


Sources of ore-forming fluid related to uranium mineralization in the Jahaz deposit, North Delhi Fold Belt, India: Inferences from carbon and oxygen isotopic studies

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ABSTRACT

The Jahaz uranium deposit is one of the several uranium occurrences along the “*albitite line*” of the North Delhi Fold Belt, India. U-mineralization in the Jahaz area is metasomatic-type, medium-tonnage, low-grade, and occurs as veins and dissemination in the intensely altered rocks. Detailed petrographic studies of the mineralized zones indicate a close association of calcite and metallic minerals. Hence, carbon and oxygen isotopic analyses of calcites were carried out to decipher the sources of hydrothermal fluids related to U-mineralization. The calcites of the Jahaz area are categorized into three types (calcite-1, calcite-2, and calcite-3) based on their mode of occurrences in host rocks. Calcite-2 and calcite-3, occurring in cavities and fractured portions of the rocks are linked to uranium-sulfide mineralization. The results of carbon and oxygen isotope analyses of calcite-2 and calcite-3 indicate that the hydrothermal fluids were derived from a magmatic source. The $\delta^{18}\text{O}$ values align with metamorphic fluids, while the slight positive correlation in the $\delta^{13}\text{C}-\delta^{18}\text{O}$ implies fluid mixing during calcite precipitation at a lower temperature. The isotopic signatures of $\delta^{18}\text{O}$ strongly suggest a mixing of fluids derived from granitic magmatism, metamorphism and meteoric nature. The close association of uranium and metasomatic mineral phases in intensely altered rocks indicates that fluid induced rock alterations played an important role to form enriched zones of uranium in Jahaz deposit.

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1. INTRODUCTION

Na-metasomatic uranium deposits are one among the 15 categories of uranium (U) deposits, well recognized globally, and occurs in Ukraine, Brazil, Canada, Australia, China, Cameroon and India (Dahlkamp, 2009). Na-metasomatism (albitization) is a hydrothermal process in which calcium and potassium in minerals are replaced by sodium (Norberg

et al., 2011). The Na-metasomatic uranium deposits are characterized by intense hydrothermal alterations such as chloritization, albitization, calcitization, and are closely related to U-mineralization (Cuney et al., 2012). Fluids responsible for the formation of Na-metasomatic U-deposits likely have diverse origins. Magmatic water is indicated in the Valhalla deposit (Polito et al., 2009), while a mixture of formation water and metamorphic sources has been attributed

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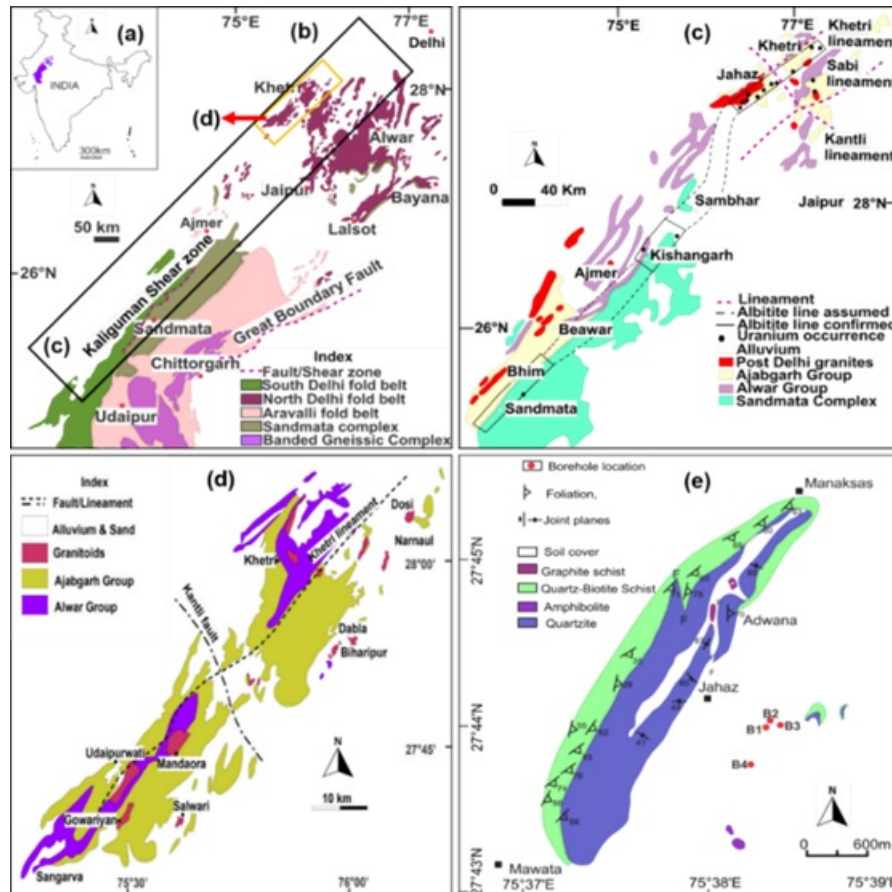


Fig. 1. (a) Inset: Aravalli Craton in NW India. (b) Geologic map of the Aravalli-Delhi fold belt (modified after Khanam et al., 2022). The black rectangular box is enlarged and given in Fig. 1c. The yellow rectangular box is enlarged and given in Fig. 1d. (c) Geologic map of the “albitite line” showing selected uranium occurrences in parts of the Indian states Rajasthan and Haryana (after Mishra et al., 2022). (d) Geologic map of Khetri Belt (after Kaur et al., 2015). (e) Geologic map of the study area Jahaz (after Mishra et al., 2022).

for Ukrainian deposits (Cuney et al., 2012). Other sources include fluids expelled from sedimentary sequences due to regional thrusting in the Lagoa Real deposit, Brazil (Lobato et al., 2015) and meteoric water in the case of Longshoushan deposit, China (Zhong et al., 2020).

The Atomic Minerals Directorate for Exploration and Research (AMDER) in India has been exploring Na-metasomatic type of uranium deposits since 1960. More than 350 localities with significant radioactive anomalies have been identified from the Khetri Belt (KB) of the North Delhi Fold Belt (NDFB; Jain et al., 1999; Fig. 1a–c). These localities are associated with various lithounits and lie within a 170 km long NNE–SSW trending shear zone known as the ‘albitite line’ along the Khetri lineament of the NDFB (Fig. 1c). The U-mineralization in the NDFB is of metasomatic type, low-grade and medium tonnage (Khandelwal et al., 2010). Jain et al. (2016) reported the mineralogical association and trace element content in the

rocks of the Jahaz area. Mishra et al. (2022) documented the stages of albitite formation and an association of sulfide-calcite minerals in altered rocks of the Jahaz deposit.

The carbon and oxygen isotopes are one of the reliable proxies to understand the source of hydrothermal fluids, due to their consistent fractionation and sensitivity to variations in temperature and pressure during fluid-rock interactions (Schauble, 2004). Hence, we made an attempt to infer the sources of ore-forming fluid based on the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses in calcite grains of albitized rocks, closely related to U-mineralization.

2. GEOLOGICAL SETTING

The Aravalli Craton, Rajasthan, is in the north-western part of Peninsular India, and comprises the Archean basement rocks and the Proterozoic fold belts (Fig. 1a, b) (Bhowmik and Dasgupta, 2012).

The Banded Gneissic Complex (BGC; Heron, 1953) and the Sandmata Complex (SC; Roy et al., 2012) are the basement rocks, and are unconformably overlain by the Proterozoic rocks of the Aravalli Fold Belt (AFB) and the Delhi Fold Belt (DFB; Meert et al., 2010). The rocks of DFB have been classified into an arenaceous-dominated older sequence (Alwar Group) and an argillaceous-dominated younger one (Ajabgarh Group; Sarkar and Dasgupta, 1980). The northern and southern parts of the DFB were affected by different deformation and metamorphic episodes (Naha and Roy, 1983; Kaur et al., 2011a). Hence, DFB has been divided into the North Delhi Fold Belt (NDFB) and the South Delhi Fold Belt (SDFB) based on depositional ages of ~ 1.72 Ga and ~ 1.05 Ga, respectively (Fareeduddin and Banerjee, 2020). The NDFB is further classified into three belts: Khetri, Alwar and Lalsot-Bayana (Fig. 1d; Singh, 1984). The Khetri Belt (KB) consists of quartzites, tremolite-bearing marbles, biotite schists (\pm garnetiferous-andalusite) and amphibolites. The KB has been divided into the North Khetri Belt (NKB) and the South Khetri Belt (SKB), separated by the NW-SE trending Kantli Fault (Gupta et al., 1998; Fig. 1d). The rocks of KB experienced four phases of deformation (Naha et al., 1988) and Kaur et al. (2017) recognized three metamorphic episodes in the KB. The rocks of KB were metasomatized extensively at ~ 900 – 850 Ma and can be correlated with the third metamorphic stage (U-Pb dating; Kaur et al., 2016).

The study area, Jahaz (Fig. 1e), is mostly soil-covered and rock exposures are found along the NNE-SSW trending Maota-Jahaz hill (Yadav et al., 2010). Quartzites, garnetiferous quartz-biotite schists, graphite-schists and amphibolites are the major metamorphic rocks found in the area and correlated with the Ajabgarh Group of SKB in the NDFB. Jain et al. (2016) reported a shear zone with extensive brecciation and alterations in the Jahaz area based on sub-surface borehole investigations. The metamorphic rocks are found to be albitized and brecciated to varying degrees. The uranium-sulfide mineralization is broadly confined to the brecciated and albitized metamorphic rocks (Mishra et al., 2022).

3. METHODOLOGY

Rock samples were collected from boreholes (B1–B4 as shown in Fig. 1e) and surface exposures near a river section of the Jahaz deposit. Polished thin-

sections were prepared and studied using a polarizing microscope NIKON ECLIPSE E200 at the Department of Earth Sciences, Indian Institute of Technology Roorkee (IIT), India. The calcite grains within albitized rocks are closely related with U-mineralization. Therefore, the C and O isotope analyses of representative calcite samples were carried out on Thermo Scientific MAT253 Plus 10 kV Thermo MAT 253 isotope ratio mass spectrometer (IRMS) with Kiel IV carbonate preparation device at the Stable Isotope Laboratory, Department of Earth Sciences (IIT Roorkee), India. The analytical procedure given by Zha et al. (2010) was adopted to delineate the isotopic composition of the samples. The results are presented as $\delta^{13}\text{C}_{\text{VPDB}}$ and $\delta^{18}\text{O}_{\text{VSMOW}}$ relative to Vienna Pee Dee Belemnite (VPDB) and Vienna Standard Mean Ocean Water (VSMOW). The analytical precision is 0.01‰ for $\delta^{13}\text{C}$ and 0.03‰ for $\delta^{18}\text{O}$.

4. RESULTS

4.1. Petrography of rocks

The host rocks are divided into three categories based on the intensity of alteration: unaltered, less to moderately, and intensely altered rocks. Garnetiferous quartz biotite schist (GQBS; Fig. 2a), amphibolite (Fig. 2b), quartzite (Fig. 2c) and graphite schist are the dominant metamorphic rocks in the study area. The major minerals in the GQBS are biotite, quartz, plagioclase, muscovite and almandine (Fig. 2e). Amphibolite consists of ferro to magnesiohornblende, bytownite/anorthite, and quartz with a minor amount of ilmenite (Fig. 2f). Quartzite predominantly consists of quartz, whereas muscovite, orthoclase, and tourmaline are less abundant (Fig. 2g).

Less to moderately altered (LTMA) rocks have retained parent metamorphic minerals, color, and texture (Fig. 2h). The minerals of LTMA rocks formed due to the replacement of pre-existing metamorphic minerals, and are considered as the first metasomatic stage. Albite-1, calcite-1, amphibole-1, chlorite-1, quartz-1, and sericite formed due to the alteration of pre-existing minerals in the GQBS and amphibolite. The metasomatically formed minerals of intensely altered rocks occur in vugs and cavities, developed by dissolution and precipitation, and are termed as the second metasomatic stage (Fig. 2i). Albite-2 is feathery, calcite-2, amphibole-2, chlorite-2, apatite, and quartz-2 occur as veinlets and also in cavities (Fig. 2i–k). The uranium and sulfide (pyrite, pyrrhotite, chal-

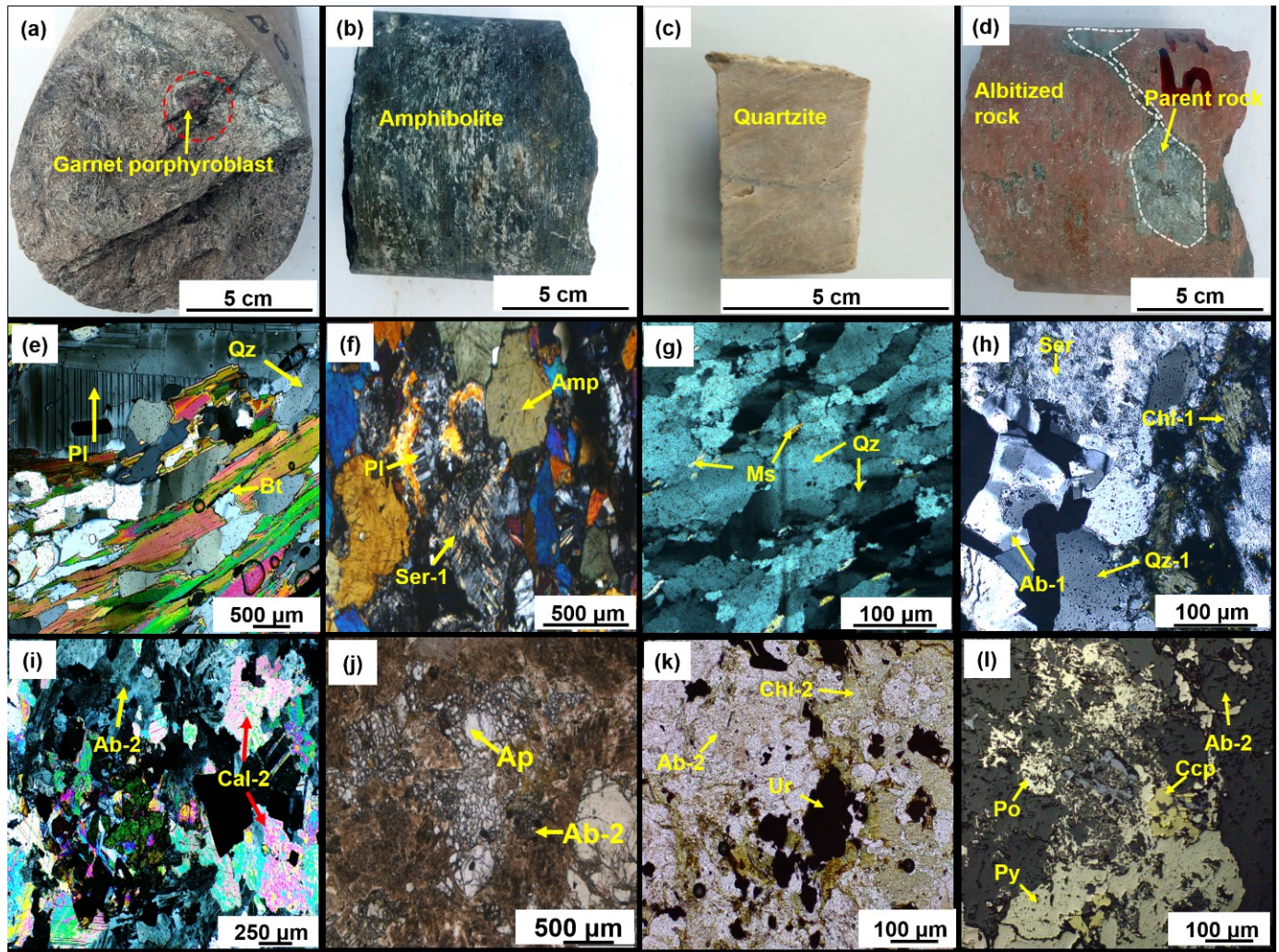


Fig. 2. Hand specimens (a–d): (a) Garnetiferous quartz biotite schist. (b) Amphibolite. (c) Quartzite. (d) Albitized rock. Photomicrographs (e–l): (e) Plagioclase, quartz and biotite in GQBS. (f) Amphibole and plagioclase closely associated in amphibolite. (g) Quartz and muscovite in quartzite. (h) Albite-1, quartz-1, chlorite-1 and sericite found in LTMA. (i) Albite-2 and calcite-2 in albitized rocks. (j) Apatite and albite-2 in the albitized rock. (k) The close association of Uranium, chlorite-2 and albite-2. (l) Chalcopyrite, pyrrhotite and pyrite found in albitized rocks. Abbreviations: Ab-Albite, Amp-Amphibole, Ap-Apatite, Bt-Biotite, Cal-Calcite, Ccp-Chalcopyrite, Chl-Chlorite, Ms-Muscovite, Pl-Plagioclase, Po-Pyrrhotite, Py-Pyrite, Qz-Quartz, Ser-Sericite, Ur-Uraninite.

copyrite, and molybdenite) minerals are closely associated with intensely altered rocks (Fig. 2k, l). It has also been observed in many thin sections that quartz-3 and calcite-3 occur as veinlets and are occasionally associated with pyrrhotite/chalcopyrite. These veinlets cut across both the altered and unaltered rocks and are related to late hydrothermal stage (Fig. 3b).

4.2. Petrography of calcite

The calcites are categorized into three types (calcite-1, calcite-2, and calcite-3) based on the mode of their occurrences in rocks (Fig. 3). Calcite-1 is very fine, sparsely present in the LTMA amphibolite/GQBS rocks and unassociated with mineraliza-

tion (Fig. 3a, d). In contrast, calcite-2 is coarse grained and occurs in cavities of the intensely altered amphibolite/GQBS (Fig. 3b, e). The calcite-2 is observed to be spatially and temporally associated with albite-2, chlorite-2 and sulfide mineralization in the albitized rocks. Therefore, the formation of uranium and calcite-2 are considered to be a part of the metasomatic assemblage. Calcite-3 is found within veinlets in fractured portions of the rocks and occasionally linked to sulfide mineralization (Fig. 3c, f).

4.3. Isotopic compositions

The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of calcite-2 and calcite-3 are summarized in Table 1. $\delta^{18}\text{O}$ values measured

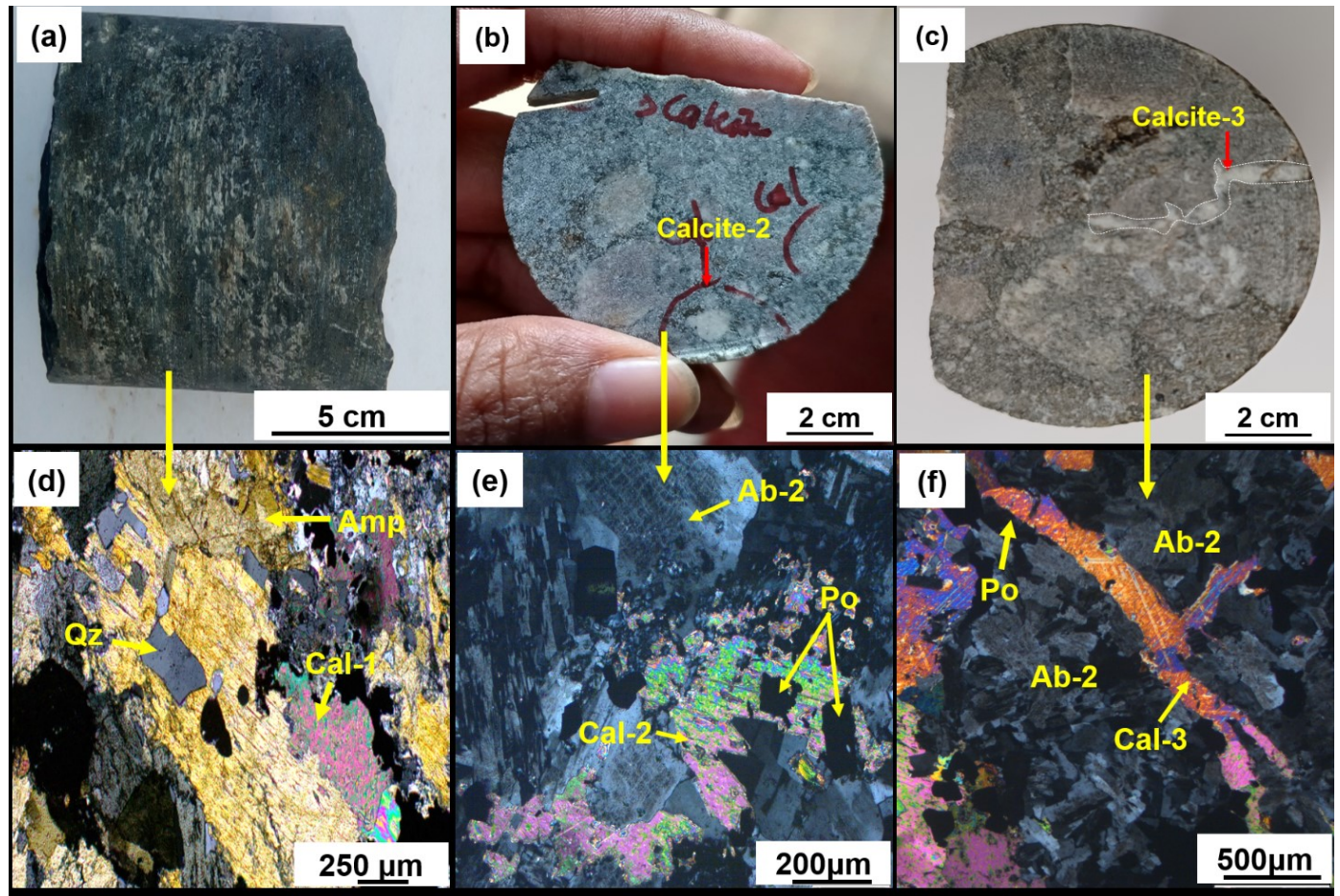


Fig. 3. (a) Hand specimen of less to moderately altered amphibolite. (b–c) Hand specimen of calcite-2 and calcite vein (calcite-3) associated with albitized rocks. (d) Calcite-1 in the LTMA amphibolite. (e) Calcite-2 and pyrrhotite. (f) Calcite-3 cross-cut albitized rock associated with pyrrhotite. Abbreviations: Ab-Albite, Amp-Amphibole, Cal-Calcite, Po-Pyrrhotite, Qz-Quartz.

Table 1. Carbon and oxygen isotopic compositions of calcite grains.

S.No.	$\delta^{13}\text{C}$ - VPDB	$\delta^{18}\text{O}$ -VPDB	$\delta^{18}\text{O}$ SMOW	Mineral
1	-6.15	-18.24	12.05	Calcite-3
2	-6.52	-16.82	13.52	Calcite-3
3	-6.53	-17.87	12.44	Calcite-3
4	-6.88	-18.43	11.86	Calcite-3
5	-7.11	-18.95	11.32	Calcite-3
6	-6.04	-19.46	10.80	Calcite-3
7	-6.78	-18.53	11.75	Calcite-2

against PDB were converted to the V-SMOW scale using the equation $\delta^{18}\text{O}$ (V-SMOW) = $1.03092 \times \delta^{18}\text{O}$ (PDB) + 30.92. For calcite-2, $\delta^{13}\text{C}$ (VPDB) and $\delta^{18}\text{O}$ (V-SMOW) values range from -6.78‰ and 11.75‰, respectively (Fig. 4a, b). In calcite-3, $\delta^{13}\text{C}$ (VPDB) values vary from -7.11‰ to -6.04‰, while $\delta^{18}\text{O}$ (V-SMOW) ranges from 10.8‰ to 13.52‰ (Fig. 4a, b). The $\delta^{13}\text{C}$ values of these calcites are depleted relative to PDB, falling between -7.11‰ and -6.78‰, while $\delta^{18}\text{O}$ values are enriched relative to V-SMOW, spanning 10.8‰ to 13.52‰ (Table 1).

5. DISCUSSION

The narrow $\delta^{13}\text{C}$ range of -7.11 to -6.78‰ suggests that the hydrothermal fluid from which calcite precipitated was derived from magma exsolution during a late magmatic stage, aligning well with the typical magmatic range of -7 to -2‰ (Fig. 4a; Rollinson, 1993; Zheng and Hoefs, 1993). The $\delta^{18}\text{O}$ values of calcites predominantly fall within the metamorphic fluid range, while also indicating contributions from other hydrothermal fluids, including granitic, sedi-

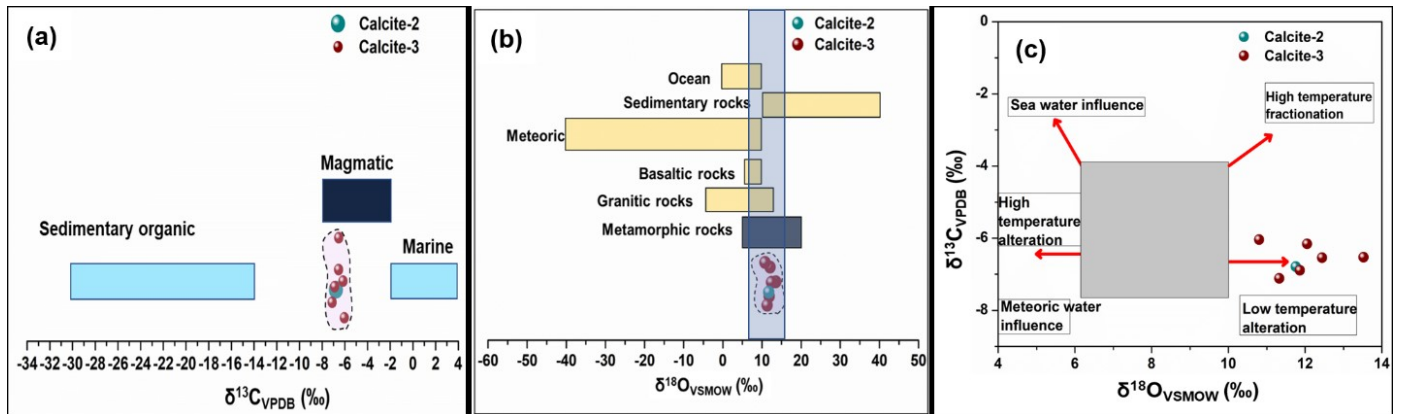


Fig. 4. Isotopic composition in calcites: (a) Carbon isotopic compositions (modified after Hu et al., 2022). (b) Oxygen isotopic compositions (modified after Zheng and Hoefs, 1993). (c) Carbon and oxygen isotope compositions (‰ relative to V-PDB and V-SMOW, respectively) of fluid calculated for calcites (modified after Demény et al., 1998).

mentary, and meteoric sources (Fig. 4b; Rollinson, 1993; Demény et al., 1998). The bivariate plot of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values for calcites (Fig. 4c) reveals a slight positive correlation, which may reflect the mixing of two isotopically distinct fluids or calcite precipitation influenced by temperature effects during fluid-rock interaction (Zheng and Hoefs, 1993; Zhou et al., 2018). The $\delta^{13}\text{C}$ (VPDB) versus $\delta^{18}\text{O}$ (V-SMOW) plot further supports the interpretation that the calcites in albitized rocks formed under low-temperature conditions (Fig. 4c). Thus, Fig. 4a and b indicate the contribution of fluids from similar sources related to the formation of both calcite-2 and calcite-3. This gives an idea that the fluids responsible for intense alterations continued to form minerals during the late hydrothermal stage. The isotopic signatures of $\delta^{18}\text{O}$ (Fig. 4b) strongly suggest a mixed fluid source, derived from granitic magmatism, metamorphism and meteoric input. The close association of uranium and metasomatic mineral phases in intensely altered rocks implies that fluid induced rock alterations played an important role to form enriched zones of uranium in Jahaz deposit.

6. CONCLUSIONS

1. The results of carbon and oxygen isotopic studies of calcite-2 and calcite-3 reveal that the hydrothermal fluids were derived from a magmatic source.
2. The $\delta^{18}\text{O}$ values primarily indicate interaction with metamorphic fluids, while the slight positive correlation in the $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ plot suggests fluid mixing or temperature effects during calcite precipitation.

3. The carbon-oxygen isotopic signatures of calcite strongly suggest a mixed fluid source, derived from granitic magmatism, metamorphism and meteoric input.
4. Magmatic and additional hydrothermal fluids were responsible for metasomatism and U-mineralization in the intensely altered rocks.

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