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Platinum-group minerals from the Nuasahi ultramafic-mafic complex, Orissa, India

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THE Precambrian ultramafic-mafic complex of Nuasahi (21°16′N, 86°20′E), Orissa, in the Eastern Indian Shield is reported to contain economically significant amounts of the platinum-group elements (PGE), with Au and Ag in an Fe-Cu-Ni-Co-sulphide mineralized brecciated zone at the interface of the chromiferous ultramafites and gabbro. This is the first reported occurrence of four platinum-group minerals (PGM), sudburyite, michenerite, palladian-bismuthian melonite and irarsite from the chromite-sulphide assemblage of this sulphide mineralized area. The elongated north–south trending ultramafic and mafic rocks are emplaced within the metasediments and metavolcanics of the Iron Ore Group (3200 Ma, Saha *et al.*, 1988). A more or less stratiform sequence from ultramafic to mafic, olivine-websterite, dunite, harzburgite, chromitite, orthopyroxenite, norite, gabbro, anorthosite and titaniferous magnetite is preserved with a general north–south trend and easterly dip. Three chromitite horizons, the Durga lode, the Laxmi lode (Laxmi-2 and Laxmi-1) and the Shankar lode (from west to east) are being mined for chrome ores.

Sulphide mineralization and chromite-sulphide assemblage

The easternmost chromiferous horizon, i.e the Shankar lode, is highly disrupted with the formation of the northerly trending brecciated zone (7–15 m wide) extending over a length of 1 km along the strike and impregnated by the gabbro-noritic rock at the hanging-wall side. This zone is a heterogenous assemblage of differently oriented angular to subrounded blocks/fragments of massive, spotted and banded chromitite, serpentinite, coarse-grained pyroxenite, some hybrid rocks which are pervaded by the leucogabbro, dolerite and clinopyroxenite. Enrichment of sulphide is found in the matrix material of this zone with disseminated chromite

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crystals of relatively large size. Some magnetic chromites are also present in the matrix. Locally sulphides also occur as veins, stringers and concentrated pockets in the breccia zone. The hanging-wall gabbro-noritic rock (hybrid in character) invariably contains a significant amount of sulphides which are interstitial to the silicates. Sulphide mineralization is also found in the gabbroic rock of the eastern part but the amount diminishes gradually towards the east, i.e. in the gabbro regions *sensu stricto*.

The chromite-sulphide assemblage of the matrix part of the brecciated zone contains 1.37 ppm Pt, 8.81 ppm Pd, 6.63 ppm Ag and 0.31 ppm Au. In the same assemblage the Ni, Cu and Co contents are 10015 ppm, 25101 ppm and 335 ppm respectively. (The analyses were done by ICP-MS using the following geostandards for noble metals SABS-South Africa, CH1-copper-silver-gold-bearing sulphide ore typical of the Campbell-Chibongaman mine of Chibongaman, Quebec and Matte PTM-1 produced from Sudbury ore, provided by Falconbridge Nickel Mines Limited). The key features of this chromite-sulphide assemblage are as follows:

(1) Very often the assemblage shows chromite-dominated and sulphide-dominated areas. In places, silicate-rich areas occur between these two. In sulphide-rich areas chromite grains occur as rounded to subrounded cumulates enclosed within a sulphide-silicate matrix. In other types of chromite-sulphide assemblage, chromite grains are dispersed all over the sulphide-rich matrix. The dispersed chromite grains are often rimmed by a silicate phase (clinochlore). Zoned plagioclase with a concentric rim of sulphide (both chalcopyrite and pyrrhotite) at the zonal boundary, are found in the sulphide-rich area. Chalcopyrite, pyrrhotite and pyrite are the dominant sulphide minerals in the assemblage with millerite and bornite as local concentrations. Cobaltite-gersdorffite are mostly found in the sulphide-rich part of the assemblage and poikilitically included within the chalcopyrite-rich matrix. In places, tongues of surrounding chalcopyrite have encroached into the cobaltite-gersdorffite euhedra.

(2) Two types of chromite grains are found in the sulphide-rich part of the assemblage. The coarser variety contains a large number of highly irregularly shaped inclusions of sulphides, silicates and oxide phases with platinum group minerals. The finer variety of chromite does not contain such phases except some tiny inclusions of oxides. The coarser chromite grains often show a 'fused together' texture where two or more chromite grains are joined at their margins forming a composite grain. This composite chromite grain shows selective concentration of included phases in different parts.

(3) Among the included sulphides, chalcopyrite in general is more abundant than pyrrhotite. Very often in one composite chromite grain the sizes of the inclusions are highly variable, e.g. in one part sulphides are much larger while in another part of the same chromite grain they are finer and wormlike. Moreover, an inclusion-free area in the same chromite grain is also evident. In places the relationship between included sulphides and silicates with the host chromite appears to be highly reactionary – both silicate and sulphides have reacted with the host chromite, often retaining some islands of relict chromite.

Platinum-group minerals (PGM)

The polished thin sections, polished sections and thin sections of the sulphide mineralized samples were studied under the microscope (both in transmitted and reflected light). The suspected PGMs were confirmed in two samples in an SEM-EDS study using a Cambridge Leica stereoscan 440 model scanning electron microscope, equipped with EDS, with a SiLi detector. The system detector resolution was 63 eV and ZAF online data correction was used. The SEM-EDS analytical data for PGM always produce totals much less than 100% but the ratios of the constituent elements for each of the minerals are in proportion and the data have been normalized to 100%. These semiquantitative data permit the minerals to be identified. These data are compared with the various published data for different PGMs.

In Nuasahi the PGM have so far been identified only in the chromite-sulphide assemblage of the sulphide mineralized zone. Four PGMs, sudburyite, michenerite, palladian-bismuthian melonite and irarsite (in decreasing order of abundance), are reported here with their optical and chemical characters and textural relations with the associated phases.

Sudburyite (PdSb). Of the four identified PGMs in the chromite-sulphide assemblage, sudburyite is the most abundant and always found to be included within coarser chromite grains (Fig. lA). The grains are very much irregular in shape and locally show sharp contact with the associated chalcopyrite and pyrrhotite as well as with the host chromite. Some chromite grains enclose as many as 10 differently sized sudburyite grains. The mineral is cream yellowish white in air with a well polished surface. It is distinctly anisotropic, in shades of yellowish to reddish brown. The reflectance is much higher than that of chalcopyrite and pyrrhotite.

The microprobe analyses for four sudburyite grains show that its Pd content is ~41 wt.% and the Sb content is approxiniately 48 wt.%. Besides Pd and Sb it contains Ag (up to 3 wt.%), Fe (up to 2 wt.%), Ni

(1 wt.%), Te (up to 9 wt.%) and Bi (up to 3 wt.%). Sudburyite occurs in Ni-Co arsenide- and sulpharsenide-rich parts of Ni-Cu sulphide deposits in the Sudbury, Ontario area and at the 'Y' deposit, S.W. China, which is serpentinite-hosted (Cabri, 1981). In Sudbury, sudburyite occurs as small, often elongated inclusions in either sulpharsenides or arsenides and is also closely associated with breithauptite, galena, nickeline and chalopyrite (Cabri and Laflamme, 1974). In this occurrence, Ni replaces the Pd by amounts up to 8.7 wt.%, possibly even up to 10.3 wt.% and often influence the reflectance. Minor amounts of Bi, As and Te replace the Sb. Microprobe analyses of sudburyite from Wellgreen Cu-Ni-Pt-Pd deposit, Yukon, Canada (mostly included in gangue, magnetite, chalcopyrite and pyrrhotite), show that by up to 3. 1 wt.% Ni replaces Pd, and up to 22.2 wt.% Te and 11.2 wt.% Bi replace Sb (Cabri *et al.*, 1993)

Michenerite (PdBiTe). The grains are subhedral to euhedral and mostly included within chalcopyrite of the sulphide-silicate matrix of the chromite-sulphide assemblage (Fig. 1B). Five grains have been identified so far from the assemblage. In one instance it occurs within vein pyrrhotite along with melonite and an unnamed AgBiTe-bearing phase. Michenerite is cream white in air with a well polished surface. Anisotropy is very weak – in shades of dark bluish grey. Michenerite is the principal palladium PGM in Cu-Ni sulphide deposits worldwide but rare in the Merensky Reef (Bushveld Complex) and has not

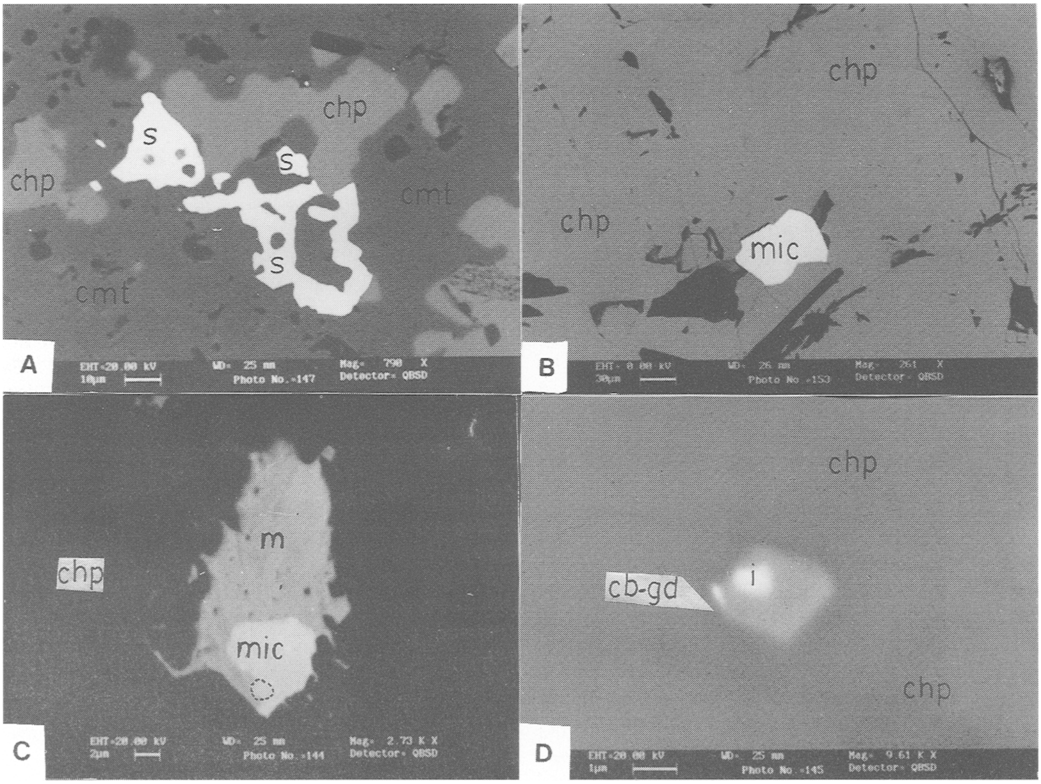

FIG. 1. Scanning electron microscope (SEM) photomicrographs of the PGMs in chromite-sulphide association of Nuasahi ultramafic-mafic complex, Orissa, India: (A) sudburyite (S, white) inclusion within chromite (cmt). The associated sulphides (light grey) are of chalcopyrite (chp). The dark grey areas represent the chromite groundmass (scale bar: 10 µm); (B) michenerite (m, white) crystal included within chacopyrite (chp, light grey). the black areas represent mostly tremolite/ferro-tremolite crystals (scale bar: 30 µm); (C) melonite (m)-michenerite (mic) association included within the chalcopyrite (chp) groundmass. The encircled portion represents an AgBiTe-bearing phase (scale bar: 2 µm); (D) irarsite (i) crystal included within a euhedral crystal of cobaltite-gersdorffite (cb-gd) which is further included within chalcopyrite (chp) groundmass (scale bar: 1 µm).

been reported from the Stillwater Complex, Montana, or the Lac des Iles deposit, Ontario, (Cabri, 1981). Cabri *et al.* (1973) described michenerite from the Vermillion mine and from the Frood mine of Sudbury, Canada, as creamy white grains and isotropic mineral. Michenerite was found in samples from all mines of Sudbury except Falconbridge, as studied by Cabri and Laflamme (1976) and appeared to occur as the principal palladium mineral of the Sudbury deposits. They described the mineral as creamy-white grains with a tinge of grey, and isotropic, but a sample from the Victoria mine (Mu 00238) contained anisotropic michenerite. In the Sudbury ore, michenerite is most frequently observed as inclusions in non-platinum group minerals, especially in chalcopyrite (Cabri and Laflamme, 1976)

Our analytical data for michenerite show that its Pd content is ~23 wt.%, Te 35 wt.%, Bi ~26 wt.%, and Sb ~12 wt.%. Besides these it contains Pt (up to 1 wt.%), Ag (up to 3 wt.%), Fe (up to 2 wt.%), Cu (up to 1 wt.%), Pb (up to 3 wt.%) and Ni (up to 1 wt.%). The Fe and Cu values may be due to the interference of matrix chalcopyrite during analyses.

Palladian-bismuthian melonite $[(NiPd)(TeBi)_2]$. Melonite is a mineral of Ni and Te but Pd has been reported to replace Ni in melonite (Cabri, 1981). In Nuasahi it is found to occur in the chalcopyrite groundmass of the chromite-sulphide assemblage along with michenerite and an AgBiTe-bearing, small rounded phase (Fig. 1C). Melonite occurs as large irregular bodies and is associated with a fracture-filling vein pyrrhotite. The mineral is bright yellowish white in air and very light cream-yellow in oil. The reflectance of melonite is higher than that of associated michenerite. It is anisotropic in shades of bluish grey to brownish grey. The analysis shows that the mineral contains about 14 wt.% Pd and 8 wt.% Bi besides the major constituents, i.e. Ni and Te. Its Ni content is about 8 wt.% and its Te content is ~70 wt.%. The published data for the melonite from Sudbury Ore, Crean Hill, Ontario show the Pd content to range 9.1–12.7 wt.% and the Bi content 5.6–16.5 wt.% (Cabri and Laflamme, 1976). The small rounded grain of AgBiTe in this assemblage, contains about 21 wt.% Ag, 28 wt.% Bi and 47 wt.% Te with minor Fe, Ni and Cu.

Irarsite. The mineral has been found included within larger cobaltite-gersdorffite euhedra (Fig. 1D) in the sulphide-rich area of the chromite-sulphide assemblage. It is an intermediate member of the hollingworthite (RhAsS)–irarsite (IrAsS) series with Ir > Rh (Ir ~18 wt.% and Rh ~12 wt.%). Its As content is about 21 wt.% and S content is ~22 wt.%. The analysis shows the presence of Fe (~8 wt.%), Co (8 wt.%), Ni(4 wt.%) and Cu (~8 wt.%) besides the major constituents. The mineral irarsite is common as minor inclusions in samples from the former Driekop and Onverwacht mines, Transvaal. It is also found in Pt-Fe alloys associated with Uralian- and Alpine-type ultramafics, again as very small inclusions in Cu-Ni sulphide ores at Werner Lake and Sudbury, Ontario; Pipe mine, Manitoba; and Hitura, Finland (Cabri, 1981).

Discussion

The occurrence of PGE in ultramafic-mafic rocks and their genetic relation with magma have now become a thrust area in the field of exploration and economic geology. The Nuasahi chromite deposit is one of the largest chromite deposits in India and has been mined for chromite by different entrepreneurs for the last four decades. Geological investigation has long been concentrated on the different petrological, chemical and ore genetic aspects of chromite mineralization. As research is in progress to find the petrogenetic history of the ultramafic-mafic complex, we are not able yet to characterize the chromite deposit of Nuasahi.

Chromitite in association with sulphides has already been proved to contain significant amounts of PGEs, e.g. Bushveld UG-chromitite, MG-chromitite, UG2-chromitite and the A-horizon of the Stillwater complex (von Gruenewaldt *et al.*, 1986; Naldrett and von Gruenewaldt, 1989). Petrogenetically, the chromite-sulphide assemblage of Nuasahi is very important in view of its complex mineralogical assemblage and textural features. The textural features in the chromite-sulphide assemblage and the paragenetic relation between the included phases (silicates, base metal sulphides PGM and oxides) are complex. Moreover, the enormous number of inclusions within a single chromite grain and their highly irregular shape also differ from the other occurrences. Another important feature is the presence of a reasonable number of sudburyite grains included within the chromite. Silicate, base metal sulphides and PGMs in chromite are reported in several ultramafic-mafic intrusions of ophiolites, Alpine-type peridotites and stratiform complexes (Augé, 1986; Augé and Maurizot, 1995; Lorand and Ceuleneer, 1989; McElduff and Stumpfl, 1991; Gervilla and Leblanc, 1990; Hurlbert and von Gruenewaldt, 1985; von Gruenewaldt *et al.*, 1986; Talkington and Lipin, 1986). The close relationship between chromite and the Ir-group of PGEs (Ir, Os, Ru) is well documented in the occurrences noted above but the chromitites which contain sulphides are also enriched in the Pd-group of PGEs (von Gruenewaldt *et al.*, 1986; Naldrett and von Gruenewaldt, 1989).

The sulphide mineralized zone with PGE concentration in the Nuasahi complex is characterized by:

(1) a prominent brecciated zone; (2) pegmatitic mineralization; and (3) localization at the interface of the chromiferous ultramafic unit and a younger chromite depleted mafic unit. The Fe-Cu-sulphide minerals are the dominant phases over the Ni-sulphide minerals and in the chromite-sulphide assemblage, the Ni/Cu ratio is 0.39. Mafic magma commonly produces Ni-Cu-sulphides rich in Cu and PGE with Ni/Cu ratios <2 as shown by Chai and Naldrett (1992). The high Pd content over Pt, which is well documented by the Pd-bearing PGMs, and high Ag content in chromite-sulphide assemblages suggest the lineage with a fractionated melt. The reaction textures, the large number of included phases, fusing of chromite grains with selective concentration of the included phases, and the silicate reaction rim around chromite grains all suggest a post-crystallization modification of earlier crystallized chromites by a sulphide-rich melt which was possibly derived from the gabbroic magma at high *T*, enriching the PGEs in the sulphide mineralized area.

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