Iron oxide–copper–gold mineralization at Thanewasna, western Bastar Craton

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Iron oxide–copper–gold (IOCG) at Thanewasna, Maharashtra, India is a new genetic type of ore deposit, being reported from the western margin of Bastar craton, based on integrated field, drilling, mineral chemistry and Raman microprobe studies. It is the fourth such IOCG type being reported from India. Hydrothermal mineralization is structurally confined to *en echelon* dilatational quartz–chlorite veins along NW-SE trending brittle–ductile shear zone hosted in calc-alkaline granitoid. The mineralization is characterized by chalcopyrite, magnetite and barite which occur as dissemination, stringers and veins associated with hydrothermal K-alteration and chlorite alteration. Chemical analysis shows significant amounts of Cu, Fe, Ba and anomalous Au content. Ore petrography and scanning electron microscope and electron probe micro analyser studies show assemblages of Cu–Fe–Au–Ag–Ni–Ba–REE minerals typical of IOCG type deposits at Thanewasna. Ore textures, mineralogy and alteration characteristics are typical of IOCG-type deposits, further supported by mineral chemistry of magnetite (V versus Ti/V) using EPMA, and thus define a IOCG metallogenic province in Thanewasna area with significant implications for future exploration.

Keywords: Hydrothermal mineralization, IOCG, mineral chemistry, ore deposits.

IRON oxide–copper–gold (IOCG) deposits are recognized worldwide and include a number of giant, high-tonnage, low-grade Cu–Au deposits that are generally associated with hydrothermal breccias[1–10]. The IOCG and related iron oxide–apatite (IOA, 'Kiruna type') class of mineral deposits has been the subject of intense debate, in terms of both their classification and genetic mechanism[1,3,5,10]. In spite of this, IOCG type deposits have attracted much attention in recent years, both in terms of academic research and exploration activity, because of enormous geological resources with polymetallic character (e.g. Cu, Au, Fe, Ag, U and rare earth elements (REE). Many iron and copper–gold deposits around the world have been included in the IOCG type since the synthesis of IOCG concept from giant Olympic Dam deposit, Australia in 1992 (ref. 1). Since then, new discoveries and reclassification of existing deposits have led to the recognition of many IOCG deposits[2–6].

The IOCG deposits are diverse in age, tectonic setting, $P–T$ conditions, characteristic alterations, host-rock package and mineralization style[2,7–9]. These deposits are characterized by dominant Cu sulphides ± Au with abundant magnetite or hematite occurring in host rocks ranging from Late Archaean to the Cenozoic in age. The ores of IOCG deposits are commonly associated with volcanic and/or intrusive rocks, and their close relationship with shear zones is typical for this type of mineralization[10]. Mineralization and alteration halos in IOCG deposits may reach hundreds of metres in width and many kilometres in length[11]. These deposits can form at shallow (Olympic Dam type), moderate (Sossego, Ernest-Henry type) or deep (Salobo) levels within the first 10 km of the crust[12].

Currently known metallogenic IOCG deposits of the world occur in Precambrian shields as well as in circum-Pacific regions, but the most prospective settings are located in the Proterozoic granitic and felsic gneiss terranes[3,13,14]. Bastar craton in central India is well known for its world-class giant porphyry copper deposits associated with post-tectonic granitoid at Malanjkhnad[15] about 350 km NE of Thanewasna, Maharashtra. However, this craton is still an unknown entity in terms of the characteristics that define IOCG deposits. In this communication, Thanewasna Cu deposit is being reclassified as IOCG type of deposit[16] based on numerous evidences from field, drilling and laboratory studies. This is the fourth such deposit being reported from India after Khetri[17], Bhukia[18] and Turamdih, Singbhum[19].

Thanewasna deposit is located about 200 km southeast of Nagpur in the western Bastar Craton (WBC) and along the northern margin of the Godavari rift (Figure 1 *a*). The study area forms a part of the Precambrian basement of WBC, which comprises mainly of tonalite–quartz diorite to granite, charnockite, meta-pyroxenite and meta-gabbro traversed by undeformed Mul granite[20–22] (Figure 1 *b*). These rocks are overlain by Mesoproterozoic platformal Pakhal sediments deposited along NS to NNW-SSE rift bounded basins[21]. The emplacement of Mul granite (1587 Ma, Dora, unpublished data) in WBC has developed high temperature gradients in Thanewasna area, which is the major cause of fluid circulation and alteration.

Copper mineralization is mainly associated with quartz–barite vein that occurs predominantly in the form of *en echelon* veins along NNW–SSE striking shear zone hosted in quartz diorite–tonalite in the south and I-type granite in the north[15]. This shows evidence of brittle and ductile deformation. Mineralization is associated with hydrothermal alteration dominated by K–Na alteration, chloritization, argillic alteration and silicification. The potassic alteration is related to faulting and/or shearing during regional deformation. Faulting/shearing

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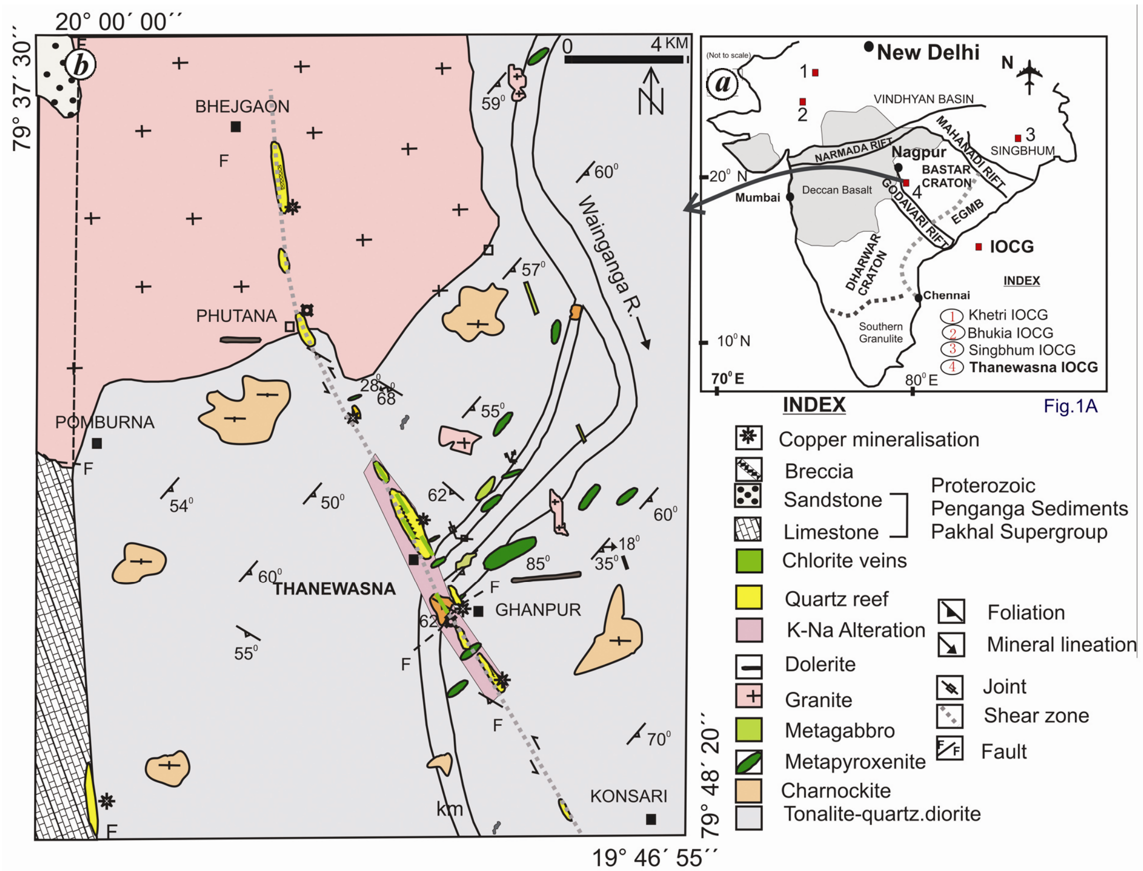

Figure 1. ***a***, Location map of iron oxide–copper–gold (IOCG) deposits of India. ***b***, Geological map of Thanewasna area, western Bastar Craton, Central India (modified after Dora[16]).

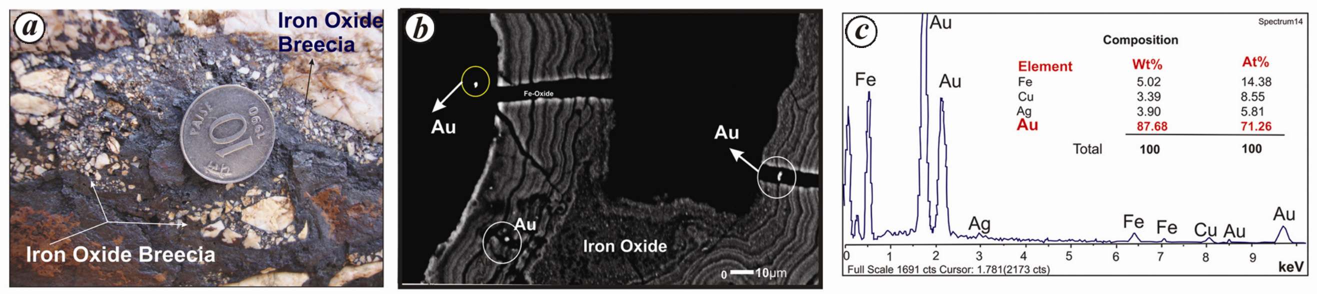

Figure 2. Field photographs and back-scattered electron (BSE) image of sulphide–gold–silicate relationships at Thanewasna. ***a***, Field photograph showing matrix-dominated Fe-oxide breccia. ***b***, BSE image of bright grain identified as gold associated with Fe-oxide from Thanewasna IOCG. ***c***, SEM–EDS spectrum of gold.

has provided a channel for fluid circualtion; as a result, alteration halos are rectricted along a linear pattern within 500 m influence of the shear zone. This has helped leaching bulk of the elements from wall rock and transporting along structural weak plan, and being redeposited in the Thanewasna quartz reef. Chlorite alteration is mainly associated with mineralization formed after the development of the shear zones proximal to the ore zone. Intense K-metasomatism (red-rock alteration) is devoid of mineralization and it occurs further away from ore body[20]. Brecciation and Cu ± Au mineralization have formed after the bulk of red-rock alteration. Fe-oxides leached during metasomatisim and have been redeposited in structural site to form Fe-oxide bodies and associated breccia[10]. Iron oxide is transported in mineralized fluids along the pre-existing weak plan and acts as a catalyst in the precipitation of other metals at lower temperature. The mineralization comprising Cu–Fe sulphides and iron oxides occurs as fine to coarse disseminations, stringers and veins. One event of Cu–Au mineralization at

Table 1. Economic potential of Qtz–Chl veins from Thanewasna IOCG, Bastar craton, Central India

Sample no.	Nature of samples	Type of mineralization	Alteration type	Mineral assemblages	Assay values			
					Cu (%)	Fe (%)	Au (ppb)	Ba (%)
T-3	Qtz–chlorite–barite	Surface mineralization	Chloritic alteration	Chl ± Qtz ± Ba	0.20	13.99	nd	0.58
T-11	Chlorite–clay		Argillic alteration	Qtz–Chl–Kao	1.12	16.76	nd	0.95
T-19A	Iron Oxide Breccia		Iron alteration	Fe–Qtz	1.30	78.11	1080	176
TWC-1/1	Qtz–Chlorite veins	Sub-surface mineralization	Chloritic–sericitic alteration	Chl–Alb–Qtz–Au	3.01	nd	nd	nd
TWC-2/1	Qtz–Chlorite veins		Chloritic–alteration	Chl–Alb–Qtz–Au–Fe	1.37	nd	800	nd
TWC-2/2					1.40	10.25	1800	nd
TWC-2/3					1.45	nd	1350	nd
TWC-6/1	Qtz–Chlorite veins				3.01	nd	400	nd
TWC-6/2					4.02	nd	300	nd

Nd, not determined.

Thanewasna is associated with brecciation of iron oxides (Figure 2 *a* and *b*). Breccia displays a range of textures from incipient crackling to matrix-dominated breccia, suggesting their development in brittle–ductile regime.

In the study area, drilling has established a number of mineralization bands associated with quartz–chlorite veins, hosted in quartz diorite rock of calc-alkaline affinity. Samples were analysed using XRF for major oxides like Fe_2O_3, $BaSO_4$ and mineralized samples were analysed using atomic absorption spectroscopy (AAS) for trace element concentration (Cu, Ni, Au) and inductively coupled plasma mass spectrometry (ICP-MS) for REE. Chemical analysis of the mineralized veins indicates anomalous and economic values for Cu (1.0%–3.1%), Fe_2O_3 (10.25%–78.11%); Au (125–1800 ppb), Ba (1833–19746 ppm) and LREE (Ce, 10–67 ppm) (Table 1)[23,24]. Total reserve has been estimated around 6.64 million tonnes of copper at 0.50% cut-off grade up to 180 m vertical depth, and the grade of mineralization continues to increase with depth[23]. Ore microscopic and scanning electron microscope (SEM) study reveals the presence of assemblages of Cu–Fe–Ni–Au–Ba–REE. Gold occurs as fine disseminations within pyrite and iron oxide (Figure 2 *b*), the composition of which was determined by SEM-EDS (Figure 2 *c*). These typical mineral assemblages have distinctive chemical fingerprints and their mineral chemistry is used in the process of ore formation and source-rock tracers[25,26]. Chemical trace element analysis of magnetite by EPMA shows very low TiO_2 (0.02–0.10 wt%) and relatively high V_2O_3 (0.02–0.29 wt%) (Table 2). However, the overall Ti content (pfu) and Ti/V ratio of Thanewasna mineralization are similar to those reported from IOCG deposits elsewhere[25–27] (Figure 3 *a*).

The emplacement of Mul granite (1587 Ma, Dora, unpublished data) into granitoids of WBC during Godavari rifting, provided the heat source for driving hydrothermal fluid circulation and also leaching of K, Fe, Cu, Au during sodic–calcic alteration and creating a fluid with the potential to contribute to the overall metal budget of the deposit. The mineralization is further enriched due to remobilization during periodic reactivation of the shear along the NNW-SSE Thanewasna lineament. Fluid inclusion microthermometric data and Raman spectroscopic study suggest that the mineralization event took place during fluid mixing and phase separation of H_2O–CO_2 liquid. Gold–barite mineralization was associated with low saline (V 2.46–7.00 wt% NaCl) and copper mineralization was formed in medium to high salinity conditions (V 7–29 wt% NaCl), which records homogenization temperature over the range 150–251°C. This temperature range is also well supported by chlorite geothermometry study based on Al^{vi}; Al^{iv} and Fe/Fe + Mg ratio, suggesting formation of mineralization temperature from 217°C to 247°C (ref. 21). Raman microprobe study reveals the presence of gases phase, i.e. CO_2–CH_4–N_2–H_2S in mineralized fluid. Coexistence of CO_2–CH_4 suggests that the fluid has resulted from mantle source as well as from wall rock through sulphidation and is common in many IOCG deposits[28] (Figure 3 *b*), sulphur isotope values of sulphides near 0 per mil suggest a brine of magmatic origin and an igneous source of S.

The general features of the Thanewasna deposit display characteristics typical of IOCG deposits of the world (Table 3)[1,3,10,29–36]. The Thanewasna area has significant potential for IOCG mineralization because of the following evidences: (1) Presence of Cu, with or without Au

Table 2. Representative microprobe analysis of magnetite along with the structural formula of Thanewasna IOCG, Bastar craton

Sample no.	18Jl/1						
Serial no.	1	2	3	4	5	6	7
SiO_2	0.03	0.02	0.09	0.40	0.11	0.09	0.19
TiO_2	0.02	0.04	0.04	0.05	0.02	0.03	0.10
Al_2O_3	0.06	0.06	0.04	0.10	0.06	0.04	0.21
Cr_2O_3	0.04	0.03	0.03	0.02	0.02	0.03	0.07
V_2O_3	0.18	0.15	0.02	0.03	0.02	0.12	0.29
Fe_2O_3	66.91	67.03	66.86	66.12	67.00	66.68	64.71
FeO	30.34	30.39	30.36	30.82	30.48	30.37	30.01
MnO	0.00	0.00	0.00	0.00	0.01	0.00	0.02
CaO	0.01	0.01	0.03	0.05	0.01	0.00	0.03
Total	97.58	97.73	97.46	97.59	97.74	97.36	95.63
a.p.f.u.	Cation						
Si	0.01	0.01	0.03	0.13	0.03	0.03	0.06
Ti	0.00	0.01	0.01	0.01	0.00	0.01	0.02
Al	0.02	0.02	0.01	0.04	0.02	0.01	0.08
Cr	0.01	0.01	0.01	0.00	0.01	0.01	0.02
V	0.05	0.04	0.01	0.01	0.01	0.03	0.08
Fe(iii)	15.90	15.90	15.90	15.68	15.89	15.88	15.66
Fe(ii)	8.01	8.01	8.02	8.12	8.03	8.03	8.07
Ca	0.00	0.00	0.01	0.02	0.00	0.00	0.01

Table 3. Comparative geological characteristics of typical IOCG type of Olympic Dam, Australia with Thanewasna IOCG, Bastar craton

Features	Thanewasna	Olympic dam
Deposit size	6 .64 Mt; 1.69 and 0.89 Cu%	2 000; Mt 2.5% Cu
Age	Mesoproterzoic 1587 ± 14	Mesoproterzoic 1588 ± 4 Ma
Craton position and tectonic setting	Craton margin, Bastar Craton; anorogenic	Craton margin, Gawlar craton; anorogenic
Causative host rocks	Granitoids-A and I-type granites	A-type syenogranite
Model	Fluid-mixing in a low to medium-level environment	High-level environment with exhalative activity and fluid mixing
Associated host rocks	Tonalite–quartz diorite and granite, sheared quartz vein and magnetite breccia	Hematite–quartz breccia
Main ore assemblage	Fe–Cu–Ba–Au–Ag–Th	Fe–Cu–U–Au–Ag–REE
Late-stage vein assemblage	Late barite–fluorite and sulphides	Barite–fluorite
Fe minerals	Magnetite (hematite)	Hematite (magnetite)
Cu and other minerals	Chalcopyrite, bornite and covellite; pyrite and arsenopyrite.	Chalcopyrite, bornite, chalcocite (±Ag and Au)
REE minerals	Allanite, monazite, huttonite	Bastnaesite, monazite, xenotime and florencite
Other significant minor phases	Pentlandite and galena	Fluorite with sulphide in barren core
Alteration styles	K-metasomatism, sericitic–silicic, chloritization and hematitization	K-metasomatism, sericitic–silicic, chloritization and hematitization
Number of fluids	Two fluids	Two fluids
Fluid temperatures and composition	175°C–250°C; $\delta^{34}S$ = 0–1.8‰	(i) 400°C; $\delta^{18}O$ = 10‰ (ii) 200–400°C; $\delta^{18}O$ = 10‰
Salinity	7–29% NaCl equiv.; 1–3 NaCl–barite	7–42% NaCl equiv.

and economic metals. (2) Geochemical association of Fe–Cu–Au–Ag–Ni–Ba–F–REE. (3) Structural control of hydrothermal mineralization along the shear zone. (4) Distal Na–K and proximal K–Fe alteration. (5) Mineralization is associated with chlorite alteration. (6) Multiple hydrothermal breccia with magnetite matrix as a characteristic feature. (7) Mineralization is synchronous with Mul granite intrusion (1587 Ma) (Table 3). (8) Presence of favourable H_2O–CO_2–CH_4 fluids in the mineralization system. (9) Occurs in the craton margin for high heat flow, appears to be the favourable site for IOCG-type mineralization. (10) Trace element analysis of magnetite by EPMA also shows IOCG type for Thanewasna copper deposit. Thanewasna Cu deposit exhibits the aforesaid characteristics similar to many IOCG type deposits of the world. It is proposed that this deposit may be grouped into the IOCG genetic type. Several genetic models for the IOCG deposits have been proposed during the last 24 years in Gawler Craton IOCG Province, South Australia[1,3,5,34,35]; Cluncurry, Australia[28,37]; Fennoscandnavia,

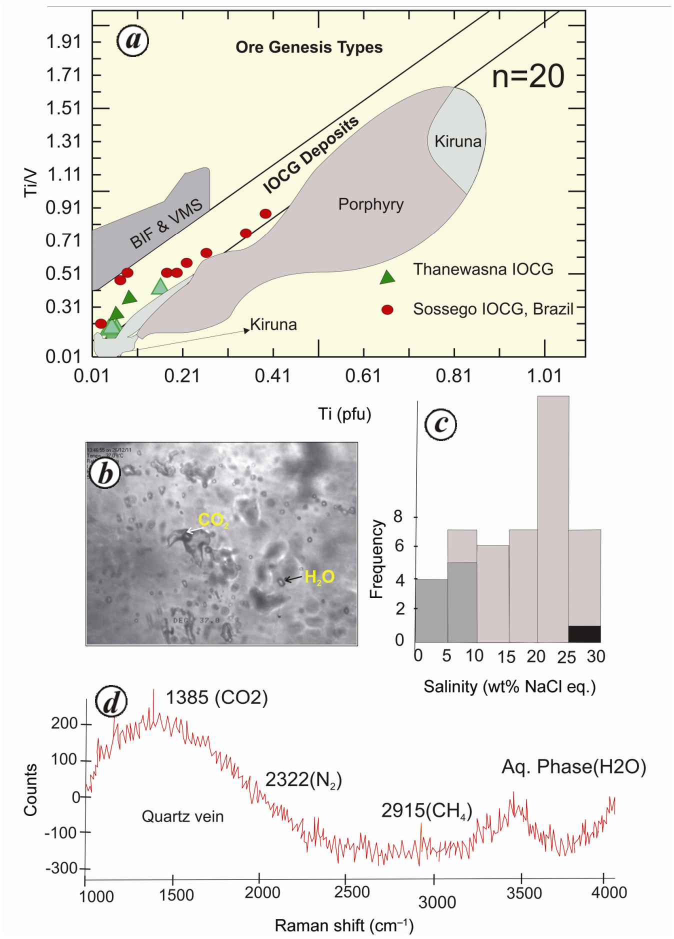

Figure 3. ***a***, Trace element composition of magnetite (Ti versus Ti/V) showing IOCG signature, field of Kiruna, BIF, VMS and porphyry at Thanewasna (after Monteiro *et al.*[26]). ***b***, ***c***, Photomicrograph and histogram representing microthermometric data of the primary fluid inclusions illustrating (***b***) two-phase aqueous fluid inclusions (CO_2–H_2O-rich) showing dark bubble and (***c***) salinity (wt% NaCl equiv.). ***d***, Raman spectra of CO_2 and other gases and aqueous phase from mineralized fluid at Thanewasna IOCG.

Sweden[33]; Great Bear, Canada; Candelaria-Punte del Cobre[31], Chile; Marcona IOCG district in southern Peru; Rajasthan, India[18,38]; Para State, Brazil[26]; Ruigtepoort, South Africa and SW China[39]. Among the known IOCG deposits, the Thanewasna deposit is perhaps more or less similar to giant Olympic Dam, Australia[9] (Table 3) and Candelaria-Punte del Cobre, Chile[31].

Entrepreneurs have shown their exploration interest in this type of deposit due to persistence of mineralization up to great depth (~10 km)[13]. The present study would not only throw light on the genetic aspect but also guide in further deep exploration at Thanewasna, which may help in adding additional resources. New genetic type of deposit at Thanewasna also helps in the search for new deposits of economic importance in the adjoining areas of WBC and Pakhal rift-bound sediments (M. L. Dora, unpublished data), where many of the favourable ironstones are poorly known. Hence, it is an IOCG deposit in WBC which focuses on the regional and local geological features that can help unveil prospective zones and targets in these terrains which may otherwise have been ignored or underexplored.

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