm to3.31ppm [27,28] which indicates the presence of PGM enrichment in these rocks. The detailed work at Ikauna area indicate that the mineralization is lithologically controlled and the PGM brought by ultramafic rocks from beneath which have been spread in the area. The rocks which are converted from ultramafic are containing PGM while some quartz veins emplaced in the rocks originated from late stage of crystallization from ultramafic also containing PGM.

PGM finding encourage the regional geological traversing to adjoining. Geological traversing in different area like Hanumatgarh, Rajoula, Bigai, Gidwaha, and Madaura ultramafic rocks has been found. Hanumatgarh, Bhikhampur, Rajoula and Madaura areas are found potential for platinum exploration because they are showing similar properties of alteration and mode of occurrence. Some more lenses of ultramafic rocks are delineated in aforesaid areas. These finding of new lenses of ultramafic rocks extend the potential area for PGM in further E-W direction of 10 to 20km in strike length of Madaura-Ikauna-Pindar tract. In boreholes ultramafic rocks encountered upto 90-110m depth which reflect the subsurface extension of these rocks. The compilation of analytical results indicates from Ikauna area that there are several PGE mineralized zones found at different level which extend in 2km strike length in the area. Medium grade PGM reserve is estimated in Ikauna area till date. PGM reserve may be also found in Madaura-Ikauna-Pindar tract need rigorous detailed exploration for PGM.

Discussion

Detailed exploration and analyses of samples from trenches and boreholes of east Ikauna area indicates that the mineralized bodies in which concentration of PGM are found above economic values. It has been observed that PGM occur in many hosts in varying concentrations at different deposits throughout the world [5]. In general, chromite, sulphides and silicates host PGM mineralization in most of the deposits. Talc schists and chlorite schists are the metamorphic products of peridotites with surrounding rocks. Therefore the PGM occurred in these schist rocks is primarily hosted in peridotite. Peridotite contains mainly olivine, orthopyroxene and amphiboles but sometimes sulphide mineralization is also found. Therefore probably these silicates and sulphides are the host of PGM. In boreholes the quartz vein encountered in the peridotite which is PGM, gold & silver rich indicate that this PGM is typically hosted by sulphides. The value of PGM is more in peridotites than the quartz vein indicating that probably PGM concentration is more in silicates than sulphide because peridotites contain less sulphide mineralization. The enriched zones in boreholes indicates that the value of PGM is decreasing with rock change such as highest value is found in peridotites then decreases in talc schist and increases in quartz vein again decreases in diorites.

Gneisses, granites and diorites are devoid of PGM although they are found in close contact with peridotites. This signature shows that PGM had not mobilized in these rocks although there is intense metamorphism and deformation, occurred in due course of time. Different host of PGM in the Ikauna area can be arranged in order of decreasing PGM content as follows peridotites>chlorite schists>talc actinoliteschists>quartz vein. The analyses of samples from different rocks of the Ikauna area indicate that the mineralization probably being hosted by peridotites and associated metamorphic rocks and high values of MgO, Fe_2O_3, Ni, Co and Cr indicate that PGM primarily carried by Mg rich magma.

Ultramafic rocks of Pindar area show high MgO, Ni,Cr, PGE and extremely low in Al_2O_3, CaO, K_2O and TiO_2. Extremely low abundances of HFSE, MREE, Zr,Y and high abundances of Ni, Co, Nd and Ir from the lherzolite, olivine websterite, dunite and harzburgite suggest high degree of partial melting, under S-undersaturated conditions from the juvenile mantle. The high MgO, Ni/Cu ratio, relatively low Pd/Ir ratio and Al_2O_3 indicate komatiite-peridotite affinity for the source rock. Petrographic study supported by geochemical data suggests that parent magma was enriched in PGE. The presence of granular aggregates of segregation of chromites, Ni sulphides and PGMs in the interstitial spaces of olivine cumulates, and along cleavages of pyroxenes is related to prevalence of S-saturation during cooling conditions. The presence of PGM in association

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with Fe-bearing phases (magnetite, pyrrhotite, chromite, etc.) or as disseminated sulphide minerals along with chromite indicate that FeO-rich phases were perhaps triggering the crystallization of the sulphide-rich phases in the magma during the cooling. Nearly similar conditions for the appearance of PGM in the matrices of olivine cumulates have been proposed for the ultramafic rocks of Madaura [49]. Similar kind of observation is found in Ikauna Ultramafic, which indicates that these ultramafics are genetically similar. PPGM is found generally higher than IPGM in Ikauna as well as Pindar area which enhance the economic importance of the Madaura-Ikauna-Pindar tract.

Ultramafic rocks of Madaura- Ikauna-Pindar tract's enrichment with PGM, Au and Ag give vital clue for crustal evolution of BC and the fundamental geochemical controls of platinum group of metals PGM and their formation and distribution in Earth's crust and to understand the characteristics of primary mantle derived magmatic processes. The magma of forming these ultramafic/mafic rocks emplaced from deeper level and also indicative of plume activity. These intrusive ultramafic/mafic rocks in Bijawar are economically important. Chakraborty et al. [61] have reported fluid induced metamorphism in mafic dykes of Mahakoshal Group of rocks indicative their association with the rifted margins. Bijawar and Mahakoshal Group of rocks are economically important for gold and PGM mineralization with mafic/ultramafic intrusives, those also confirms with their formation related to rifting. Both Bijawar and Mahakoshal Group of rocks are along contact of exposed BC with Vindhayan sediments in the northern part and at its contact with the Satpura Mobile Belt in the southern part indicative of two phases of almost contemporaneous magmatic activity. These mafic/ultramafic intrusives of Bijawar and Mahakoshal Group of rocks indicated that the related rift might have been caused by the Plume/ Superplume during Paleoproterozoic period. It is confirmed from the study of contemporaneous Cuddapah Basin [29].

Conclusion

The critical assessment ultramafic rocks of the Madaura-Ikauna-Pindar area indicate that the mineralization probably being hosted by peridotites and associated metamorphic rocks and high values of MgO, Fe_2O_3, Ni, Co and Cr indicate that PGM primarily carried by Mg rich magma. This similar kind of observation is found in Pindar peridotites [49] which indicate that these utramafics are genetically similar. The high values of PGM indicate that Madaura-Ikauna-Pindar tract has good potential to be a PGM deposit of Northern India. The high concentration of chalcophile elements indicates that ultramafic enclaves of BC may be rich with chalcophile elements like other Greenstone Belt.

Ultramafics of Madaura- Ikauna-Pindar tract's enrichment with PGM, Au & Ag gives vital clue for crustal evolution of BC regarding plume activity and rifting process. These mafic/ultramafic intrusives of Bijawar and Mahakoshal Group of rocks indicated that the related rift might have been caused by the Plume/Superplume during Paleoproterozoic period (1.9Ga) in Indian continent [29]. This rift and plume activities are responsible for sulphide mineralization and reworking of preexisting mass of the contact zone of BC. There may be some differences in the individual cases based on actual location of the plume/superplume of other basins and movement of cratons. The same plume might also be responsible for breakup of contemporaneous Columbia supercontinent [62] as similar contemporary magmatic rocks are also found in other parts of the world which formed the then supercontinent like North China, Baltica, Laurentia, Australia, Siberia and the Kaapvaal and Zimbabwe (South Africa) cratons [63].

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