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Magmatic and Hydrothermal Ore Deposits

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This article briefly reviews all contributions by Indian geoscientists between the period 2015 and 2019, in the field of magmatic and hydrothermal ore deposits. 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 continued with its modest initiation.

Keywords: Metallic Ore Deposits; India; Research

Introduction

One book and two review articles, on various aspects of ore deposits were published during the report period. The book entitled “Minerals and allied natural resources and their sustainable development: principles, perspectives with emphasis on the Indian scenario” by Deb and Sarkar (2017) includes all possible natural resources such as metallic and non-metallic ore deposits, both inorganic and organic energy resources, and two vital resources for human civilization, i.e., water and soil. From the context of this review, the book furnishes a classification of all possible metallic (and non-metallic) ore deposits, their genetic aspects (including tectonic settings), and most importantly Indian examples, apart from classical deposits world over. While Deb and Pal (2015) reviewed the mineral resources of Proterozoic intra-cratonic basins, the article by Mishra (2015) deals with the Precambrian metallogeny of India.

Scrutiny of the published studies reveals that metals such as Cr, PGE, Au and U continued their earlier momentum. Some studies on chromite and PGE appear to be igneous petrology-centric, which is inevitable while working on magmatic ores. As pointed in the last reports, unlike countries like Australia, Canada and South Africa, industry-academia collaboration, an extremely valuable component in ore deposit research, is still missing. This compilation

incorporates all the published work on magmatic (chromite, PGE) and hydrothermal (gold, uranium, REE, Nb-Ta, W, base metals) deposits from India. If some work is missed out, the author expresses regret for such unintended omission.

Chromite and PGE Ores

From discrimination plots of the REEs, PGEs and other trace elements, of the mafic rocks of east Khasi Hills, Meghalaya Plateau, 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. The Re–Os isotope systematics of the chromitites and associated websterites and anorthosites were studied in the layered Chimalpahad Anorthosite Complex that occurs within the Peninsular Gneissic Complex. The average initial $^{187}\text{Os}/^{188}\text{Os}$ composition (and γ_{Os} values) of chromite, websterites and anorthosites were found to be 0.1045 (-17.67), 14.86 (+467), and 11.79 (+215) respectively. Mantle extraction ages of the chromites point to depletion of primitive mantle at ca. ~3.5 Ga (Dharma Rao *et al.*, 2015). The molar ratios Cr# and Mg# in Podiform chromite of the Manipur ophiolite belt range from 67-82 and 66-71 respectively. The estimated P-T conditions for chromite crystallization are 19-25 kbar and 1080-1240 °C, with $f\text{O}_2$ varying between 0.30

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and 0.58 log units above the FMQ buffer, implying formation in the upper mantle from a boninite parental magma. The chromite grains contain trail-bound inclusions of silicates, Ni-Fe sulfides and Fe-Ni metals, indicating alteration from a crustal fluid (Maibam *et al.*, 2017).

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 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 (chalcopyrite, pyrrhotite, pentlandite). Occurrence of rare greenockite (CdS) associated with chromite-PGE in the Bangur gabbro of the Baula-Nuasahi mafic-ultramafic complex in eastern India was reported by Mishra and Hazarika (2016). This rare phase occurs in siderite-chlorite micro-veinlets 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 resulted in concurrent precipitation of greenockite and siderite postdating the PGE mineralization by reaction with Fe-rich minerals, aided by decrease in pH and/or increase in fO_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 Σ PGE (9-42 ppb), the Gadwal boninites are characterized by high Σ PGE (82-207 ppb). Such strikingly different PGE abundance is interpreted as a result of fractionation of olivine and chromite/sulfide respectively from the parental komatiitic and boninitic melts. The S-under saturated character of Bababudan komatiites is attributed to decompression and assimilation of lower crustal materials during magma ascent and emplacement. In contrast, 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 contributory factors for their S-under saturation (Saha *et al.*, 2015).

Palladium contents of 1-3 ppm (average Pt/Pd = 0.15) have been reported from a layered magnetite in the Archean layered Nuasahi Massif (Odisha). The first formed, primary assemblage of platinum-group minerals (PGM) contains Pd-sulfides [vysotskite, (Pd,Ni)S], Pd-Pb alloys (zvyagintsevite, Pd₃Pb), and a Pd-In alloy. These central magnetite grains are commonly surrounded by blebs of ilmenite and magnetite that contain the majority of the PGM. These are dominated by Pd-antimonides, apart from PtAs₂ (sperrylite), RuS₂ (laurite), and IrRhAsS (irarsite/hollingworthite). These PGMs also occur in the interstitial silicates, with rare occurrences in the central magnetite grains. Prichard *et al.* (2018) proposed that the PGEs, along with minor Cu-sulfides, crystallized during a minor sulfide saturation event that occurred as the magnetites crystallized. Later fluid-assisted introduction of Sb and As produced the main PGM assemblage, dominated by Pd-antimonides, associated with secondary Cu minerals and sperrylite. The Pd mineralization in the magnetites constitutes the third stage PGE concentration at a higher stratigraphic level, in the layered Nuasahi Massif, besides the lower, two-stage concentrations in chromitites.

The layered ultramafic unit in the Mesoarchean Sukinda Massif comprises serpentinized dunite, orthopyroxenite and chromitite, apart from brecciated ultramafic rocks cemented by gabbro-granodiorite clasts. The positive correlation between MgO and Ni, and MgO and Cr in these rocks is due to fractionation of early cumulus olivine/chromite from the high-Mg parental magma (Mondal *et al.*, 2019). While the correlation between Zr and Cu suggests that the parental boninitic magma was S-under saturated, the flatter trend in the Zr-Cu plot from the matrix gabbro indicates sulfide saturation to have occurred later in the evolved boninitic magma. The Σ PGE content in the ultramafic-hosted massive chromitites (\approx 176-875 ppb) and in breccia-hosted chromitite fragments (\approx 61-279 ppb) are higher than the serpentinite (\approx 19-71 ppb), orthopyroxenite (\approx 14-19 ppb) and gabbro (\approx 3-11 ppb). Further, there is a relative enrichment of IPGE (Ir + Os + Ru \approx 528-634 ppb) over PPGE (Pd + Pt + Rh \approx 93-332 ppb), which is manifested by dominance of Os-Ir-Ru (+

minor Pt) alloys besides laurite (RuS_2), irarsite (Ir, Ru, Rh, Pt) AsS , and sperrylite (PtAs_2) in chromite. The IPGE vs. MgO/Cr plot indicates fractionation during the early stage of magmatic differentiation from a S-under saturated boninitic magma. Dominance of the Os-Ir-Ru alloys suggestive crystallization at high temperature and low $f\text{S}_2$ within a S-under saturated boninitic magma ascending from the upper mantle. This study reveals potential for PGE mineralization in the Sukinda area, possibly an extension of the neighboring Baula-Nuasahi area (Mondal *et al.*, 2019).

The 3.1 Ga IOG mafic volcanics from the Jamda-Koira Iron Ore basin of the Singhbhum Craton and Paleoproterozoic Malangtolivolcanics exhibit calc-alkaline and tholeiitic to calc-alkaline compositional characters respectively, despite 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, followed by 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 contents (Singh *et al.*, 2016). Geochemical features such as the Fe-rich nature and high $f\text{O}_2$ condition did not favor sulfide saturation during magma evolution in the Deccan province, unlike the Siberian continental flood basalts. Further, crustal contamination also failed to increase the sulfur budget (*cf.* Laxman and Vijay Kumar, 2018). Although the Deccan rocks lack Cu sulfide mineralization, these authors suggest that they may contain native Cu mineralization.

Gold

Hazarika *et al.* (2015a) carried out monazite U-Th- Pb_{total} dating and rigorous P-T pseudosection analyses for the Hutti-Maski greenstone belt (HMGB) and the south Kolar greenstone belt (SKGB) to assess their metamorphic and geochronological evolution. The estimated timings of felsic volcanism for the HMGB and the SKGB rocks are ca. 2669 ± 22 Ma and 2661 ± 32 Ma respectively. The HMGB rocks underwent mid-amphibolite facies metamorphism at ca. 2564 ± 12 Ma with peak P-T of ~ 6 kbar and ~ 620 °C. The

SKGB greenstones, on the other hand, experienced 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 metamorphosed to higher grades than their counterparts in the Abitibi province and the Yilgarn Craton.

A combined EPMA-LA-ICP-MS study concerning analysis of major and trace elements intexturally 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.*, 2015b). Tourmaline composition show evolutionary trends in compositional space that suggest a single low-salinity and reduced metamorphic fluid, with characteristically low ΣREE , which was responsible for proximal alteration and attendant gold mineralization at Hutti. The type I and type II tourmalines from Hira-Buddini display oxydravite-povondraite trends, with compositional overlap that implies 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.

A comprehensive 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 attempted by Hazarika *et al.* (2016). Scheelite displays three types of REE patterns, which include 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 corresponding increase in 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 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) for the Hutti deposit.

Raman spectroscopic studies performed on gaseous inclusions in auriferous quartz veins from the inner and proximal zones of the Jonnagiri granitoid-hosted gold deposit, confirm presence of disordered graphite, occurring as thin films within fluid inclusions, apart from variable proportions of CO_2 , CH_4 and H_2O . Computed Perple_X -aided phase diagram in the C-O-H system at 300 °C and 2 kbar explain chemical evolution of the C-O-H fluids. The estimated $f\text{O}_2$ values on the graphite saturation surface range from $10^{-35.71}$ to $10^{-32.65}$, when X_{O} varies from 0.1 to 1.0. However, $f\text{O}_2$ decreases drastically to $10^{-49.31}$ at $X_{\text{O}} = 0.1\text{E}-07$, where almost pure CH_4 is stable. Decrease in $f\text{O}_2$, as demonstrated by the occurrence of gaseous fluid inclusions with disordered graphite and varying proportions of CO_2 - CH_4 in the gaseous part, acted as the causative factor in decreasing gold solubility during fluid-rock interaction and precipitating gold from a metamorphic fluid at Jonnagiri (Chinnasamy and Mishra, 2017). On the contrary, the $\delta^{13}\text{C}$ - and $\delta^{18}\text{O}$ values, along with pertinent trace element geochemical features of carbonates in the auriferous quartz-carbonate veins from Jonnagiri have been interpreted to imply mantle and/or juvenile magmatic source of the ore fluid (Kesarwani *et al.*, 2019). Further, these authors propose that the Jonnagiri deposit is similar to the granitoid-hosted gold deposits in the Jiadong Peninsula, North China craton, characterized by non-metamorphic (magmatic) fluid source, contrary to previous studies on Jonnagiri (Chinnasamy and Mishra, 2013) and many granitoid-hosted orogenic gold deposits, elsewhere in the world (Saravanan *et al.*, 2009). 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 above authors argued that this set of calculated C-isotopic

composition could not have resulted by metamorphic devolatilization of greenstones and they rather reflect mantle/magmatic derived CO_2 or carbonates. Further, in a more recent study involving $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ and geochemistry of auriferous quartz-carbonate veins in the Ajjanahalli and Gadag gold deposits (western Dharwar Craton), Swain *et al.* (2018) proposed mantle-derived gold mineralizing fluid. 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).

Turbidite-hosted auriferous zones in the Gadag greenstone belt contain 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 REE pattern of altered wall rocks with prominent negative Eu anomaly point to differential response of the host rock and intensity of alteration depending on the composition of the host rocks and hydrothermal fluids. The ore fluids were of low salinity (2.0 to 6.6 wt. % NaCl equiv.) of metamorphic parentage 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 (Ugarkar *et al.*, 2016). Mineral association and major/trace element chemistry of magnetite and apatite from the albitite- and carbonate-hosted Bhukia gold-Cu deposit point towards an analogous iron oxide copper gold-iron oxide apatite (IOCG-IOA) ore forming setting in the Aravalli-Delhi Fold Belt (Mukherjee *et al.*, 2017).

Based on various major and trace elements, the Kudrekonda meta-volcanic rocks in the Shimoga greenstone belt (western Dharwar Craton) are classified as boninites, with magma generation in an intra-oceanic arc setting by partial melting of a spinel lherzolite mantle source. Gold occurs in Fe-oxides/quartz in the BIF and the mineralization is of convergent margin orogenic type. Gold mineralization in boninites was a consequence of transportation and precipitation of Au by a metamorphic fluid in shear zones. Au occurs in disseminated sulfide lenses containing pyrite, arsenopyrite, chalcopyrite and minor galena. Epigenetic BIF-hosted gold mineralization is attributed to migration of oxygen depleted, reducing,

sulfurous-auriferous hydrothermal fluids to the site of BIF deposition that served as chemical traps for the auriferous fluids (Ganguly *et al.*, 2016).

A combined mineralogical, fluid inclusion and $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ study in auriferous quartz-calcite veins from the Chigargunta and Bisanatham deposits in the south Kolar greenstone belt is recently undertaken by Pal *et al.* (2019). The estimated ore fluid compositions are low to medium salinity H_2O - NaCl - CO_2 - $\text{CH}_4 \pm \text{N}_2$ and low salinity H_2O - NaCl , respectively at Chigargunta and Bisanatham. The ranges in mineralization P-T conditions are 1.7-3.5 kbar/285 °-378 °C (Chigargunta) and 0.8-1.2 kbar/365 °C-405 °C (Bisanatham). Deduced fluid $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values suggest derivation by metamorphic devolatilization of marine carbonates within the greenstones.

Nature and source of the ore forming fluids for different orogenic gold deposits/ prospects in the Dharwar Craton is recently reviewed by Mishra *et al.* (2018). Typical low salinity aqueous-gaseous (H_2O - $\text{CO}_2 \pm \text{CH}_4 + \text{NaCl}$) fluid altered diverse host rocks (mafic greenstones, BIF, granitoid) and precipitated gold in a narrow P-T window (0.7-2.5 kbar and 215-320 °C). While the estimated fluid O- and C-isotopic values are ambivalent, S-isotopic compositions of the pyrite-precipitating fluids show distinct craton-scale uniformity in terms of its reduced nature and a suggested crustal sulfur source. Chemical composition of tourmaline suggests fluids derived by metamorphic devolatilization reactions of the greenstones (volcanics and interlayered sedimentary rocks), with minor granitic contributions that precipitated gold. Apart from water, the metamorphic fluid had enough sulfur and arsenic, necessary for formation of orogenic gold deposits. Chemistry of scheelite, pyrite and arsenopyrite imply fault-valve action that resulted in pressure fluctuation, which was the causative factor behind gold precipitation, besides wall rock sulfidation reactions (Mishra *et al.*, 2018).

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 suggest 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 the Pan-African orogeny along the MBSZ. Gold precipitation took place from such H_2O - CO_2 - CH_4 - $\text{Au}(\text{HS})_2^-$ fluid as a result of phase separation and fluid-rock interaction (Sahoo *et al.*, 2016).

Chakravarti *et al.* (2019) studied the nature and genesis of gold mineralization hosted by radioactive, matrix-supported, oligomictic quartz-pebble conglomerates from the eastern Iron Ore Group and the Dhanjori basin within the Singhbhum Craton. LA-ICP-MS analysis of various As-bearing pyrites reveals presence of gold (up to 52 ppm). Gold was initially incorporated in the earliest pyrite due to microbial action and was later leached by hydrothermal fluid leading to increasing concentration in younger pyrites. The above authors proposed a 'modified placer' origin (à la Witwatersrand) for the quartz-pebble conglomerate-hosted gold mineralization in the Singhbhum Craton.

Uranium, REE, Nb, Ta, W ores

Compositional characteristics of uraninite within the Mahagiri Quartzite (Singhbhum Craton), such as elevated Th content and high ΣREE content indicate a 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).

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 co-genetic with apatite.

Albitite-hosted uranium mineralization within the BGC in Bichun area, Jaipur district, Rajasthan contains minerals such as davidite, brannerite and uraninite. While the davidite U–Pb age is ca. 930 Ma, the Sm–Nd model age (T_{DM}) furnishes a range from 1851 to 2200 Ma with $\epsilon_{Nd(930\text{ Ma})}$ varying between –10.7 to –15.5, implying the Banded Gneissic Complex (BGC) as the source of uranium (Yadav *et al.*, 2016).

A mineral-chemical study (optical microscopy, Raman spectroscopy and EPM analyses) was performed to assess the alpha radiation and subsequent alteration at the interface of uraninite inclusions in silicate minerals in a migmatitic sample from the Samarkiya area, Bhilwara district, Rajasthan. Important observations include anomalous coloration, reaction aureoles of chlorite (in biotite) and K-feldspar (in plagioclase) and dissolution textures within the matrix monazites. Compositional trends of the reaction aureoles in albitic plagioclase reveals organized distribution of K-feldspar-, LREE- and clay-rich zones; while the same in biotite is composed of secondary chlorite. Such growth sequence of the secondary phases indicates an influx of a K-rich fluid, following intense radiation damage, efficiently superimposed by LREE-metasomatism and later acidic alteration. These changes took place under low-temperature ($\leq 150^\circ\text{C}$) conditions, wherein radial cracks (within plagioclase) and cleavages/fractures (within biotite) favored fluid infiltration-circulation into the reaction aureoles. Decrease in the LREEs from the matrix monazites and their enrichment as a discrete LREE phase within the damaged aureoles in plagioclase demonstrate micrometer-scale LREE mobility (Ozha *et al.*, 2016). EPMA dating of uraninite from the Samarkiya area, central Rajasthan reveals three distinct ages. While the oldest age of ca. 1.88 Ga, obtained from uraninite in the basement, represents the first stage of mineralization, large population of uraninites, both from the basement and the supracrustal, has an age of ca. 1.24–1.20 Ga, which is interpreted to be the major and pervasive event of uranium mineralization. Later, during Neoproterozoic (ca. 1.01–0.96 Ga), either some uraninites were altered leading to complete Pb-loss, or new uraninite crystallized/re-crystallized as a result of fresh hydrothermal event. Thus, the area underwent various metamorphic/hydrothermal events resulting in uraninite precipitation, alteration and recrystallization, imprints of which are preserved in uraninites. Further,

the three discrete episodes spanning ca. 0.92 Ga represents growth of different generation of uraninite, where the last one pertains to amalgamation of the Rodinia Supercontinent (Ozha *et al.*, 2017).

Rare metal (LCT-type) zoned pegmatites associated with the granites of the Kawadgaon area in the Bastar Craton contain ore minerals such as columbite-tantalite, ixiolite, pseudo-ixiolite, wodginite, tapiolite, microlite, fersmite, euxenite, aeschynite, beryl, cassiterite, monazite, xenotime, zircon, ilmenite, triplite, and magnetite. High initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio and other geochemical features of granites indicate their derivation from older crustal rocks. Pegmatites were derived from the granitic melt by fractional crystallization (Singh *et al.*, 2017). Columbite-tantalite furnished U–Pb concordia upper intercept age of 1978 ± 16 Ma, which is presumably related to younger granitic activity that ranges from 2300 to 2100 Ma in the Bastar Craton (Singh *et al.*, 2018).

Various occurrences of uranium (and REE) have been reported by the geoscientists of the Atomic Minerals Directorate for Exploration and Research. These include: surficial U-bearing magnesian-calcrete from Khemasar, Churu district, Rajasthan (Rao *et al.*, 2015); Palaeoproterozoic Khetabari Formation, Bomdila Group, Sie-Rimi area, West Siang district, Arunachal Pradesh (Basu *et al.*, 2015); U mineralization in the basement granitoids from Umthongkut Area, West Khasi Hills District, Meghalaya (Srivastava *et al.*, 2015); U-REE mineralization in the BGC and Delhi rocks in north-central and northern Rajasthan (Yadav *et al.*, 2015); Uranium mineralization in the carbonate rocks from the upper Krol Formation, Nainital Syncline (Sinha *et al.*, 2016); U mineralization in metasomatized calc-silicate rocks at Raghunathpura, Mahendragarh District, Haryana (Roy *et al.*, 2016); Vein type uranium mineralization in the Paleoproterozoic Bijawar Group of Rocks, Lalitpur District, U.P. (Rawat *et al.*, 2018); granite-hosted pitchblende and coffinite mineralization in the Bhima Basin, Karnataka (Patnaik *et al.*, 2016); U mineralization in the Delhi metasedimentary rocks, Buchera area, Jaipur district, Rajasthan (Patel *et al.*, 2018).

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 phonolite, has been recently

discovered at Kamthai in the Barmer district Rajasthan. The identified REE phases are bastnäsite, synchysite, carbocernaite, cerianite, ancylite and parisite. The first phase magmatic calcio carbonatite is alvikite type, rich in carbocernaite whereas the second hydrothermal phase, sövite type, is enriched in bastnäsite. With a total REE reserve of 4.91 million tons, Kamthai has the potential to turn into a world class REE deposit (Bhushan, 2015) and also in carrying out research on carbonatite-associated REE mineralization in the coming years. The Siriwasan carbonatite (Gujarat) is sövite and constitutes minerals such as pyroxene, amphibole, apatite, pyrochlore, perovskite and titanite. REE contents in sövites are related to the amount of pyrochlore, perovskite and apatite. The C- and O isotope composition of sövite (and ankeritic) plot in the mantle field. However, mixing of carbonatitic melt with surrounding Bagh limestone is also evident. Similarity in Sr and Nd isotopic ratios of the Siriwasan and nearby Amba Dongar carbonatites suggest analogous magma source (Viladkar and Gittins, 2016). U- and Ta rich magmatic pyrochlores have been reported from the Newania carbonatite, Udaipur, which underwent hydrothermal alteration that resulted in removal of Na, Ca, F from the A-sites (Viladkar *et al.*, 2017).

Tungsten metallogeny in Rajasthan is characterized by wolframite mineralization in quartz veins associated with S-type granites in Degana, Balda, and Sewariya-Govindgarh. Whole rock Rb-Sr ages for the Balda and Degana granites are respectively 795 ± 11 Ma and 827 ± 8 Ma, which are casually related to Rodinia breakup (Vijay Anand *et al.*, 2018). REE modelling of the Sewariya-Govindgarh pluton indicates partial melting in different crustal level for magma generation. Further, the Rb-Sr mineral isochron for the Govindgarh granite furnished an age of 860 ± 7 Ma (Sivasubramaniam *et al.*, 2019).

Base Metals

The Agnigundala Sulfide Belt is situated in the northeastern part of the Cuddapah basin, is perhaps the only Proterozoic analog of the Mississippi Valley Type sulfide deposit in India. The belt constitutes Cu mineralization at Nallakonda, rare Cu-Pb mineralization at Dhukonda, and Pb mineralization at Bandalamottu. Mineralogical and stable isotope (of S, C, and O) studies suggest that the ore fluid

responsible for sulfide mineralization in the Agnigundala Belt was a low-temperature (< 200 °C) oxidized fluid. The ore fluid precipitated Cu at Nallakonda at comparatively higher temperature, also deposited copper-lead at Dhukonda and lead at Bandalamottu under progressive cooling during fluid migration. Sulfur was derived by abiotic thermochemical reduction of basinal water sulfate, and the metals were leached from the lower red-beds with evaporite-bearing continental to shallow marine sediments. Syn-sedimentary faulting caused puncturing of the ore brine pool and migration of the ore fluid through the cover syn-rift sediments undergoing diagenesis. In spite of deformation of the ore bodies, they surprisingly lack significant evidence of sulfide remobilization (Bhattacharya and Bandyopadhyay, 2018).

Cobaltiferous mackinawite and pentlandite occurs in the assemblage chalcopyrite-pyrrhotite \pm pyrite-magnetite-chlorite-blue amphibole (Cl-rich hastingsite –paragasite-sadanagaite) in the Madan-Kudan mine, Khetri Copper Belt, Rajasthan. The sulfide veins hosting the above assemblage often contain Cl-rich marialitic scapolite, implying vein formation from Cl-rich saline fluid (Baidya *et al.*, 2018). On the basis of mineral replacement texture, and chemical composition, three different types of amphiboles (A1, A2 and A3) were identified in the sulfide-bearing amphibole-feldspathic quartzite from the Kolihan- Chandmari mines, Khetri Copper Belt. While the A1 amphiboles are Fe-Mg-Mn type (cummingtonite-grunerite), the A2 (magnesio-ferrihornblende) and A3 (hastingsite, sadanagaite, tschermakite) amphiboles belong to calcic group. On the basis of modes of occurrence and pertinent mineral replacement textures, the relative timing of formation their established sequence of formation is A1 followed by A2 followed by A3. The A1 type (Fe-Mg-Mn) is metamorphic, which was replaced by Ca-rich A2 and both A1 and A2 were further replaced by Na-Ca-K-Cl-rich A3. On the basis of higher Na and Cl contents and ubiquitous Cl-rich marialitic scapolite, higher calculated Fe^{3+} , Eu/Ce anomalies, the A3 amphiboles seem to have precipitated from a saline fluid (evaporite or basinal brine), which was oxidized. Further, from the association of sulfide-oxide mineralization (chalcopyrite- pyrrhotite-magnetite-pyrite \pm uraninite \pm allanite) with the A3 amphibole, the mineralization is proposed to belong to the IOCG

clan (Baidya *et al.*, 2017).

Trace element chemistry of magnetite in different ore types in the Khetri Cu-(Au, Fe) deposit can be used as fingerprints of the ore forming environs. For example, magnetites from the metamorphosed BIF preserve low Ga and Ge but high Ni, P and Cu contents compared to hydrothermal magnetite grains. While shearing and associated hydrothermal alteration enriched elements such as Ni, P, Cu, Al and Mn, elevated contents Ti, V, Co, Cr, Ge and Mg was a consequence of chemical modifications brought in by external fluids. Magnetite composition was primarily controlled by fluid compositions, oxygen fugacity besides minor effects from temperature, fluid-rock interaction and co-precipitating mineral phases (Chen *et al.*, 2015). Pb-Pb age of 1362 ± 29 Ma is obtained in high-Th monazite from Kolihan deposit, Khetri Cu Belt, may correspond to metamorphism of the host rocks. Hydrothermal monazites from the Madan-Kudan and Kolihan deposits yielded U-Pb ages of 833 ± 5 to 840 ± 6 Ma, which are interpreted to represent the timing of the Cu-Ag sulfide mineralization. Since this time slice is well in accordance with the timing of regional Ca-Na metasomatism (~830 to 850 Ma), the metasomatic fluid caused sulfide mineralization in the Khetri Cu Belt (Li *et al.*, 2019).

Hydrothermal chlorites associated with the Cu \pm Au mineralization at Thanewasna, Bastar Craton are predominantly chamosite with minor clinocllore. Intra-crystalline chlorite thermometry reveals increase in mean temperature of chlorite formation from ~200 °C (host rock) to ~230 °C (proximal alteration) to ~250 °C (distal alteration), suggesting these chlorites belong to 'high sulfidation epithermal system' (Dora and Randive, 2015). Sulfide mineralization at Thanewasna is characterized by the mineral assemblages of Cu-Fe-Au-Ag-Ni-Ba-REE minerals typical of IOCG type, which is further supported by magnetite chemistry (Dora *et al.*, 2017)

From the occurrence barite, Ba-calcite, celsian, hyalophane, phlogopite and pyrite, Pruseth *et al.* (2016) proposed barite dissolution reaction that facilitated fS_2 increase during metamorphism of stratiform massive sulfide ores at Rajpura-Dariba, which in turn triggered sulfide partial melting in the ZnS-PbS-Cu₂S-FeS₂-S system. Results of melting

experiments elucidated the observed mineral paragenesis of the strata-transgressive vein ores. 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 a product of independent fractional crystallization of the immiscible sulfide and PbS-sulfosalt melts.

Phase relations in the Sb-rich half of the Ni-Sb (+Ag) at 600 °C are dominated by a melt field and imply that the breithauptite, Sb-Ni phases, 2FeS.Ag₂S, 2Ag₂S.FeS, (Fe,Ag)S, 3PbS.Ag₂S, CuPbSbS₃.Ag₂S, a Sb-Ni-Ag-Fe-S phase, and a Ag-Sb-Ni-Cu-Fe-S phase encountered at Sindesar-Khurd (Rajasthan) signify a disequilibrium assemblage formed by direct crystallization from or by the reaction of a sulfide partial melt with major sulfide phases such as galena and pyrrhotite. Melt generation with compositions close to CuPbSbS₃.Ag₂S implies that while the Pb-bearing phases might have crystallized from a melt, which was dominated by PbS, the Fe-bearing phases resulted due to reaction of this melt with pyrrhotite. The Sb-Ni phases associated with breithauptite are perhaps non-stoichiometric. Nisbite (NiSb₂) produced from an initially Ag-poor Ni-rich melt that produced a residual melt with 33.33 at. % Ni, after Ag fractionation. The presence of high Sb in the Sb-Ni phases compared to that in nisbite also suggests that these phases could have formed by the removal of Ag from relatively Ni-poor melts that would have coexisted with breithauptite, confirms the hypothesis of melt-induced sulfide remobilization at Sindesar-Khurd. The presence of breithauptite in remobilized ores associated with metamorphosed massive sulfide deposits possibly indicates sulfide partial melting (Govindarao *et al.*, 2017). Despite being a commonly observed textural feature in sulfide deposits, chalcopyrite disease (in sphalerite) has not been convincingly explained as yet. Experiments were conducted in the system ZnS-PbS-FeS-Cu₂S-As₂S₃ at 600 °C and the run products, along with the obtained melt, were annealed at 350 °C, to appraise the role of sulfide partial melting in the formation of chalcopyrite disease. Chalcopyrite blebs developed only in S-rich sphalerites, as a consequence of nonstoichiometry-driven diffusion of Cu. Thus, the

mechanism involving sulfide partial melting is the primary causative factor behind the development of chalcopyrite disease in sphalerite. Accordingly, chalcopyrite disease may be used as an easily identifiable potential indicator of sulfide partial melting in metamorphosed massive sulfide deposits (Govindarao *et al.*, 2018).

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