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Fluid Inclusion Petrography and Microthermometry of Barren/Mineralized Quartz Veins-Reef of Malanjkhand Cu Deposit, Central India: Implication on Ore and Non-Ore Forming Environment

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Abstract

Quartz reefs and veins of variable thickness have been intruded in host Paleoproterozoic Malanjkhand granites in the mine area and are primarily restricted to phyllic as well as potassic alteration zones. They are mainly of two types: mineralized and barren. Fluid inclusion petrography depicts mainly five types of inclusion which are aqueous biphase, monophase, monocarbonic, H_2O-CO_2 and polyphase (L+V+H). They are called here Type I, Type II, Type III, Type IV, and Type V, respectively, and are present in both mineralized and barren quartz veins/reefs. All types of inclusion are common except type V, which appears rare in both. However, the sizes of type II and IV are unexpectedly small. The micro thermometry results imply a relatively high temperature (209.4-376.4°C) of fluid entrapment in the mineralized counterpart. However, it is considerably lower (133.9-182.2°C) for the barren counterpart. Although the salinity of fluid appears low for mineralized quartz veins/reef (0.63-0.87 wt.% NaCl equivalent), while for barren counterpart, it is considerably higher (0.92-0.98 wt.% NaCl equivalent). The observed textural and microthermometry results advocate that the Malanjkhand hydrothermal system has resemblances with the porphyry system and indicates probable genetic linkage between barren and mineralized quartz veins/reef.

Keywords: Fluid Inclusions, Quartz Veins/Reef, Aqueous Inclusions

Introduction

Fluid inclusion studies in hydrothermal ore deposits have recognized to be an important instrument for obliging the physico-chemical conditions of the hydrothermal fluids responsible for vast and pervasive alteration and mineralization processes (Bean and Titley, 1984; Roedder, 1984; Bodnar *et al.*, 2014). The fluid-inclusion physiognomies, such as fluid composition, temperature, and density, vary in different types of ore deposits. Because of the variation in these parameters, fluid inclusions are considered a useful tool for mineral exploration (Haynes and Kesler, 1987; Noronha *et al.*, 1992). Fluid evolution and ore mineral precipitation in hydrothermal systems are recorded by multiple generations of fluid inclusion assemblages and mineral inclusions, and their trapping sequence can be established through careful thin-section petrography (Klemm *et al.*, 2008; Seo *et al.*, 2009).

Due to their economic significance, Malanjkhand Cu deposits have been intensely investigated and much is known about the host-granite forming environment, age, andtectonism (Sarkar *et al.*, 1996; Panigrahi and Mookherjee, 1997; Sikka and Nehru, 1997; Stein *et al.*, 2004; Asthana *et al.*, 2016). However, the fluid inclusion studies of mineralized and barren quartz veins and reefs are relatively less and produce variable results (Jaireth and Sharma, 1986; Panigrahi *et al.*, 2008). Moreover, it is still a major debate whether the Malanjkhand Cu deposit is a porphyry deposit or not. The present work is focused on the fluid inclusion study of mineralized and barren quartz veins and reef in order to find the nature of fluid, temperature of fluid entrapment and to established the genetic link between barren and mineralized quartz reef. Attempts have also been made to test its very porphyry nature.

Geology of the Area

Malanjkhand is associated with three different lithological terranes: the Sausar Mobile Belt (SMB) to the northwest, which forms the southern part of the Central India Tectonic Zone (CITZ); the Sakoli Fold belt (SF) to the southwest; the Kotri-Dongargarh (KD) belt to the south. The Sausar Mobile Belt (SMB) lies to the northwest part of Malanjkhand and marks the northern part of CIS (Fig. 1a). The southernmost unit in the SMB is the Bhandara-Balaghat granulite domain bounded by the CIS to the south. The Ramakona-Katangi granulite belt lies to the northwest of CIS (Stein

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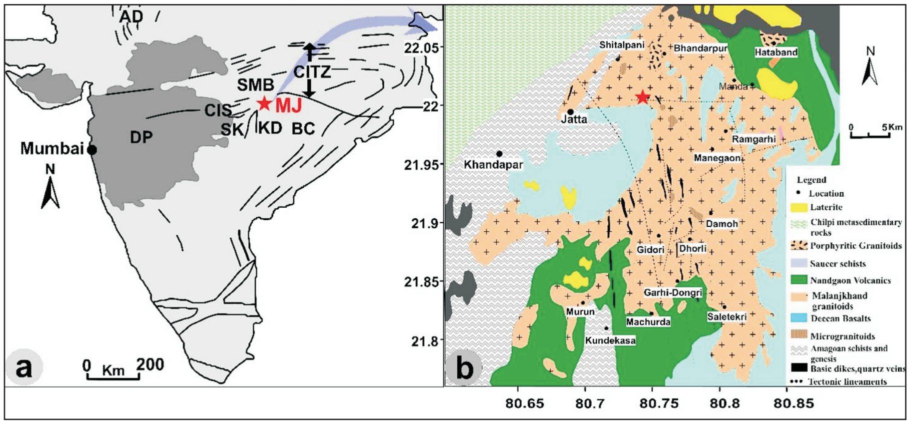

Fig.1. (a) Generalized tectonic map of central and peninsular India (after Acharyya and Roy, 2000; Stein et al., 2004). AD: Aravalli Delhi Fold Belt, CITZ: Central Indian Tectonic Zone, SMB: Satpura Mobile Belt, CIS: Central Indian Shear, SK: Sakoli Fold Belt, KD: Kotri Dongargarh Belt, BC: Bastar Craton, DP: Deccan Provenance; MJ: Malanjkhand; (b) Geological map of Malanjkhand and surrounding area (*After* Bhargava and Pal, 2006; Kumar and Rino, 2006)

et al., 2004). The western part of peninsular India is covered by the vast and widespread volcanic-plutonic complexes of the Deccan Province (Bhowmik *et al.,* 1999, 2000; Pal and Bhargava, 1998; Bhargava and Pal, 2000; Arya *et al.,* 2018, 2021; Arya and Gupta 2022).

The geology of Malanjkhand pluton and associated lithotypes including the mineralization aspects have been discussed systematically in previous publications (Tripathi, 1979; Rai and Venkatesh, 1993; Sikka and Nehru, 1997; Panigrahi and Mookherjee, 1997; Pal and Bhargava, 1998; Stein *et al.,* 2004; Kumar *et al.,* 2004a, b; Kumar and Rino, 2006, 2007; Arya *et al.,* 2018, 2021; Arya and Gupta 2022). Malanjkhand pluton is an elongated N-S trending composite felsic body emplaced at a shallow level and is situated in the Balaghat district of Madhya Pradesh, covering an area of ca. 1500 sq. km (Fig. 1b). The granitoids of Malanjkhand pluton are associated with the Nandgaon Group of volcano-sedimentary lithounits (Ramachandra and Rao, 1998), and are overlain by the Chilpi metasediments in the south-eastern and western parts of the pluton. The older Amgaon schist and gneisses are exposed in the northwest and west of Pluton, respectively. Nandgaon volcanics are exposed in the south and east of Pluton. In the northeast of Malanjkhand pluton, the Deccan volcanics are exposed.

Sample Selection and Methodology

Representative samples of quartz reef and quartz veins of applicable thickness were collected from the Malanjkhand copper mine. It was properly marked with the respective location during sample collection to avoid mixing with samples from other locations. Out of all the samples collected from different locations, the best 8 samples comprising 4 mineralised and 4 barren quartz reef and veins samples are selected based on transparency and coarser grain size so that the inclusions can be easily seen.

The fluid inclusion study is carried out at the WIHG Fluid Inclusion Lab. For fluid inclusion analysis, doubly polished plates (0.05-0.1 mm thick) were prepared. Profuse water supply to prevent the damage of inclusions due to local heating and fine polishing on both surfaces was also used during sample preparation. For inclusion, petrography sample chips mounted on glass slides by Canada balsam are used, while for thermometric runs, dismounted chips of less than 1 cm size (convenient to use in the heating-cooling chamber) are used. The doubly polished sections were studied using optical microscopy, and small chips ($0.5 cm^2$) containing fluid inclusions were broken off and mounted in the heating/freezing stage. Photographs were taken from each microscope field of view for re-identification of individual inclusions. Fluid inclusions were also marked to relocate them for microthermometry. Microthermometry is performed using calibrated Linkam THMSG 600 fluid inclusion stage fitted on to Nikon E600 microscope. The data presented in Table. 1 is corrected within $\pm 0.2\ ^0C$ at sub-ambient temperature and $\pm 3\ ^0C$ at total homogenisation temperatures. Fluid inclusions were examined using a petrographic microscope to determine the size, shape, abundance, distribution and type of inclusions present in the rock samples. Individual inclusions were studied for their approximate size and the relativephase volumes using the spherical approximation (Roedder, 1984). Flicon computer program of Brown (1989) has been used for the fluid inclusion calculation.

Results and Discussion

Fluid Inclusion Petrography

Quartz in the reef as well as in the veinlets is considerably populated with fluid inclusions. Different samples contain more or less similar type of inclusions but they show a wide difference in the shape, size, position and abundance of the inclusions. Quartz reef

Table 1: Summarized microthermometry of type I and III of inclusions found in mineralized and barren quartz veins and reef.

Vein/reef type	Inclusion type	Homogenization range (^oC)	Avg. Homogenizations temperature (^oC)	Salinity (wt% NaCl equivalent)	Density (gm/cm^3)	Size and abundance
Mineralized quartz veins/reef	Type I : n=17 Type III : n=14	209.4-376.4 -	301.21 -	0.99-4.07 -	0.63-0.87 0.63-0.72	2-16 µm; most abundant 1-4 µm; common
Barren quartz veins/reef	Type I : n=13 Type III : n=16	133.9-182.2 -	158.24 -	3.92-13.19 -	0.92-0.98 0.53-0.75	2-10 µm; common <4 µm; most abundant

contains larger and abundant inclusions as compare to barren quartz veins. Monophase and biphase inclusions are common in all the samples type. Polyphase inclusion has been observed in only two samples. Fluid inclusions in quartz are generally very small (<20 microns). The inclusions occur as isolated, in clusters or in trails suggesting primary as well as secondary origin of inclusions. The primary inclusions in all the two ore associations are predominantly of aqueous biphase type while the secondary inclusions contain aqueous biphase, aqueous monophase and monophase pure carbonic inclusions. On the basis of detailed petrographic studies following type of inclusions have been observed in mineralised and non-mineralised samples:

Mineralized Quartz Veins/Reef

The mineralized quartz sample shows abundant inclusions. The following types of inclusions are present in the samples.

Type I: These are aqueous biphase inclusions (Fig.2a) comprising a liquid and a vapour at room temperature. They occur in almost all the quartz grains. Their liquid-vapor proportion varies from 85 to 90 vol% liquid and 15 to 10 vol% gas. The shape of the inclusion is circular, oval, irregular, tabular as well as rectangular. The size of the inclusions varies from < 2 microns to 16 microns. The gas bubble in some of the inclusions shows movement, while in others, it is stationary. These inclusions occur as isolated inclusions and along healed fractures as trails. The inclusions that occur in trails are secondary, while those present in scattered form are primary. The secondary inclusions that occur in trials are comparatively smaller than that of primary inclusions.

Type II: These are monophase aqueous inclusions (Fig.2a-b) at room temperature and are entirely liquid-filled. The average population density is low as compared to type I inclusions. These are mainly rounded, while some of them are irregularly subhedral. They occur as trails, while few of them occur as disseminations. The disseminated one is primary in origin, while those present in trials are secondary. However, some pseudo-secondary trails of this type of inclusions are also present. The size ranges from < 2 to 4 microns.

Type III: These are monophase carbonic inclusions (Fig.2a), which comprise the carbonic phase at room temperature. These inclusions are less abundant than biphase inclusions. They are mainly circular and less commonly irregular in shape. Size ranges from <1 to 4 microns. They are commonly secondary in origin and occur mainly along healed fractures. At places, they are found to coexist with biphase aqueous inclusions.

Type IV: These are H_2O-CO_2 inclusions (Fig.2 a-b), and the proportion of CO_2 is about 20% by volume. These are mainly circular in shape and size is up to 2 microns.

Type V: These are polyphase inclusions (L+V+Halite) and appear uncommon in abundance. The proportion of various phases present is 75:10:15 vol%, respectively. These are irregular in shape (Fig.2b).

Barren Quartz Veins/Reef

The sample of quartz contains smaller and fewer inclusions as compared to mineralized quartz reefs. Inclusion types present in this sample are as follow:

Type I: These are biphase aqueous inclusions (Fig.2c) at room temperature and similar to those present in mineralized samples. However, the variation observed in the population of these inclusions. These are uniformly distributed in all the grains. The primary inclusions are scattered all over the grains while these secondary inclusions are aligned along the healed fractures as trails. The size varies from 2 to 10 microns. The liquid to gas proportion is 90-95 to 10 -5 vol%, respectively. The bubble in some of the inclusions shows motion. Shape of these inclusions is irregular and oval while few are elongated.

Type II: These are monophase aqueous inclusions (Fig.2 c-d)

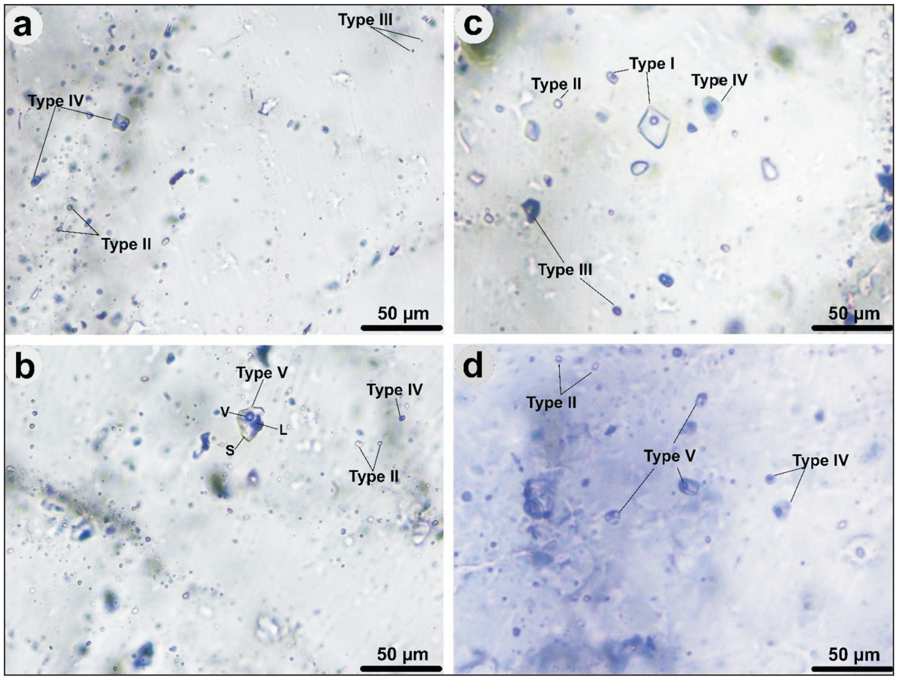

Fig.2. (a)Type II, III and IV inclusions in mineralized quartz vein, (b)Type II, IV and V inclusions in mineralized quartz reef, (c)Type I, II, III and IV inclusions in barren quartz reef, (d) Type II, IV and V inclusions in barren quartz vein.

at room temperature and are in abundance. They are present in various shapes including tabular, oval, and circular and subhedral. The size ranges from <2 microns to 6 microns. They are common in all the grains as disseminations and in the form of trails. They are primary as well as secondary in origin, respectively**.**

Type III: These are monophase carbonic inclusions (Fig.2c) and are most abundant. They occur mostly as disseminations as well as in trails. They are smaller in size up to 4 microns. They are usually rounded while few are irregular. They are mainly primary inclusions while few of them seem to be secondary in origin.

Type IV: These are H_2O-CO_2 inclusions (Fig.2 c-d) and the proportion varies from 40-70 vol% and 60-30 vol%, respectively. These are circular in shape and primaryin origin.

Type V: These are polyphase inclusions (L+V+Halite) and are relatively very uncommon in abundance. The proportion of various phases present is 55:30:15 vol%, respectively and are very irregular in shape (Fig.2d).

Microthermometry

The microthermometry results for Type I and III have been tabulated in Table. 1. However Type II and IV inclusions have not been utilised for thermometry due very small size while Type V due to uncommon abundance. Monophasic aqueous inclusions do not show any nucleation of the bubble hence, they are not metastable fluid. Cryometric data were obtained from the two types from both the bodies. The final ice melting temperature mineralized veins are relatively higher type I (-2.1 to -0.8°C), type III (-56.2 to –44.5°C). However, it is considerably low for barren quartz veins *i.e.,* type I (-9.3 to -1.4°C), type III (-63.1 to -53.6°C). Similarly, the homogenization temperature of mineralized quartz veins issubstantially higher than barren quartz veins. Nevertheless, the observed salinity and density of barren quartz veins are significantly higher than mineralized counterpart with respective types of inclusion (Table 1).

As mentioned above the monophase carbonic (type III) and H_2O-CO_2 (type IV) phase are common in both and type III gives temperature of melting of CO_2 -57 to -58.2°C intended for mineralized quartz vein. Similarly, for unmineralized quartz veins it provides -56.3 to -63.1°C. Which is close to temperature of melting of CO_2 (56.6oC). This agrees general trend observed in CO_2-H_2O and CO_2-H_2O-NaCl system where CO_2 preferentially fractionate to low density fluid. Moreover, it has been observed that those one phase aqueous inclusions occur along with vapour inclusions suggesting boiling condition during entrapment (Jaireth and Sharma, 1986). Hence, it is clear from petrography, microthermometry and above discussion that the primary inclusion has been precipitated through CO_2 bearing aqueous brine fluids. Additionally, it has been observed that the monophase aqueous inclusions occur along with vapour inclusions suggesting boiling of fluid during entrapment (Mollai *et al.*, 2009). Boiling has been shown to be one of the main mechanisms of ore deposition in many ore deposits particularly in copper porphyry deposits (Roedder, 1984). Freezing studies have shown that hydrothermal solutions entrapped in fluid inclusions were compositionally close to CO_2-bearing aqueous solutions of halite particularly for mineralized quartz veins. Hence, it is logical to conclude that basic ore-forming elements were transported mainly as chloride complexes. Moreover, there are few inclusions which do not homogenize up to the highest temperature limit suggesting liquid immiscibility existed during ore deposition and was probable favored the ore deposition. Interestingly, there are few inclusions which do not homogenize up to the highest temperature limit suggesting liquid immiscibility existed during ore deposition and was probable favored the ore deposition.

The result of fluid inclusion study suggests that the density and salinity of barren quartz isgreater than that of mineralized quartz reef. This is possible in cooling hydrothermal fluid with increase in salinity and density at later stages when mineral formation was ceased. Furthermore, higher temperature of formation of mineralized quartz veins probably depicts that it would be a prior event of ore deposition followed by barren fluid precipitation.Some of the known porphyry Cu deposits such as Porphyry Copper Deposit, Butte, Montana (Rusk and Mark*,* 2008) and Nannihu giant porphyry copper deposit, China (Yang *et al.*, 2012) are supposed to be form by moderate salinity CO_2-bearing fluid at moderate temperature. The same has been observed in Malanjkhand Cu-deposit. This possibly links Malanjkhand with porphyry system.

Conclusions

Mineralised quartz reef was formed from low CO_2-bearing H_2O rich hydrothermal solutions containing up to 5 wt% NaCl eq. salinity and was at temperatures between 209 and 376.4°C. The result of fluid inclusion study suggests that the density and salinity of barren quartz is greater than that of mineralized quartz reef. Barren quartz reef was formed at relatively lower temperature *i.e.*, 133.9 to 182.9°C. The very nature of fluid inclusion suggests its link with porphyry system.

Authors' Contributions:

DA: Conceptualization, Investigation, Formal Analysis, Writing-Original Draft, Methodology, Data Curation, Visualization, Supervision, Reviewing and Editing, Software. **SG:** Conceptualization, Investigation, Formal Analysis, Writing-Original Draft, Methodology, Data Curation, Visualization, Reviewing and Editing, Software. **GA:** Formal Analysis, Writing-Original Draft, Methodology, Data Curation, Visualization, Software.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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