

Review Article

Metallogeny

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This article briefly reviews all contributions by Indian geoscientists in the period 2011–2016 in the field Metallogeny. The contributions covered are mainly on deposits and prospects of chromite, PGE, gold and uranium. Very few contributions have been made on base metals. However, experimental sulfide phase equilibrium research, related to metamorphic remobilization of massive sulfides, has been initiated.

Keywords: Metallogeny; India; Research

Introduction

Three review articles on various metallogenic aspects were published during the report period. Deb (2014) wrote an exhaustive review on Precambrian geodynamics and metallogeny of the Indian Shield *vis-a-vis* formation of three Precambrian supercontinents, i.e., Kenorland, Columbia and Rodinia. While Deb and Pal (2015) reviewed the mineral resources of Proterozoic intra-cratonic basins, the article by Mishra (2015) is on the Precambrian metallogeny of India. Scrutiny of the published work reveals lack of significant studies on metallogeny of Fe and Mn. On the other hand, metals such as Cr, PGE, Au and U continued their earlier momentum. As pointed in the last report, unlike countries like Australia, Canada and South Africa, industry-academia interaction, an extremely valuable component in ore deposit research, is still missing. This compilation incorporates all the published work on Indian metallic ore deposits. If some work is missed out, the author expresses regret for such inadvertent omission.

Chromite and PGE Ores

Ghosh and Konar (2011) calculated the parental melt composition of Sittampundi chromitites and concluded that the Al₂O₃ content is consistent with that of the MORB, where as the higher FeO/MgO ratio is

suggestive of initial mafic melt underwent fractional crystallization to form a Fe-Al-rich melt from which chromitite crystallized. Dutta *et al.* (2011) identified three textural types of chromite in the Sittampundi Complex. These are: (i) cumulus grains in chromitite layers; (ii) disseminated grains in clinopyroxenite and anorthosite; and (iii) small grains included in clinopyroxenes and plagioclase. Chromites in these textural settings preserve distinctive chemical compositions; the most striking being metasomatic alteration of chromite to green spinel. Fe-Al rich compositions of chromite and high calcic nature of plagioclase in host anorthosite are attributed to H₂O- and Al₂O₃ rich nature of the parental melt that was generated in an oceanic arc setting. A mineral-chemical study (Dharma Rao *et al.*, 2013) on chromites in the Sittampundi anorthosite reveals Fe-Al-rich nature of chromites, strikingly different from those of stratiform intrusives such as Bushveld and Stillwater, but similar to the anorthosite-hosted chromitites in the Fiskenaesset complex, Greenland.

Sm-Nd isotopic studies on the chromite-bearing mafic-ultramafic rocks of the Nuggihalli greenstone belt yielded a whole-rock age of 3125±120 Ma and an average ϵ_{Nd} (3.1 Ga) value of +2.7. These results along with the measured low ⁸⁷Sr/⁸⁶Sr value of 0.70096–0.70111, for the gabbro, point towards derivation of the parental magmas from a depleted

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mantle source (Mukherjee *et al.*, 2012). Further, these authors hypothesize formation of the Mesoarchean greenstone-hosted Nuggihalli chromite deposit related to amalgamation of a supercontinent. In another geochemical study of chromitites and greenstones of the Nuggihalli belt, Mukherjee *et al.* (2014) observed immobile nature of most of the trace elements, including the PGEs. The PPGE (Pd, Pt, Rh)-enriched PGE pattern in magmatic rocks other than chromitites and serpentinites, is interpreted because of early IPGE (Ir, Os, Ru) fractionation in chromites. High PGE abundance in chromite is attributed to inclusions of IPGE minerals (laurite and other IPGE-bearing sulfarsenides). Sulfide saturation in the ultramafic melt was perhaps prompted by fractional crystallization of early formed silicates/chromite and followed by segregation of immiscible sulfide melt without any crustal contamination.

Based on the Cr# and Mg#, the restitic peridotite of the Andaman ophiolite complex, four types of chromian spinels were identified. These include those with high and relatively lower Cr# respectively formed from boninitic and basaltic melts with varying extents of partial melting. Further, chemical compositions of the chromian spinels reflect diverse tectonic setting for their peridotitic hosts apart from melt-rock interactions and melt mixing/mingling (Ghosh *et al.*, 2014). The deduced parental melt of the high-Cr podiform chromitite in the Andaman ophiolite had 12–13 wt. % Al_2O_3 and 0.2–0.5 wt. % TiO_2 and the same for the low-Cr chromitites was 16 wt. % Al_2O_3 and 0.5–0.9 wt. % TiO_2 (Ghosh and Bhatta, 2014). Geochemical investigation of a mafic intrusive in the Khasi Hills, Shillong Plateau reveals relative enrichment of PPGE compared to the IPGE. From discrimination plots of REEs, PGEs and other trace elements, Hazra *et al.* (2015) proposed generation of the parental mafic melt by columnar batch melting (up to 25 %), involving dehydration, wedge-melting and assimilation fractional crystallization process at a continental margin arc setting.

Jena *et al.* (2016) identified various platinum group minerals (PGM) such as sudburyite, laurite, sperrylite, braggite, merenskyite, hollingworthite, testibiopalladite, michenerite, malanite, isoferroplatinum in the chromite-base metal sulfide association within the Bangur gabbro at Baula-Nuasahi area, Odisha. The PGMs occur as inclusions

in chromite, at the silicate-chromite grain boundaries, and within base metal sulfides (mainly chalcopyrite, pyrrhotite, pentlandite). Due to their micron-scale size nature and varying hosts (chromite, silicate and sulfide), these authors propose a combination of beneficiation methods for PGE recovery. Mishra and Hazarika (2016) reported occurrence of rare greenockite (CdS) associated with chromite-PGE in the Bangur gabbro of the Baula-Nuasahi mafic-ultramafic complex in eastern India. The greenockite occurs in siderite-chlorite micro-vein without any precursor Cd-bearing phase. The associated chalcopyrite contains high Cd, which is considered as the source for greenockite. Transport of Cd as bisulfide complex in a low temperature alkaline and reducing fluid led to concurrent precipitation of greenockite and siderite postdating the PGE mineralization by reaction with Fe-rich minerals, assisted by decrease in pH and/or increase in $f\text{O}_2$.

High MgO mafic volcanics of the Bababudan and the Gadwal greenstone belts, respectively in the western and eastern Dharwar Craton have been geochemically classified as komatiites and boninites respectively. While the Bababudan komatiites have low ΣPGE (9–42 ppb), the Gadwal boninites are characterized by high ΣPGE (82–207 ppb). Such contrasting PGE abundance is interpreted due to fractionation of olivine and chromite/sulfide respectively from the parental komatiitic and boninitic melts. The S-undersaturated character of Bababudan komatiites is attributed to decompression and assimilation of lower crustal materials during magma ascent and emplacement. On the contrary, geochemical features such as higher Al_2O_3 and Pd contents, lower Cu/Pd (Gd/Yb)_N values, and negative Nb-, Zr-, Hf, Ti anomalies of the boninites imply high degree of H_2O saturated melting of the refractory mantle wedge, wherein influx of subduction-derived fluid and sulfide retention in the residual mantle were the causative factors for their S-under saturated nature (Saha *et al.*, 2015).

According to Singh *et al.* (2013), the total PGE contents in the peridotites of the Manipur Ophiolite Complex (MOC) vary from 22.2 to 79.3 ppb, which is slightly higher than those of primitive mantle peridotites, and the Alpine-type mantle peridotites. Their variable mantle-normalized PGE patterns along with the observed Pd/Ir values (1.7–11.42) and Pt/

Pt* values (0.26–1.40) are characteristic of residual mantle material. PGE concentrations of both the high-Al and high-Cr chromitites of the MOC are low (<600 ppb) and have similar chondrite-normalized PGE patterns. Further, the low PGE content in these chromitites may be a reflection of lack of S-saturation of the parental magma during early stage crystallization. Variation in PGE abundances, Pd/Ir and Pt/Pt* ratios suggests that inhomogeneous PGE distribution, probably as a consequence of random occurrence of PGM inclusions in the chromitites.

The ultramafic-mafic rocks in the Mesoarchean Nuasahi Massif formed from two magmas. While the lower ultramafic unit formed by fractional crystallization of a boninitic magma, the upper gabbros formed from mixed magmas. The fractionated fluid-rich mixed magma intruded into the shear zone forming the pegmatitic gabbroic matrix and also introducing base-metal sulfides and PGE mineralization within the breccia zone. (Khatun *et al.*, 2014). The 3.1 Ga IOG mafic volcanics from the Jamda-Koira Iron Ore basin of the Singhbhum Craton and Paleoproterozoic Malangtoli volcanics respectively exhibit calc-alkaline and tholeiitic to calc-alkaline compositional characters, in spite of greenschist to lower amphibolite facies metamorphic overprinting. PGE abundance in the IOG volcanics was controlled by sulfide fractionation whereas that in the Malangtoli samples is ascribed to chromite and sulfide fractionations. The S-saturated, PGE depleted character of the IOG volcanics implies low degrees of partial melting and crustal contamination. Variable degrees of partial melting and crustal contamination account for the S-saturated to under saturated nature of the Malangtoli basalts having a wide variation in their PGE content (Singh *et al.*, 2016).

Dora *et al.* (2011) reported occurrence of PGMs and gold in association with Fe-Ni-Cu sulfides and chromite in gabbro-pyroxenite rocks in the Gondpipri area, Western Bastar Craton. On the basis of SEM-EDS analyses, the PGMs have been identified as moncheite and Pd-moncheite. In another recent study, tsumoite (BiTe) and other PGMs (moncheite, merenskyite, Pd-mellonite, and Pf-Pd-Te-Bi-Fe-S alloy) have been identified (Dora *et al.*, 2014) to occur with Ni-Cu sulfide mineralization in the Gondpipri mafic-ultramafic complex. Mineralization comprises magmatic stage (pentlandite + pyrrhotite ±

chalcocopyrite) involving sulfide liquid immiscibility and a later remobilization of the PGEs by a metamorphic fluid leading to precipitation of PGMs under varying fugacities of S₂, Te₂ and Bi.

Gold

Hazarika *et al.* (2015) undertook monazite U-Th-Pb_{total}/CHIME dating and rigorous P-T pseudosection analyses for two rich gold provinces in India, i.e., the Hutti-Maski greenstone belt (HMGB) and the south Kolar greenstone belt (SKGB) to assess their geochronological and metamorphic evolution. The timings of felsic volcanism are constrained at ca. 2669 ± 22 Ma and 2661 ± 32 Ma for the HMGB and the SKGB respectively. While the HMGB rocks experienced mid-amphibolite facies metamorphism at ca. 2564 ± 12 Ma with peak P-T of < 6 kbar and < 620°C, the SKGB rocks underwent a lower amphibolite facies metamorphism at ca. 2546 ± 12 Ma and the peak P-T reached < 4.6 kbar and < 600°C. A pervasive post-peak metamorphic K-rich fluid alteration event is recorded at ca. 2414 ± 18 Ma in the HMGB, which is similar to a post-metamorphic shear-induced hydrothermal activity at ca. 2414 ± 26 Ma from the SKGB. These two late Archean greenstone belts are < 100 Ma younger and witnessed a higher grade of metamorphism than their counterparts in the Abitibi province and the Yilgarn Craton.

Primarily on the basis of calculated $\delta^{18}\text{O}_{\text{fluid}}$ values, two stages of alteration and gold mineralization have been proposed by Rogers *et al.* (2013) for the world class orogenic gold deposit at Hutti. Fluid derived by metamorphic devolatilization of the greenstones was responsible for proximal biotite-K-feldspar alteration and gold mineralization. The second stage of mineralization comprises the major auriferous laminated quartz vein, for which lighter O-isotopic values ($\delta^{18}\text{O}_{\text{fluid}} = 3.6\text{‰}$) were obtained. Such lighter fluid O-isotopic signature is interpreted by Rogers *et al.* (2013) to have resulted by mixing of granite-derived- and formational fluids.

An integrated EPMA-LA-ICP-MS study concerning analysis of major, REEs, and selected trace elements in texturally constrained tourmalines from alteration zones at Hutti and Hira-Buddini was undertaken, in order to compare and evaluate possible fluid sources related to tourmaline precipitation during

gold mineralization (Hazarika *et al.*, 2015). Similarity in tourmaline compositions with evolutionary trends in compositional space from different textural associations suggests that a single low-salinity and reduced metamorphic fluid, with inherently low ΣREE , was responsible for proximal alteration and gold mineralization at Hutti. The type I and type II tourmalines from Hira-Buddini display oxydravite-povondraite trends, with compositional overlap that suggests fluid mixing at a paragenetically early stage. The early hydrothermal fluid was more saline, oxidizing, and had a granite-derived component with high ΣREE contents. A later evolved, relatively low-salinity and reduced fluid is recorded by the last generation (type III) tourmalines at Hira-Buddini.

An exhaustive LA-ICP-MS study involving analysis of REE- and other important trace elements in scheelite, apatite, and calcite in two mineralization stages of Hutti was recently attempted by Hazarika *et al.* (2016). Scheelite displays three types of REE patterns, which include (i) type-I MREE-enriched with negative Eu-anomaly (stage-1), type-II HREE-enriched with minor positive/negative Eu-anomaly, and type-III varying from slightly MREE-enriched to MREE-depleted with correspondingly increasing positive Eu-anomaly (stage-2). The occurrence of minute MREE-enriched scheelite grains in the stage-1 mineralization assemblage is attributed to high ambient temperature (475°C), while abundant scheelite precipitation during stage-2 was aided by decrease in temperature (~300°C) and further abetted by fluid pressure fluctuations due to fault-valve action. The MREE-depleted patterns of stage-2 scheelites, do not necessarily indicate a precipitation from a different fluid, but are due to rapid MREE removal in early formed scheelites. The close system REE behavior is further supported by REE conservation in the altered rocks. Tourmalines from both the stages have low contents of Na, LILEs, HFSEs and comparably low $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratios, suggesting analogous nature of the two fluids of metamorphic parentage, contrary to the proposed two-fluid model of Rogers *et al.* (2013).

The granodiorite-hosted Au mineralization at Jonnagiri is associated with greenstones that underwent amphibolite grade metamorphism with a peak P-T conditions at ~5 kbar and 500°C. Hydrothermal alteration is manifested by a chlorite +

biotite-rich proximal zone and a muscovite-dominant inner zone, comprising laminated auriferous quartz veins. While the proximal zone had significant addition of S, C, K, Si, and Rb and depletion of Ca, Mg, and Fe, the inner alteration zone is characterized by addition of Si, K, S, C, and Au. Overall REE depletion in the altered granodiorites was a consequence of high fluid/rock during hydrothermal alteration. Gold occurs as fracture fillings in the quartz and pyrite grains, together with other sulfides. A temperature (and $\log f\text{S}_2$) range of 305° to 335°C (and -10.9 to -8.6) is obtained from arsenopyrite compositions in the $f\text{S}_2$ -buffered pyrrhotite-pyrite-arsenopyrite assemblage. From the published $\delta^{34}\text{S}$ values in pyrite, the calculated $\delta^{34}\text{S}_{\text{H}_2\text{S}}$ varies from 0.2 to 5.8 ‰, at $\log f\text{O}_2 = -32.6$ and $\text{pH} = 5.15$ to 5.95, which imply that $\text{Au}(\text{HS})_2^-$ was the dominant gold complex. The narrow range of $\delta^{34}\text{S}_{\text{py}}$ values point to magmatic (\pm mantle) source, or involvement of fluid with an average crustal sulfur composition. Gold precipitation was a consequence of post-peak metamorphic fluid phase separation involving immiscibility of gaseous species, fluid-rock interaction, and decrease in $f\text{O}_2$ of the ore fluid (Chinnasamy and Mishra, 2013).

Deol *et al.* (2012) undertook a combined LA-ICP-MS and EPMA study on Fe sulfides and sulfarsenides from the Bhukia-Jagpura gold prospect, southern Rajasthan. Based on texture and chemical compositions four types of pyrite and two arsenopyrite varieties have been identified. While the early two pyrite types lacking gold were of sedimentary-diagenetic nature, the later minor Au-bearing pyrites were interpreted to be of hydrothermal origin. Löllingite and arsenopyrite-I contained higher invisible gold contents of 35–51 ppm and 0.28–10 ppm respectively. Based on pyrite with higher Co:Ni ratio and presence of Co-rich löllingite and Au-Bi-Te phases (maldonite and wehrlite, native Bi), a pre- to syn-metamorphic magmatic hydrothermal origin is proposed for the Bhukia gold-sulfide prospect.

Gold mineralization occurring along the Moyar-Bhavani shear zone (MBSZ) in the Southern Granulite Terrain at Wynad-Nilgiri, Malappuram and Attappadi has been reported by Sahoo *et al.* (2016). The Au-bearing quartz veins, along with muscovite-calcite-ankerite-chlorite-biotite-pyrite alteration, occur within the biotite/hornblende bearing gneisses and amphibolite. Fluid inclusion microthermometry in vein

quartz reveals low salinity, aqueous-carbonic fluid which underwent phase separation. Rb-Sr and Sm-Nd isochrons of hydrothermal muscovite and calcite yield an age of ca. 450 Ma for the vein formation, which indicates extensive fluid influx during Pan-African orogeny along the MBSZ. Gold precipitated from such $\text{H}_2\text{O}-\text{CO}_2-\text{CH}_4-\text{Au}(\text{HS})_2^-$ fluid as a result of phase separation and fluid-rock interaction.

From $\delta^{13}\text{C}_{\text{PDB}}$ and $\delta^{18}\text{O}_{\text{SMOW}}$ values in carbonates Sarangi *et al.* (2012) obtained average fluid $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ compositions of -5.81 ± 1.14 ‰, 13.78 ± 5.1 ‰ for the Ajjanahalli and -4.64 ± 0.7 ‰, -6.50 ± 0.6 ‰ for the Guddarangavvana Halli gold prospects in the western Dharwar Craton. These isotopic compositions are interpreted as juvenile magmatic source of the ore fluid. Recently Swain *et al.* (2015) undertook a C- and O-isotopic study of carbonates in auriferous quartz-carbonate veins from various mines in the Gadag Gold Field, western Dharwar Craton. The calculated fluid $\delta^{13}\text{C}_{\Sigma\text{C}}$ compositions for these deposits range from 2.1 to 9.6 ‰ and $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ from 6.8 ‰ to 25.9 ‰, respectively. The above authors argued that these calculated C-isotopic compositions could not have resulted by metamorphic devolatilization of greenstones; they rather reflect mantle/magmatic derived CO_2 or carbonates. However, it is worth noting that the C-isotope compositions of carbonates act as tracers of carbon, not of the ore fluid (see McCuaig and Kerrich 1998). Petrographic, SEM-EDS and EPMA studies reveal occurrence of nano sized Au grains within two generations of pyrites at the Babaikundi area in the North Singhbhum Mobile Belt (Jha *et al.*, 2015). The occurrence of the invisible lattice bound gold within pyrite may be a result of the substitution reaction ($\text{Fe}^{+3} \leftrightarrow \text{Au}^{+3}$). Presently gold nanoparticles have low metallurgical implications but with the growing advancement and increased usage in photonic, electronic and biomedical instruments they may be considered significant for further investigations.

Turbidite-hosted auriferous quartz veins occur along the en-echelon shear planes, fractures and schistosity planes and are surrounded by the altered wall rocks in the Gadag greenstone belt (Ugarkar *et al.*, 2016). The auriferous zone comprises quartz, ankerite, chlorite, sericite, carbonaceous matter, with

minor plagioclase, monazite and xenotime. The associated ore minerals are arsenopyrite, pyrite, pyrrhotite, chalcopyrite, sphalerite, galena, scheelite; and gold occurs within quartz and arsenopyrite. LREE-enriched ($\text{La}_\text{N}/\text{Yb}_\text{N} = 9.54$) REE pattern of altered wall rocks with prominent negative Eu anomaly indicate differential response of the host rock and intensity of alteration depending on the composition of the host turbidites and hydrothermal fluids. The ore fluids were of low salinity (2.0 to 6.6 wt. % NaCl) with 30 mol % CO_2 , and gold precipitation occurred over a wide temperature range (175 °C–325 °C), as a result of fluid mixing, phase separation and redox reactions.

On the basis of textural and chemical features, four pyrite types were identified from the sediment-hosted gold deposit at Kundarkocha, Singhbhum Craton (Hazarika *et al.*, 2013a). Fine grained early framboidal pyrites in the carbonaceous phyllite host possess lower Co, As contents but higher Au values. Pyrite of next generation has lower contents of Co and Ni, moderate As values; the highest mean value of invisible gold and maximum concentrations of trace elements such as Li, Ti, Zn, Rb, Sr, Y, Zr, Nb, La, Ce, Ta, Th, U and Cr. Pyrite of the third generation, which overgrows pyrite-II has moderate contents of Co, high Ni and low Au values and higher concentrations of LILEs, but lesser amount of HFSEs. Pyrites of the latest type occur as polycrystalline aggregates that contain inclusions of gold, sulfides/silicates, show oscillatory zoning of Co and As and the lowest concentrations of all other trace elements. Successive decrease in trace element contents in later pyrites is attributed to fluid-assisted recrystallization during diagenesis and low grade metamorphism. Pyrite-II through pyrite-IV has higher Au contents regardless of their As values, point to presence of invisible gold mostly as nanoparticles, with a maximum value of 500 ppm. While majority of trace elements underwent large-scale remobilizations, Au was somehow locked up in pyrite resulting in a rather lean deposit at Kundarkocha. Based on textural and chemical criteria, Sahoo *et al.* (2015) identified three generations of pyrite and arsenopyrite the Kundarkocha deposit. From EPM analysis, the Au content of pyrite and arsenopyrite turned out to be 600–2700 ppm and 900–3600 ppm respectively.

Uranium and REE

Pal and Rhede (2013) combined chemical, textural and geochemical criteria with in-situ EPMA dating of uraninite to constrain the timing of mineralization and its response during subsequent hydrothermal events at the Jaduguda uranium deposit in the Singhbhum Shear Zone (SSZ). The study indicates that the uranium mineralization represented by trace element-depleted uraninite is dated at ca. 1.80 to 1.9 Ga, which compares well with the previously reported Paleoproterozoic magmatic and hydrothermal events at ca. 1.8 to 2.0 Ga. These uraninites underwent two subsequent events of fluid-assisted alteration. These are: (i) HREE influx into the mineralized zone resulting in Ca, Fe, and REE enrichment at ca. 1.66 Ga, and (ii) pervasive removal of trace elements from uraninite at ca. 1.0 Ga.

According to Thomas *et al.* (2014), several lines of evidence indicate operation of hydrothermal activity, represented by fracture filled quartz-epidote and quartz-chlorite veins, within both basement granite and the cover sediments in Koppunuru and Rallavagu Tanda uranium prospects of the Palnad sub-basin. Fluid-rock interaction during the formation of these veins has resulted in alteration of feldspars/mafic minerals of granite and arkosic quartzite into an alteration assemblage comprising illite, chlorite, muscovite and pyrite. Source of hydrothermal fluid was basinal brine that circulated through basement granite and cover sediments and was responsible for mobilizing uranium from the granite and its precipitation at appropriate locations in the cover sediments. Causative factors for U precipitation were increase in ore fluid pH due to illitization and chloritization of wall rock, supplemented by availability of carbonaceous matter and pyrite that acted as reductants. Compositional characteristics of uraninite within the Mahagiri Quartzite (Singhbhum Craton) such as elevated Th content and high Σ REE content indicate high temperature magmatic source. The chemical formulae of the uraninite imply multiple source population and variations in oxidation states. Presence of detrital uraninite indicates existence of highly felsic and K-rich granodiorite-granite-monzogranite suites of rocks older than 3.1 Ga in the Singhbhum craton (Mukhopadhyay *et al.*, 2016).

An integrated textural-chemical study of magnetite from the Banduhurang U deposit (SSZ) by

Ghosh *et al.* (2013) reveals hydrothermal precipitation of the mineral on an earlier high Cr-Ti-bearing magmatic core. Hydrothermal magnetite-apatite mineralization started prior to or early in the evolution of the SSZ, which was perhaps associated with Cu-sulfide mineralization. Magnetite that grew at the mid to late-stage of shearing perhaps was not associated with sulfide mineralization. The last stage of magnetite formation post-dated deformation and most likely formed by recrystallization of existing magnetite or formed by metamorphism of Fe-rich protolith. A combined fluid inclusion petrographic-microthermometric study by Pal and Bhowmick (2015) in apatite from the Turamdih U (SSZ) deposit reveals that apatite initially crystallized at ~450°C and the high temperature-high salinity fluid mixed with a low temperature fluid with rather lower salinity during the later stage of apatite crystallization. Micron-scale spatial association of apatite with uraninite, monazite and magnetite point towards at least some part of U-REE mineralization was cogenetic with apatite.

Various occurrences of uranium have been reported by the geoscientists of the Atomic Minerals Directorate for Exploration and Research. These include: surficial uranium occurrence in playa-lake environment at Lachhri, Nagaur District, Rajasthan (Misra *et al.*, 2011); U mineralization with in brecciated granitoids of the Bundelkhand Gneissic Complex at Mohar, Shivpuri District, Madhya Pradesh (Bhattacharya *et al.*, 2011); surficial U-bearing magnesian-calcrete from Khemasar, Churu district, Rajasthan (Rao *et al.*, 2015); uraninite and pyrite in quartz-pebble conglomerates from Sundargarh district of Odisha (Kumar *et al.*, 2012); U enrichment in the polymictic conglomerate and mafic rock in the eastern margin of the Sindreth basin, Sirohi District, Rajasthan (Somani *et al.*, 2012); Palaeoproterozoic Khetabari Formation, Bomdila Group, Sie-Rimi area, West Siang district, Arunachal Pradesh (Basu *et al.*, 2015); high temperature uraninite associated with albitite belt of western India (Singh *et al.*, 2013); U mineralization in the basement granitoids from Umthongkut Area, West Khasi Hills District, Meghalaya (Srivastava *et al.*, 2015).

A REE-bearing carbonatite plug that intrudes into the Malani Igneous Suite of rocks and associated with alkaline rocks such as alkali pyroxenite, micro-melteigite, nephelinite and ijolite, has been recently

discovered at Kamthai in the Barmer district Rajasthan. The identified REE phases are bastnäsite, basnaesite, synchysite, carbocernaite, cerianite, ancylite and parasite. The first phase magmatic calciocarbonatite is alvikite type, rich in carbocernaite whereas the second hydrothermal phase, sovite type, is enriched in bastnaesite. With a total REE reserve of 4.91 million tons, Kamthai has the potential to turn into a world class REE deposit (Bhushan and Kumar, 2013; Bhushan, 2015) and also in carrying out research on REE mineralization in the coming years.

Base Metals

The timing of metamorphism of the polymetallic massive sulfide deposits at Rampura-Agucha and Rajpura-Dariba has been recently constrained by EPMA dating of monazite from their host rocks. While both the deposits have experienced a tectonothermal event at ca. 1.62 Ga, the Agucha deposit has a prominent Grenvillian overprinting at 1.0 Ga (Hazarika *et al.*, 2013b).

Pruseth *et al.* (2014) conducted experiments in the system ZnS-PbS-Cu₂S-FeS₂-S by the evacuated silica tube method at 600°C, pertinent to the peak metamorphic conditions of the Rajpura-Dariba

deposit. The eutectic temperature was constrained at 595°C with a melt containing 22.44 mol% FeS, 31.24 mol% Cu₂S, 5.37 mol% ZnS, 35.81 mol% PbS and 5.14 mol% FeS₂. The sphalerite that was in equilibrium with the eutectic melt contained 6.72 mol% FeS₂. The experimental results suggest that a ZnS-bearing sulfide melt (5 mol % ZnS) was produced during metamorphism at Rajpura-Dariba by partial melting of the pre-existing stratiform SEDEX ore. From the occurrence barite, Ba-calcite, celsian, hyalophane, phlogopite and pyrite, Pruseth *et al.* (2016) proposed barite dissolution reaction that promoted *f*S₂ increase during metamorphism of stratiform ore at Rajpura-Dariba, which in turn caused sulfide partial melting in the ZnS-PbS-Cu₂S-FeS₂-S system. Results of melting experiments explained the observed mineral paragenesis of the strata-transgressive vein ore. A Zn-Fe-S melt with minor Pb, Sb and Cu but no Ag fractionated from an initial melt in the above system forming a residual immiscible sulfosalt-bearing PbS melt. The final metallic melts, represented by formation of dyscrasite (Ag₃Sb) from the sulfosalt-bearing melt and breithauptite (NiSb) or ullmannite (NiSbS) from the sulfosalt-absent melt, were products of independent fractional crystallization of the immiscible sulfide and PbS-sulfosalt melts.

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