

Genesis of the Abu Marawat gold deposit, central Eastern Desert of Egypt

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ABSTRACT

Gold mineralisation at the Abu Marawat mine, central Eastern Desert of Egypt, is related to a system of massive and sheared, milky quartz veins cutting a sequence of Neoproterozoic island arc metavolcanic/volcaniclastic rocks and related banded iron formation (BIF). Sulphide-bearing quartz veins and related hydrothermal breccia bodies display a range of textures including sheared, boudinaged and recrystallised quartz, open space filling and microbreccia. These variable textures imply a complex history of crack-seal mechanism characterising the relation between mineral deposition and a major N–S-trending shear zone, during a late brittle–ductile deformation event which affected the area at about 550 Ma. Gold-base metal mineralisation is associated with brecciation and fracturing of the iron ore bands, close to silicified shears and related quartz veins. The auriferous quartz lodes are characterised by the occurrence of visible pyrite–chalcopyrite $\pm$ pyrrhotite $\pm$ sphalerite $\pm$ galena mineralisation. Gold is refractory in pyrite and chalcopyrite, but rare visible gold/electrum and telluride specks were observed in a few samples. Hydrothermal alteration includes pervasive silicification, pyritisation, sericitisation, carbonatisation confined to a delicate set of veins and altered shears, and a more widespread propylitic alteration assemblage (quartz + chlorite + pyrite + calcite $\pm$ epidote).

Fluid inclusion petrography and microthermometric studies suggest heterogeneous trapping of a low-salinity (1.4–6.7 wt.% eq. NaCl) aqueous solution and a carbonic fluid. Evidence for fluid immiscibility during ore formation includes variable liquid/vapour ratios in inclusions along individual trails and bulk inclusion homogenisation into liquid and occasionally to vapour at comparable temperatures. The trapping conditions of intragranular aqueous–carbonic inclusions approximate 264–378 °C at 700–1300 bar. Similar temperature estimates have been obtained from Al-in-chlorite geothermometry of chlorite associated with sulphides in the mineralised quartz veins. Fracturing enhanced fluid circulation through the wallrock and related BIF, allowing reaction of the S-bearing ore fluid with iron oxides. This caused pyrite formation and concomitant Au precipitation, enhanced by fluid immiscibility as H₂S partitioned preferentially into the carbonic phase. The ore fluids may have originated from granitoid intrusions (likely the post-Hammamat felsites, whereas gold and base metals might have been leached from the Abu Marawat basic metavolcanics).

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1. Introduction

Iron-formations in Archaean and Proterozoic greenstone belts on several continents are known to host economic quantities of gold (Pal and Mishra, 2002, and references therein). In Egypt, 14 occurrences of the banded iron formations (BIF) have been located, mostly in the central Eastern Desert. Similar to the iron ores of Archaean and younger volcanic terranes, the Egyptian iron formations are linked in time and space to volcanic activity (Sims and James, 1984; Botros, 1991; El Habaak and Soliman, 1999; Basta et al., 2000). The Abu Marawat area, ca. 40 km west of the Red Sea coast, is known as an Algoma-type banded iron occurrence in

the northernmost part of the central Eastern Desert of Egypt (e.g. Abdel Tawab and Zaki, 1987; Botros, 1991; Basta et al., 2000). Due to poor exposure of significantly auriferous quartz veins, gold mineralisation in the area has, however, received relatively little geological attention compared to the banded iron formation. Nevertheless, the presence of ancient mine workings associated with the BIF attracted several authors for thorough geochemical exploration for gold in the Abu Marawat area (e.g. Abdel Tawab and Zaki, 1987; EldougDoug, 1990; Botros, 1991; Dardir and El Shimi, 1992; El-Mezayen et al., 1995).

In association with Russian geological teams, the former Egyptian Geological Survey and Mining Authority (EGSMA) carried out a preliminary geochemical exploration program on the Abu Marawat area and reported several zones of geochemical anomalies/hydrothermal alteration potential for gold (Armanious, 1969;

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Sabet et al., 1977; Sabet and Bondanosov, 1984; Zaki et al., 1987; David, 1988; Botros, 1993). In 1987, Minex Minerals, a subsidiary of UK Greenwich Resources Plc, carried out a percussion and diamond drilling program. According to Minex Minerals, gold anomalies have been identified in two elongate, parallel zones (140 and 230 m long, and 5–10 m wide, respectively) of brecciated volcanic/volcaniclastic rocks and quartz stockwork. A scout program of percussion drilling was followed by 4140 m of diamond drilling from 26 holes. No details of analytical methods have been published. Eldougdoug (1990) mapped five alteration zones at the Abu Marawat area, in which assay data indicate gold concentrations ranging from traces up to 12 g/t Au in the intensively silicified volcaniclastic rocks.

The lack of detailed information on the nature and genesis of the gold-bearing quartz veins at the Abu Marawat area and their relation to both banded iron ores and shear zones warrants the present study. Structural controls on gold mineralisation, geologic context, ore mineralogy and fluid inclusion studies have been used to distinguish the auriferous quartz veins, in a way which may help to guide future exploration work in the Abu Marawat area.

2. Geological setting

The Neoproterozoic stratigraphy of the central Eastern Desert comprises island arc metavolcanic/volcaniclastic sequences locally overthrust by ophiolitic rocks and overlain by molasse-type Hammamat sediments and Dokhan Volcanics and intruded by post-Hammamat felsic subvolcanics (e.g. Akaad and El Ramly, 1960; El Ramly, 1972; Stern, 1981; Aly et al., 1991; Fig. 1). The island arc metavolcanic/volcaniclastic rocks are commonly associated with abundant banded iron formations, predominantly as oxide facies (e.g. Stern, 1981; Ries et al., 1983; Sturchio et al., 1983; El Ramly et al., 1984; Sims and James, 1984).

In the study area, the ophiolitic rocks form a ~N–S belt of allochthonous, tectonised serpentinite and related listvenite blocks

embedded in severely sheared matrix, which in turn is overthrust on sequences of felsic metavolcaniclastic rocks at the northern part of the study area (Fig. 2). The island arc rocks consist of calc-alkaline volcanic rocks (known as Abu Marawat metavolcanics), mainly of massive and laminated porphyritic rhyolite and rhyodacite, less abundant spilitised ferrobasic flows, volcanic breccias, dolerite and microgabbro dykes (EGSMA, 1992). The banded iron formations occur as ≤ 1 m thick bands alternating with the volcano-sedimentary succession at the high peaks of the Abu Marawat mountain. Botros (1991) suggested that the occurrence of pillowed basalt in the island arc successions may indicate early stages of immature island arc development. These rocks are generally metamorphosed under greenschist facies. The abundance of sub-aerial silicic lavas in the Abu Marawat metavolcanics suggests that they were erupted from a mature arc (e.g. Habib, 1987; Aly et al., 1991; Fowler et al., 2006). The arc-related plutonic rocks are manifested by coarse- and medium-grained hornblende gabbro and hornblende diorite. Intrusions of syn-tectonic tonalite and locally quartz-diorite cut the island arc rocks, and exhibit variable ductile deformation. Successions of subaerial volcanic rocks (Dokhan volcanics) mainly of quartz-feldspar porphyry and andesite porphyry are intercalated with siltstone, mudstone and polymictic conglomerate of molasse-type sediments (Hammamat Group).

Further classification of the island arc metavolcanic/metavolcaniclastic rocks includes mafic and felsic types. The mafic metavolcanics and related tuffaceous units occupy the southeastern part of the study area and are represented by massive flows and tuffs of meta-andesite and less common metabasalt/ferrobasic flows. They occur as massive or schistose rocks intensely jointed and fractured close to the major faults. The felsic metavolcanics are less common compared to the mafic metavolcanics, but are much more, at least spatially, linked to the hydrothermal alteration zones and related auriferous quartz veins. These felsic metavolcanics/volcaniclastics range in composition from dacite to rhyolite and in texture from banded schistose to tuffaceous. These rocks are highly deformed by the NW–SE and NE–SW joint/fault sets. Generally, the section of the metavolcanic rocks exposed at the Abu Marawat area is tectonically repeated and interrupted through several sub-parallel NW–SE strike-slip faults with obvious displacement attaining 1 km in some places (Fig. 2).

3. Structural setting

The central Eastern Desert is dominated by a strong NW–SE structural trend expressed in steeply dipping ductile–brittle shear zones and dissected by ENE deep-seated faults (Garson and Krs, 1976; Bennett and Mosley, 1987; Greiling et al., 1988). Structural studies document a continuous decrease of crustal shortening/ductile deformation from south to north (e.g. Fritz et al., 1996; Unzog and Kurz, 2000).

Planar and linear structures in the Abu Marawat area define three ductile to brittle deformational events namely D1, D2 and D3 (Figs. 1–3). Ductile deformation is clearly predating the brittle event, where mesoscopic and microscopic folds, fold axes and crenulations are displaced by transcurent faults and shear zones. Fig. 3 illustrates the relationship between the three fold trends and related structures. Abundant fold axes and asymmetries are best developed in the metavolcanic/volcaniclastic and allochthonous ophiolitic rocks (Fig. 3A). Structures assigned to D1 include large-scale, normal-sense ductile shear zones, a stretching lineation and NW-vergent tight, intrafolial folds with hinge lines parallel to the stretching lineation (L_1), which plunges from 30° to 12° towards NW. The axial-planar foliation, S_1 , is parallel to the bedding (S_0) of the Abu Marawat metavolcanics. S_1 develops a mylonitic or transposition character along the NW-trending highly

Ma	Event	Lithologic unit	Structures
500	Terrane uplift of the northern Eastern Desert & gravity collapse and extension (CED)	Alkali granites	Spaced cleavages and joints overprint D3 structures
		Dyke swarms	
550		Post-orogenic, pink granite	Left lateral and later gravity slip faults parallel to D3 (NNE–SSW)
		Post-Hammamat felsites	
600	Arc collision & crustal shortening	Hammamat molasse & Dokhan Volcanics	Najd sinistral transcurrent faults
650		Syn-tectonic granitoids	SE-vergent thrusts, F2 folds & N–S trending upright monoclinals and minor folds (F3) planar and linear structures
700		Pillowed metabasalt (ferrobasic flows)	Normal-sense ductile shear zones, S1 foliations, minor NW-vergent folds F1 and stretching lineation and lineation (L1)
750	Subduction	Abu Marawat metavolcanics	Bedding and So volcanic/volcaniclastic structures
800		Metagabbro-diorite	Not represented in the study area
850	Rifting	Metasediments	Allochthonous highly tectonized relicts formed elsewhere and transported to Abu Marawat area
900		Ophiolite	

Fig. 1. Compiled tectono-stratigraphic sequence of the Abu Marawat area and surroundings in the framework of the evolution of the northern Eastern Desert (based on our field observations, interpretations and Fowler et al., 2006, and references therein).

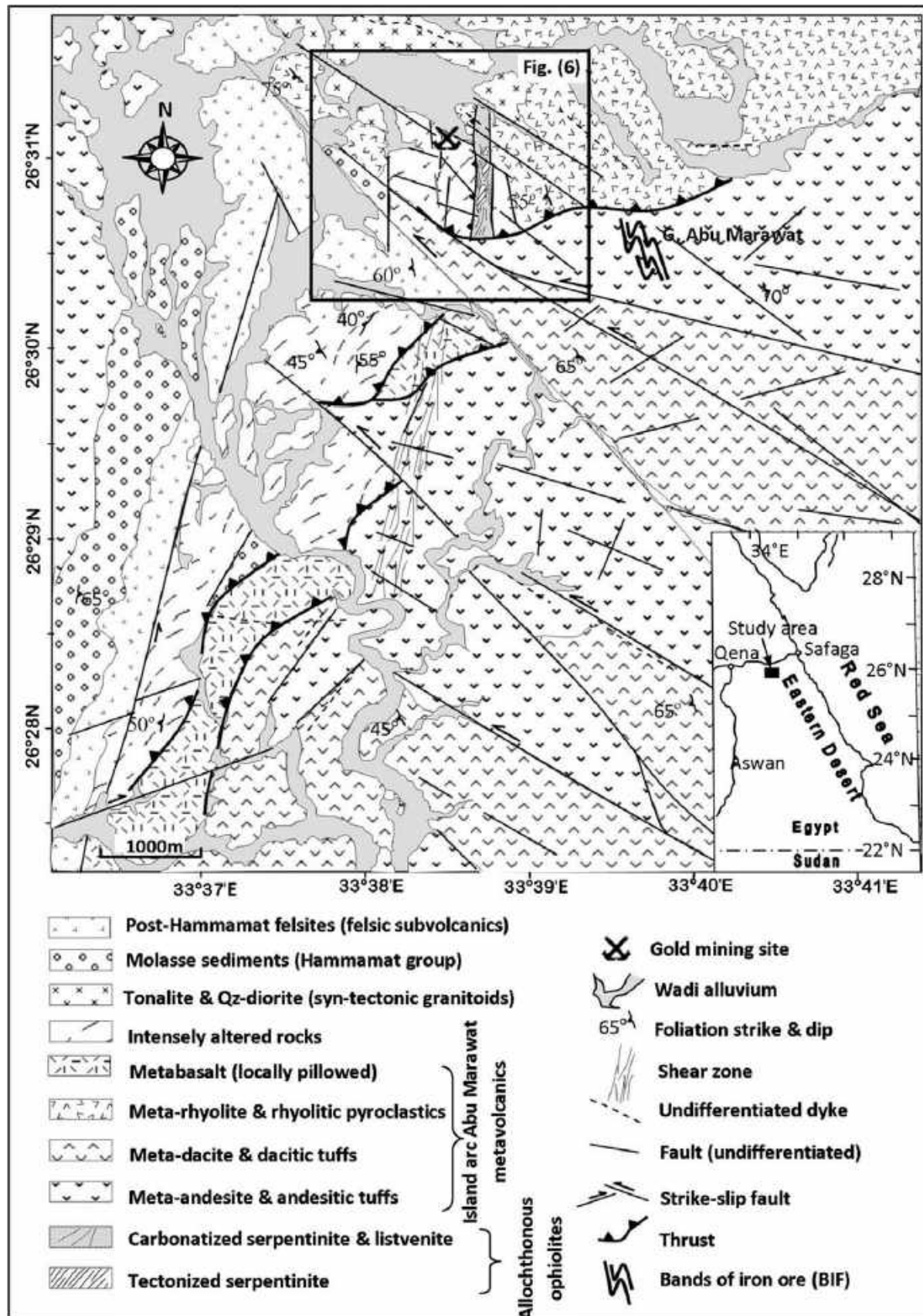


Fig. 2. Geologic map of the Abu Marawat area. (Modified from Abdel Tawab and Zaki, 1987; EldougDoug, 1990; Aly et al., 1991; El-Mezayen et al., 1995). Inset showing the location map.

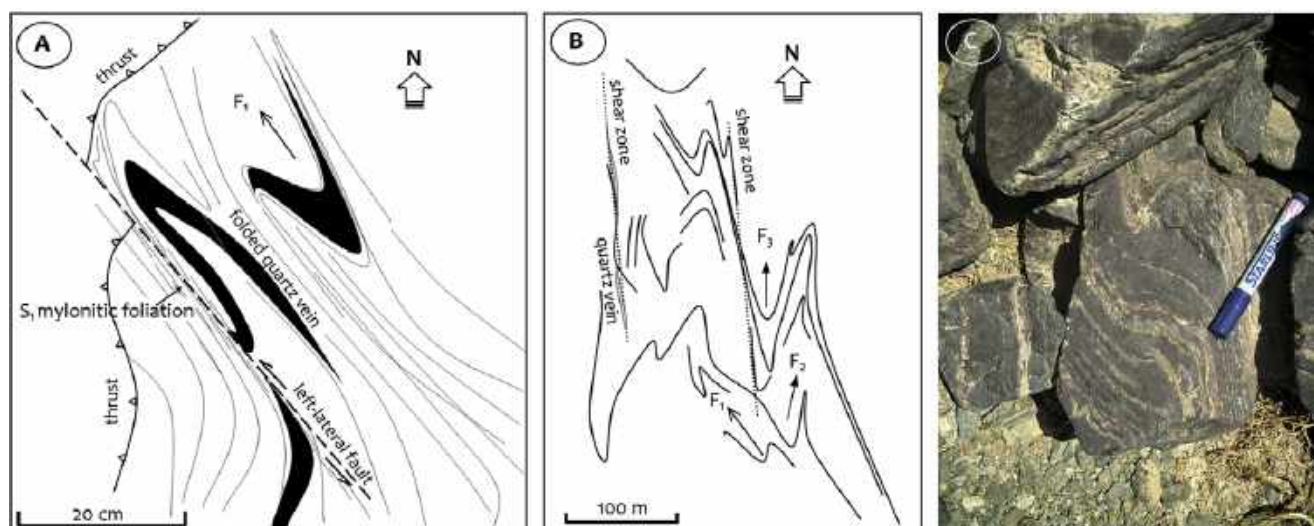


Fig. 3. (A) Field observation-based sketch showing intrafolial tightly folded quartz veins along NW–SE foliation disturbed by SE-vergent thrust and dislocated by co-axial left-lateral strike-slip fault. (B) Map-scale sketch illustrating the geometric and temporal relationships between the different fold generations, best observed in the BIF. The BIF bands are made of tightly folded, alternating iron-rich and silicate-rich layers.



Fig. 4. (A) N–S oriented S₃ crenulation foliation in carbonate-rich metavolcanic rocks. (B) Alteration halo and related mineralised veins along a major N–S shear zone (looking W). (C) Fault gouge and tectonic breccia associated with a N–S trending fault. (D) NNW–SSE bearing quartz veins displaced in a right-lateral sense by ESE–WNW faults.

deformed zones (Fig. 3B). Arc collision (~670 Ma) produced large listric SE-vergent thrusts that rotated the earlier units at moderate dips to the NE. F₂ folds likely developed at this stage (D2). The axial-planar, NNE-striking S₂ foliation dips steeply towards the east and is typical developed in the BIF (Fig. 3C). Steepening and folding of S₂ about approximately N–S upright axial planes (F₃ folds) took place during back-rotation of the NNE-thrusts and an E–W tectonic shortening event in the later stage of the collision (c.f. Habib et al., 1978; Fowler et al., 2006). Variable-size N–S folds are preserved in the felsic metavolcanic rocks and iron ore bands (Figs. 3b and c).

These folds are characterised by rounded hinges, pencil lineation and quartz boudins parallel to the foliation. S₃ is typically a crenulation cleavage which deforms the preexisting structures and is associated with co-axial shear planes (Fig. 4A). Gravity step faults that are parallel to S₃ are common and displace the quartz veins, with small net slips. N–S and E–W subvertical, spaced cleavages and joints overprint D3 structures and are considered to represent a late structural phase.

Numerous NW–SE strike-slip faults, best developed in the eastern part of the study area, are responsible for alternating,

juxtaposed slices of mafic and felsic metavolcanic/metavolcaniclastic rocks in the eastern part of the study area. Although the NW–SE strike-slip faults are distinct on Landsat imagery, drainage and alternating ridges are more strongly controlled by N- and NE-trending faults. Field observations indicate that an early sinistral displacement was overprinted by a late extensional one during the development of these faults. The NW–SE faults and related cleavage were modified by the N–S shears. The N–S faults and shear zones affect the island arc metavolcanic/volcaniclastics, allochthonous ophiolitic rocks and Hammamat sediments. The Hammamat molasse sediments and ferrobasaltic flows/breccias are highly tilted (80°) along major N- to NE-trending thrusts.

The alteration halo and related mineralised veins fill a distinct set of N–S fractures/shears (Fig. 4B). The variable plunge of striations related to the N–S faults indicate complex, overprinting displacements suggests that these faults are not only strike-slip but include oblique and normal varieties. Two generations of the N–S faults were identified, an older right-lateral strike-slip and younger left-lateral transtensive one commonly associated with fault gouge and tectonic breccia (Fig. 4C). Within the N–S oriented shear zones, the distance between shear planes is variable, ranging from a few centimetres to several metres. The shear planes are parallel, inter-linked or splayed. Less prominent ESE–WNW fractures and fault planes dissect the NW–SE and N–S fault trends and displace the NNW–SSE quartz veins in a right-lateral sense (Fig. 4D).

4. Hydrothermal alteration, lode geometry and mineralisation style

In the central part of the study area, an elongate, nearly N-trending alteration zone of intensely bleached felsic metavolcaniclastic rocks (see Fig. 4B) separates the island arc metavolcanic rocks in the east from the Hammamat molasse sediments and post-Hammamat felsites in the west. The dominant tectonic fabrics

in this zone are N–S striking shears and fractures which vary from 1 cm to 1 m in width, and locally merge into broad shear zones up to 20 m wide. Evidence of complex movements along the N–S shear zones is expressed by variable horizontal and oblique slip lineations and stretched quartz (Figs. 5A and B). Host rock on either side of these shear zones is fractured on 1–10 cm spacing, sub-parallel to the next shears, and deflection of S_3 foliation into the shear planes is distinct (Fig. 5C). Quartz veins and less common cement-supported breccias fill spaces in these structures (Fig. 5D). The host rocks and breccia fragments are pervasively altered to a quartz-carbonate-sericite assemblage, commonly with disseminated pyrite (variably oxidized) and carbonate veinlets. Hydrothermal alteration types throughout the shear zones include silicification, carbonatisation, sericitisation and iron oxides-staining. This alteration zone extends for several hundreds of metres, and is most intense close to the intersection of the N–S shears with the two major fault trends in the area, NW–SE and NE–SW.

Quartz veins (up to 5 m wide) are common along ESE–WNW ($N 108^\circ$) and N–S fracture trends (Fig. 6). Field observations, including crosscutting and overprinting relationships, indicate that the N–S-trending quartz veins are earlier than those trending ESE–WNW. The N–S veins are composed mainly of milky quartz, abundant wallrock selvages and disseminated sulphides. The internal inspection of these veins revealed two generations of quartz veins concomitant with fault re-opening and re-sealing (Fig. 7A). Adjacent to the N–S quartz veins, stockwork of quartz $\pm$ carbonate veins is best developed in the tectonised host rocks. The ESE–WNW trending quartz veins are made up essentially of massive milky quartz lacking wallrock selvages and sulphides. These veins are massive or cavernous and show splays. Some veins are boudinaged and are displaced by NNW–SSE right-lateral strike-slip faults. Other, less significant, generally thin (≤ 20 cm wide), quartz veins are common along the NW–SE fault trend. These veins are generally barren and exhibit massive, drusy and vuggy, or less commonly show fibrous structures (Fig. 7B).

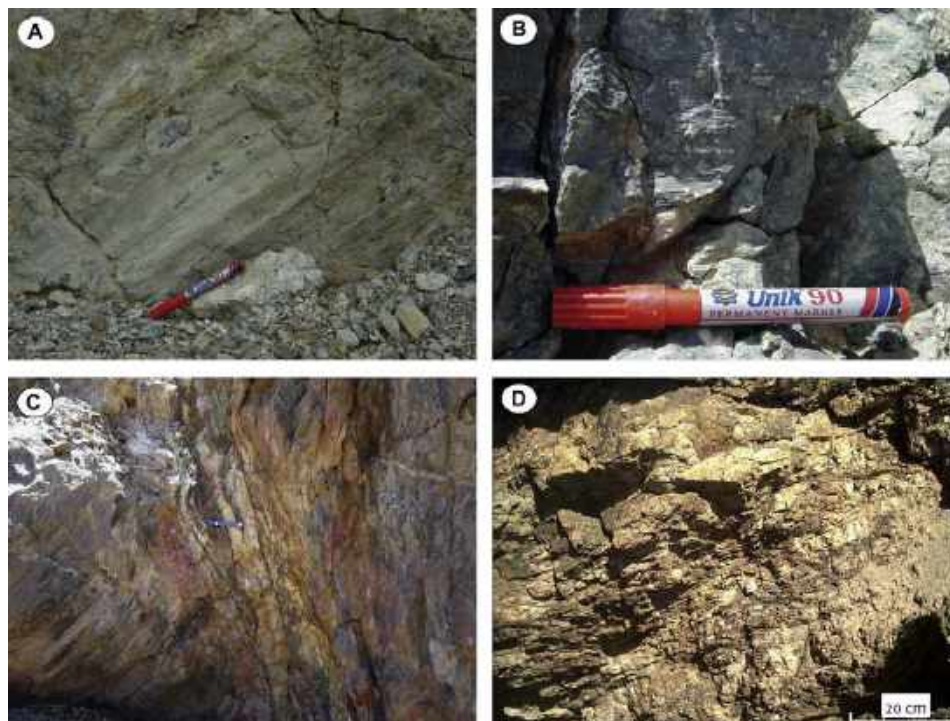


Fig. 5. (A) Moderately plunging slip lineation along the N–S shear zone (looking E). (B) Stretched quartz pockets along horizontal slip lineation within the N–S fault plane. (C) S_3 foliation deflected into the N–S shear planes and associated quartz vein (looking N). (D) Cement-supported breccia filling spaces in the N–S fault plane.

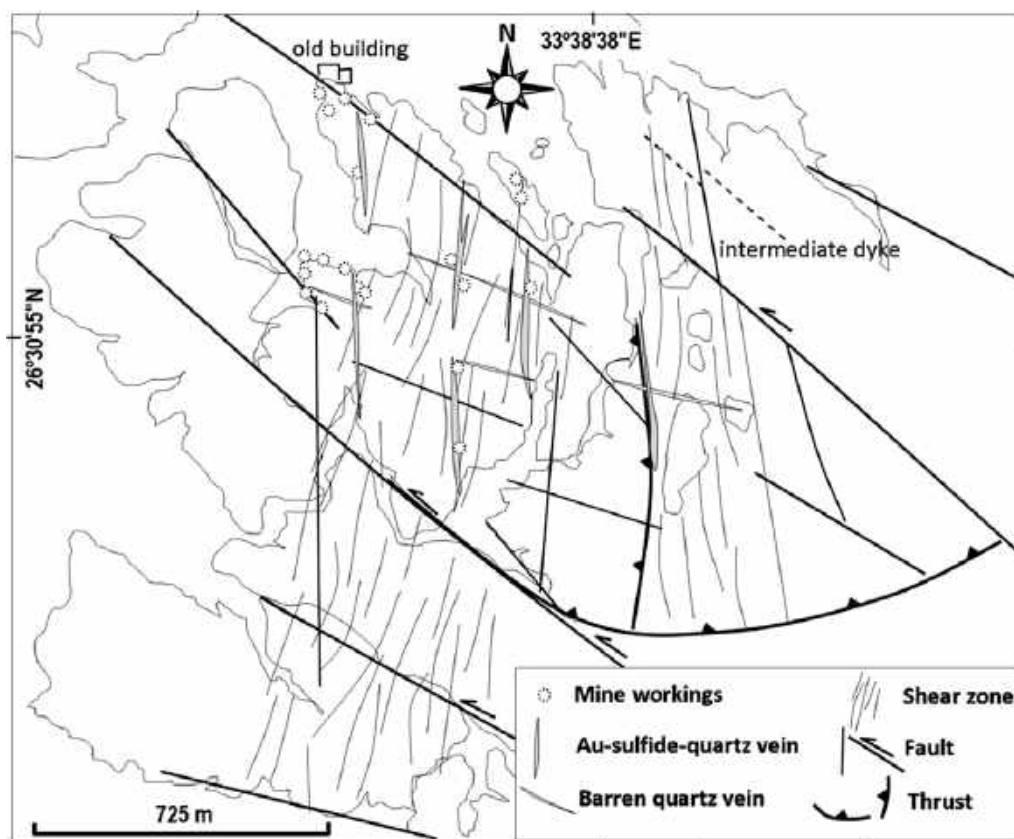


Fig. 6. Simplified map showing the distribution of the quartz veins at the Abu Marawat mine area in relation to the structural elements.



Fig. 7. (A) Two generations of quartz (older Q1 and younger Q2) in the N-S trending, mineralised quartz veins. (B) NW-SE-trending, barren quartz veins displaying vuggy structures.

The mineralised veins are by and large oriented north–south and dip $\sim 70^\circ$ W. Vein widths are generally 1 m or less and commonly vary dramatically over short distances along strike or up and down dip. Variation in thickness is attributed to margin-parallel shear zones, especially in areas where NE–SW faults cross-cut the veins. Weak plastic deformation of the coarse-grained quartz is usually evident, though significant dynamic recrystallisation is atypical. Thin slivers of wallrock are locally present in massive fault-fill quartz. Such structures gradually merge into heavily veined wallrock adjacent to the shear zones. Gold lodes are made up mainly of granoblastic quartz, with chlorite + epidote + carbonate $\pm$ sericite and disseminated sulphides (Fig. 8A). Quartz grains form polygonal aggregates of variable sizes. Subgrain development and recrystallisation is limited to grain

boundaries of the large quartz crystals in the high strain domains, where displacement is generally concordant with the sense of shear along the host shear zone (Fig. 8B).

Chemical compositions of chlorite disseminated in the mineralised quartz veins, commonly confined to wallrock selvages, were obtained using a CAMECA SX 100 electron microprobe equipped with four wavelength-dispersive spectrometers, and a Noran energy-dispersive spectrometer, at the Technical University of Clausthal (TUC). The applied analytical conditions included 15 kV acceleration voltage, 40 nA current intensity, counting time is 10 s per element, and 1–5 μ m defocused electron beam diameter. Calibration was done with available natural and synthetic standards. The data show that the analyzed chlorites have generally iron-rich chlorite compositions (Table 1) with substantial

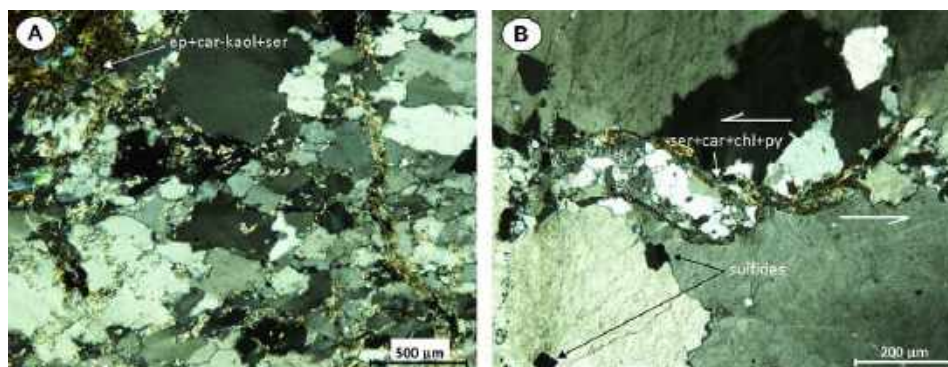


Fig. 8. (A) Granoblastic quartz, chlorite, epidote, carbonate and sericite as main constituents of the mineralised N–S quartz veins in Abu Marawat fold deposit. (B) Sulphides + alteration assemblage-rich shear plane within the mineralised quartz veins. Notice the association of quartz subgrains with the chlorite–carbonate–sericite–pyrite assemblage. Sinistral displacement along the shear plane is comparable to the sense of shear along the host shear zone (mineral symbols: ep = epidote, car = carbonate, kaol = kaolinite, ser = sericite, py = pyrite).

Table 1

Microprobe analyses of chlorite flakes disseminated in mineralised quartz veins from the Abu Marawat deposit.

	mch1	mch2	mch3	mch4	mch5	mch6	mch7	mch8	mch9	mch10	mch11	mch12
SiO ₂	26.74	24.97	24.81	26.04	23.93	25.02	24.86	25.98	26.01	24.65	25.41	24.40
TiO ₂	0.05	0.03	0.13	0.02	0.01	0.02	0.18	0.12	0.18	0.14	0.02	0.13
Al ₂ O ₃	22.68	21.27	22.13	21.32	22.64	22.34	21.87	21.39	21.71	22.44	22.07	22.08
FeO	31.20	30.12	31.32	27.89	32.81	29.38	30.47	29.76	29.26	31.19	29.92	32.43
MnO	0.15	0.21	0.19	0.21	0.22	0.21	0.16	0.18	0.19	0.18	0.16	0.22
MgO	8.76	11.52	10.45	12.49	9.93	11.71	11.24	12.16	11.93	10.47	11.61	9.80
CaO	0.69	0.98	0.02	0.05	0.23	0.34	0.03	0.04	0.31	0.31	0.07	0.05
Na ₂ O	0.02	0.01	0.00	0.01	0.04	0.00	0.01	0.00	0.04	0.04	0.02	0.00
K ₂ O	0.03	0.00	0.00	0.03	0.02	0.01	0.00	0.00	0.09	0.01	0.07	0.01
Cl	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	89.69	88.46	88.40	87.42	89.17	88.38	88.19	88.97	89.07	88.77	88.69	88.48
T2	12.58	12.83	12.85	12.74	12.88	12.73	12.83	12.63	12.60	12.80	12.70	12.94
<i>Structural formula based on 28 oxygens</i>												
Si	5.60	5.33	5.31	5.52	5.13	5.30	5.31	5.46	5.46	5.25	5.37	5.25
Ti	0.01	0.00	0.02	0.00	0.00	0.00	0.03	0.02	0.03	0.02	0.00	0.02
Al ^{iv}	2.40	2.67	2.69	2.48	2.87	2.70	2.69	2.54	2.54	2.75	2.63	2.75
Al ^{vi}	3.20	2.68	2.89	2.85	2.85	2.88	2.82	2.76	2.82	2.89	2.87	2.86
Al	5.60	5.35	5.58	5.33	5.72	5.58	5.51	5.30	5.37	5.64	5.50	5.60
Fe ⁱⁱ	5.46	5.38	5.60	4.95	5.88	5.21	5.44	5.23	5.13	5.56	5.29	5.84
Mn	0.03	0.04	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.04
Mg	2.74	3.66	3.33	3.95	3.17	3.70	3.58	3.81	3.73	3.33	3.66	3.15
Ca	0.15	0.22	0.01	0.01	0.05	0.08	0.01	0.01	0.07	0.07	0.01	0.01
Na	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.02	0.02	0.01	0.00
K	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.03	0.00	0.02	0.00
Cl	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Total	19.60	19.99	19.88	19.82	20.02	19.91	19.91	19.87	19.85	19.92	19.89	19.92
Fe/(Fe + Mg)	0.67	0.59	0.63	0.56	0.65	0.58	0.60	0.58	0.58	0.63	0.59	0.65
Al ^{iv} c	2.87	3.09	3.13	2.87	3.33	3.11	3.11	2.94	2.95	3.18	3.04	3.20
T (°C)	322	345	350	322	370	347	348	330	331	356	340	357

T (°C) = temperature estimates calculated according to Cathelineau (1988); Al^{iv}c = Al in tetrahedral sites according to Kranidiotis and MacLean (1987).

variations in FeO (27.89–32.43 wt.%), and MgO (8.76–12.49 wt.%). Variations in SiO₂, Al₂O₃ and MnO concentrations are limited. The contents of TiO₂, MnO, CaO, K₂O and Na₂O are uniformly low. The Al^{iv}-in-chlorite thermometry of Cathelineau (1988) and Kranidiotis and MacLean (1987), indicates a temperature range of 322–370 °C (Table 1), with particular temperature increase in zones where disseminated sulphides are abundant in the mineralised quartz veins.

Sericite occurs as fine-grained flakes, commonly associated with chlorite in quartz vein and adjacent wallrocks. Chemical compositional variations are controlled by phengitic substitution of Si for Al (Table 2). This is confirmed by the negative correlation between (Si + Mg + Fe²⁺) versus (Al^{iv} + Al^{vi}). Enrichment in Al^{vi} and

K in grain margins relative to their cores is attributed to some degrees of paired substitution of (Si, Mg, Fe) for Al. Constant Fe# [Fe/(Fe + Mg)] may indicate homogeneity of the circulating fluid and/or uniform host rock composition. Carbonate minerals partially or completely replace chlorite and intermingle with sericite. Chemically, the carbonate patches and disseminations have homogenous composition, mainly of calcite, while siderite, ferroan dolomite, ankerite and rhodochrosite components do not exceed 25 mol.% (Table 2). Higher concentrations of sulphide minerals are common in zones where carbonate minerals are substantial constituents of the veins and wallrock. Abundant disseminated apatite is distinct in zones where carbonate and sericite are dominant. Microprobe analyses of some apatite crystals showed fluorine content up to

Table 2

Microprobe data of sericite and carbonate disseminated in the mineralised quartz veins of Abu Marawat gold deposit.

	Sericite					Carbonate			
	ms_1	ms_2	ms_3	ms_4		mc_1	mc_2	mc_3	mc_4
SiO ₂	47.74	49.00	48.37	48.18	CaO	66.40	65.85	64.15	50.38
TiO ₂	0.11	0.18	0.12	0.40	MgO	0.34	0.59	0.58	1.36
Al ₂ O ₃	38.68	39.33	39.98	39.54	FeO	3.37	1.89	3.40	7.02
Cr ₂ O ₃	0.18	0.14	0.05	0.20	MnO	1.21	1.38	0.59	1.25
V ₂ O ₃	2.07	0.90	0.24	0.44	TiO ₂	0.00	0.00	0.00	0.01
FeO	0.99	1.21	1.20	1.32	<i>Structural formulae basis on cation per 2 oxygen atoms</i>				
MnO	0.00	0.01	0.00	0.00	Ca	0.93	0.94	0.93	0.84
MgO	0.11	0.15	0.17	0.18	Mg	0.00	0.01	0.01	0.02
CaO	0.05	0.12	0.01	0.10	Fe	0.05	0.03	0.05	0.12
Na ₂ O	0.66	0.71	1.02	0.76	Mn	0.02	0.02	0.01	0.02
K ₂ O	4.99	4.70	5.18	4.64	Ti	0.00	0.00	0.00	0.00
Ba	0.08	0.02	0.02	0.03	CaCO ₃	93.10	94.47	93.36	83.95
Cl	0.01	0.00	0.00	0.01	MgCO ₃	0.48	0.84	0.85	2.26
F	0.00	0.00	0.00	0.00	FeCO ₃	4.73	2.71	4.94	11.69
Total	95.02	95.81	95.71	95.13	MnCO ₃	1.70	1.98	0.86	2.1
<i>Structural formula based on 22 anions</i>					Sum	100	100	100	100
Si	6.12	6.19	6.13	6.13	MgCO ₃	0.00	0.00	1.00	2.00
Ti	0.01	0.02	0.01	0.04	CaCO ₃	86.20	88.94	85.71	67.92
Al ^{iv}	1.88	1.81	1.87	1.87	CaMg(CO ₃) ₂	0.95	1.68	1.69	4.52
Al ^{vi}	3.96	4.05	4.11	4.07	CaFe(CO ₃) ₂	9.46	5.42	9.88	23.38
Al	5.84	5.86	5.97	5.93	CaMn(CO ₃) ₂	3.40	3.97	1.72	4.18
Cr	0.02	0.01	0.00	0.02	Sum	100.00	100.00	100.00	100.00
V	0.21	0.09	0.02	0.04	Fe#	0.909	0.763	0.854	0.838
Fe ⁱⁱ	0.11	0.13	0.13	0.14	Mg#	0.069	0.152	0.127	0.141
Mn	0.00	0.00	0.00	0.00	Fe/Mg	9.950	3.227	5.833	5.170
Mg	0.02	0.03	0.03	0.03	Fe-Mg	0.000	0.000	0.000	0.003
Ca	0.01	0.02	0.00	0.01					
Na	0.17	0.17	0.25	0.19					
K	0.82	0.76	0.84	0.75					
Ba	0.00	0.00	0.00	0.00					
Cl	0.00	0.00	0.00	0.00					
F	0.00	0.00	0.00	0.00					
Total	13.32	13.27	13.40	13.30					
Fe/(Fe + Mg)	0.84	0.82	0.80	0.80					
XM _s	0.83	0.81	0.77	0.80					

nearly 7 wt.%. Other hydrothermal phases include rutile and subordinate epidote. Goethite is common, and is likely of supergene origin (weathering of pyrite).

[Eldougdoug \(1990\)](#) described several alteration zones at the Abu Marawat area, in which gold anomalies are distinct. These zones are mostly confined to the felsic metavolcanic/volcaniclastic rocks intensely seamed with quartz veins. Gold contents vary from 1.7 to 12 g/t in the alteration zones (averaging 3.5 g/t, $n = 33$), while quartz veins contain from traces up to 4 g/t Au and 50 g/t Ag. In addition to Au and Ag, anomalous contents of Cu, Zn, Pb, Ni and Co were also reported in both alteration zones and associated quartz veins ([Eldougdoug, 1990](#)). Enrichment in Au characterises also the tectonised BIF bands and intimately associated mafic metavolcanic/tuffsaceous rocks (av. 1.75 g/t Au). [Eldougdoug \(1990\)](#) noted that the alteration zones are confined to fractures trending almost N–S parallel to the axial plane of the major anticline highlighted by the iron ore bands (see [Fig. 2](#)).

Gold-base metal mineralisation is associated with brecciation and fracturing of the metavolcanic/volcaniclastic rocks and related BIF, close to silicified shears and related quartz veins. The auriferous quartz lodes are characterised by the occurrence of visible pyrite-chalcopryrite $\pm$ pyrrhotite $\pm$ sphalerite $\pm$ galena mineralisation. The distribution of pyrite and pyrrhotite varies throughout the mineralised veins, with pyrite being the most abundant ore mineral at a nearly constant concentration of about 80% of all sulphide phases, commonly associated with magnetite. Mixtures of chlorite, sericite, carbonate and dispersed rutile are commonly associated with disseminated sulphides in the mineralised quartz veins ([Fig. 9A](#)). Concentration of pyrrhotite increases

at zones where deformation is more intense, where pyrite is less common. The pyrite-chalcopryrite $\pm$ pyrrhotite after magnetite $\pm$ hematite assemblage is pervasive along vein margins, at contacts with the wallrock, and appears to be contemporaneous to gold mineralisation. Subhedral pyrite is developed at the expense of pyrrhotite in some cases, and both are commonly altered into goethite. Microfractures in pyrite may be filled with galena, sphalerite and rutile. Chalcopryrite forms large to fine-grained, subhedral to anhedral grains associated with pyrite (particularly along alteration minerals-filled fractures in quartz veins ([Fig. 9B](#))). Galena is common as irregular disseminations in the quartz veins, filling fractures, or intergrown with chalcopryrite and sphalerite in recrystallised quartz. Deformation of ore minerals is evident from rotated and cataclastic pyrite porphyroblasts in the mineralised wallrocks ([Fig. 9C and D](#)). Rare visible gold/electrum particles were observed as inclusions within or close to pyrite and chalcopryrite, especially where carbonate patches are common ([Fig. 9E](#)). Fine specks of telluride phases have been observed in back-scattered images commonly associated with galena, replacing pyrite or along chalcopryrite grain boundaries ([Fig. 9F](#)). Supergene phases include covellite and barite that occupy secondary fractures affecting both quartz veins and host rock. Carbonate minerals corrode sulphide borders, suggesting recurrent carbonate alteration. A paragenetic sequence of the hydrothermal alteration phases, in which an assemblage of pyrite-chalcopryrite-pyrrhotite $\pm$ gold/telluride constitutes the main mineralisation stage based on the microscopic investigations ([Fig. 10](#)). Late supergene phases including covellite-goethite and barite replace the ore and pre-ore phases.

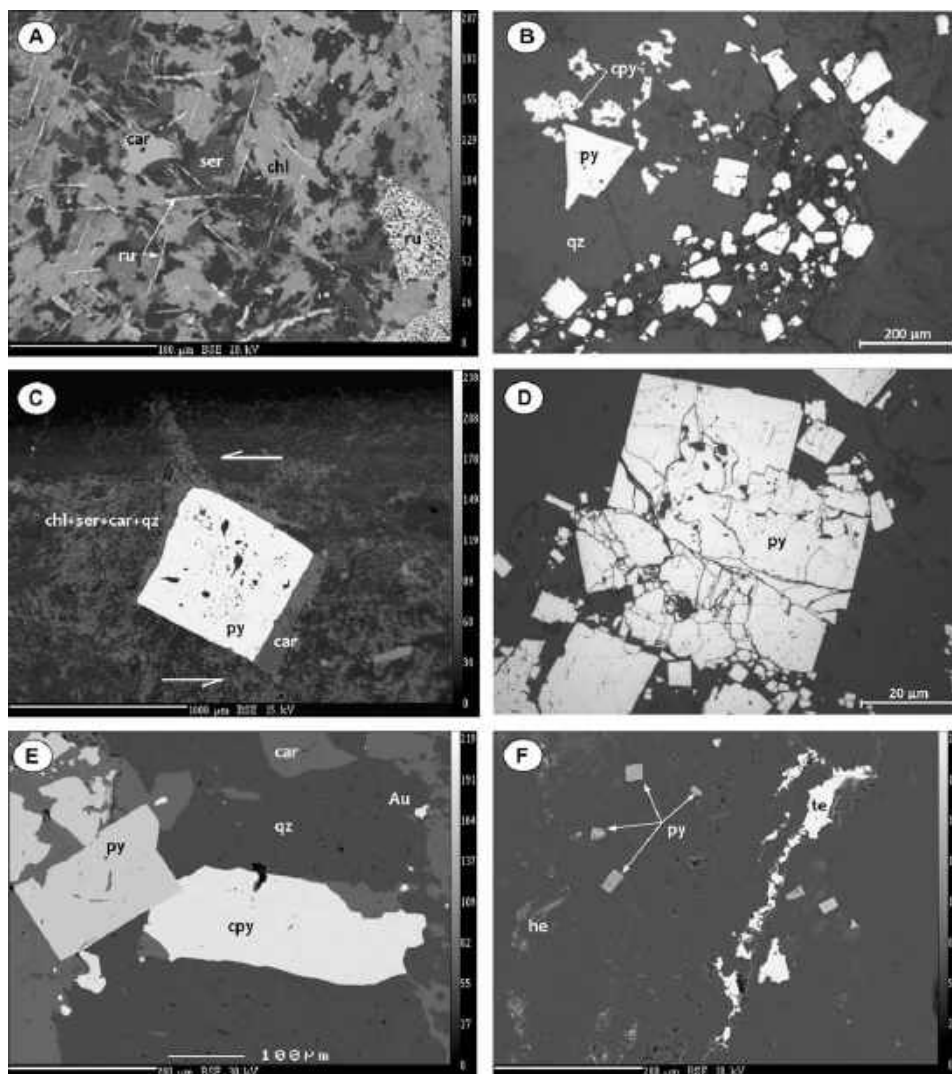


Fig. 9. (A) Hydrothermally altered host metavolcanic rock composed of mixtures of chlorite, sericite, carbonate and dispersed rutile. (B) Disseminated pyrite and chalcopyrite associated with alteration minerals along and close to fracture plane in quartz vein. (C) Sinistral rotated pyrite porphyroblast in mineralised wallrock with carbonate minerals defining the pressure shadow. (D) Deformed pyrite crystal with fine-grained (recrystallised) crystals occupy the fracture zones emphasizing post-formation brecciation. (E) Fine gold blebs associated with euhedral pyrite and subhedral chalcopyrite. (F) Disseminated pyrite and microfracture filled with telluride + galena in mineralised quartz vein (mineral symbols: mt = magnetite, he = hematite, py = pyrite, chl = chlorite, car = carbonate, ser = sericite, qz = quartz, cpy = chalcopyrite, te = telluride).

Ore mineral chemistry (Table 3) was determined on the CAMECA SX 100 electron microprobe used for chlorite (at TUC), but the applied analytical conditions were acceleration voltage is 30 kV, current intensity is 40–200 nA, counting time is 10–40 s per element, and defocused electron beam diameter is 2 μm . The analytical conditions have been found effective in lowering the detection limit of trace elements in pyrite and chalcopyrite allowing the measurement of refractory Au content in both minerals. The data indicate the presence of refractory gold in pyrite and chalcopyrite, up to 700 and 900 ppm, respectively (Table 3). Gold grains show generally high fineness (≥ 900), but a single electrum grain gave 12.3 wt.% Ag. No Bi, Sb but Te was detected. Traces of As have been detected in the auriferous pyrite and chalcopyrite. Although a positive correlation is commonly observed between Au and As contents in pyrite and chalcopyrite, some grains show totally erratic distribution. Pyrrhotite retains its stoichiometric composition with Fe and S as main constituents while other elements are either absent or occur at low concentrations below or approaching the detection limit. Sphalerite is generally iron-poor, and possesses

homogenous chemical composition. Galena contains no Bi, but abundant Ag.

5. Fluid inclusions

Petrographic investigations were carried out on 14 samples of mineralised quartz veins from the Abu Marawat area, from which eight samples have been found suitable for microthermometric measurements. The presence of preserved original vein-growth microstructures, large unstrained quartz crystals and fluid inclusions with suitable sizes ($\geq 3 \mu\text{m}$ across) were the criteria used for sample selection. Microthermometric measurements were carried out on the selected $\sim 150 \mu\text{m}$ -thick doubly polished wafers using a Linkam THMSG-600 heating/freezing stage at the fluid inclusion laboratory of the Institute of Mineralogy and Mineral Resources, Technical University of Clausthal (TUC). Measurements were carried out following the procedures outlined by Shepherd et al. (1985). The accuracy of the microthermometric results has

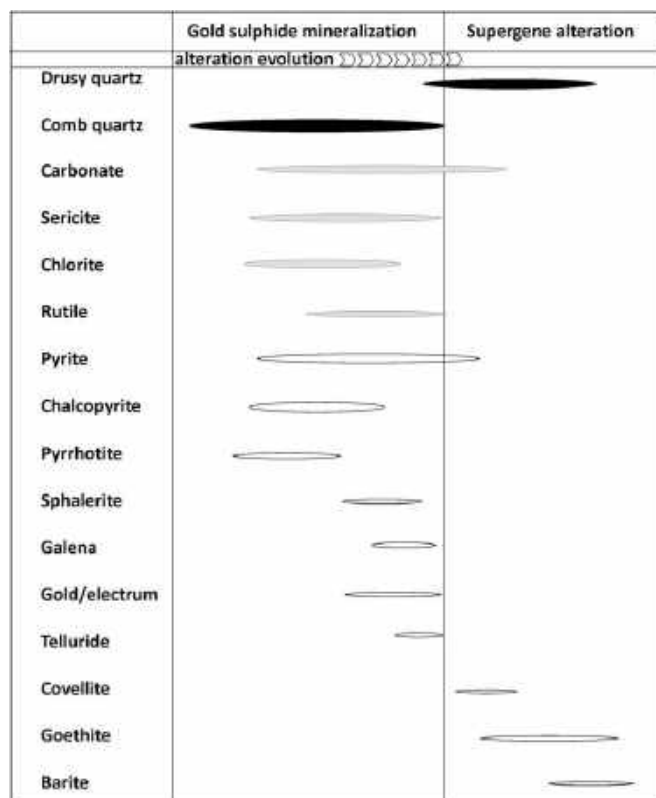


Fig. 10. Paragenetic sequence of the hydrothermal ore and gangue minerals in Abu Marawat gold deposit.

been checked by regular calibration using readily available inorganic melting point standards and synthetic fluid inclusions. A heating rate of 1 °C/min was used to record phase changes below 30 °C, whereas a heating rate of 5 °C/min was used for phase changes above this temperature. Hence, low-temperature phase changes are accurate to ± 0.2 °C, whereas temperatures above 30 °C have an estimated accuracy of ± 2 °C.

Table 3

Representative microprobe data of ore minerals of the Abu Marawat gold deposit.

Pyrite										Pyrrhotite				
Wt.%	mpy1	mpy2	Mpy3	mpy4	mpy5	mpy6	mpy7	mpy8	mpy9	Wt.%	mpy2	mpy3	mpy4	mpy5
Fe	45.21	45.53	45.39	45.70	45.77	45.63	45.64	46.65	47.49	Fe	61.87	60.93	60.51	62.03
S	53.66	53.63	53.51	53.43	53.65	53.75	53.46	52.28	51.33	S	37.24	38.97	37.48	37.38
As	0.62	0.27	0.00	0.32	0.02	0.14	0.20	0.05	0.22	As	0.00	0.00	0.00	0.00
Co	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Co	0.00	0.00	0.00	0.00
Ni	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.06	Ni	0.06	0.07	0.00	0.02
Ag	0.23	0.21	0.05	0.15	0.00	0.05	0.11	0.02	0.14	Ag	0.00	0.03	0.00	0.00
Te	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.03	Te	0.00	0.00	0.02	0.00
Au	0.06	0.04	0.00	0.07	0.00	0.03	0.05	0.02	0.06	Au	0.00	0.00	0.00	0.00
99.81	99.69	98.96	99.7	99.44	99.61	99.46	99.03	99.33	99.81	Sum	99.17	100	98.01	99.43
Chalcopyrite				Sphalerite				Galena						
Wt.%	mcpy2	mcpy3	mcpy4	Wt.%	msph1	msph2	msph3	Wt.%	mgn1	mgn2	mgn3	mgn4	mgn5	
Fe	30.20	30.68	29.85	Fe	0.22	0.20	0.68	S	13.03	13.26	13.35	13.31	13.06	
S	34.82	34.30	34.42	S	32.15	32.82	32.30	Ag	0.08	0.13	0.13	0.12	0.07	
As	0.00	0.48	0.33	Cu	0.14	0.05	0.39	Sb	0.04	0.03	0.04	0.05	0.06	
Cu	34.05	33.39	33.75	Zn	67.13	66.27	67.04	Pb	85.71	85.18	85.15	84.92	85.38	
Zn	0.03	0.04	0.06	Ag	0.05	0.26	0.34	Te	0.17	0.12	0.18	0.28	0.27	
Ag	0.26	0.34	0.04	Sum	99.69	99.6	100.75	Cd	0.19	0.17	0.17	0.19	0.22	
Au	0.07	0.09	0.05					Sum	99.22	98.89	99.02	98.87	99.06	
Sum	99.49	99.42	98.51											
Tellurides (Wt.%)							Gold (Wt.%)							
Ag	60.57	61.63	62.53	62.60	62.28	61.79	Ag	1.38	4.08	2.61	12.27			
Te	37.94	38.01	36.73	36.48	37.22	37.40	Te	0.32	0.76	0.57	0.44			
Au	0.02	0.02	0.03	0.07	0.31	0.25	Au	98.31	95.03	97.01	86.31			
Sum	98.53	99.66	99.29	99.15	99.81	99.44	Sum	100.01	99.87	100.19	99.02			

5.1. Fluid inclusion types and modes of occurrence

The mineralised quartz veins are characterised by abundant isolated individual inclusions and intergranular trails or clusters of randomly and three-dimensionally distributed inclusions. These inclusions vary in shape from negative crystal, elongate, rounded, to irregular, with diameters typically ranging from ~ 2 to 30 μm . They are commonly three-phase inclusions at room temperature (liquid H_2O , liquid CO_2 and vapour CO_2), or less commonly two-phase (liquid H_2O and vapour CO_2) and lack any daughter mineral (Fig. 11A). Two-phase carbonic inclusions (liquid CO_2 + vapour CO_2), or totally liquid CO_2 at room temperature but nucleate a vapour phase below ambient temperature. In rare cases, presence of an optically-undetected ($<10\%$) aqueous fraction in the carbonic inclusion is assumed based on the observation of clathrate melting upon heating above CO_2 melting. Therefore, the carbonic inclusions here are referred to as carbonic-dominant (Fig. 11B). Intragranular trails of aqueous-carbonic and carbonic-dominant inclusions are common in samples rich in disseminated sulphides (Fig. 11C). Less abundant aqueous inclusions, containing either H_2O liquid only or H_2O liquid and vapour at room temperature, occur along intergranular trails and less common as isolated inclusions in clear quartz (Fig. 11D). In some samples, aqueous inclusions have been observed along transgranular trails.

The aqueous-carbonic inclusions generally show variable forms (irregular, rounded, elongate and negative crystal), and can be randomly distributed, clustered in the centres of quartz crystals, or occur in intragranular trails. Their size-range is ~ 5 –30 μm . Like the carbonic-dominant inclusions, some aqueous-carbonic inclusions only nucleate a CO_2 vapour bubble upon cooling. The volumetric proportion of the CO_2 -rich phase varies from 30 to 80 vol.% but is mostly between 50 and 70 vol.%. The carbonic-dominant inclusions generally show elongate and negative crystal shapes, range in size from ~ 2 to 10 μm and occur along trails, or are less commonly isolated. The aqueous inclusions show a constant degree of filling ($L/L + V = \sim 0.90$ –0.95). They range in diameter from <5 to 30 μm and vary in shape from irregular to round or ellipsoid. Assemblages of the aqueous-carbonic and carbonic-dominant inclusions within the same cluster or trail are common. In the aqueous-carbonic inclusions, variation in $\text{H}_2\text{O}/\text{CO}_2$ is less prominent in inclusions

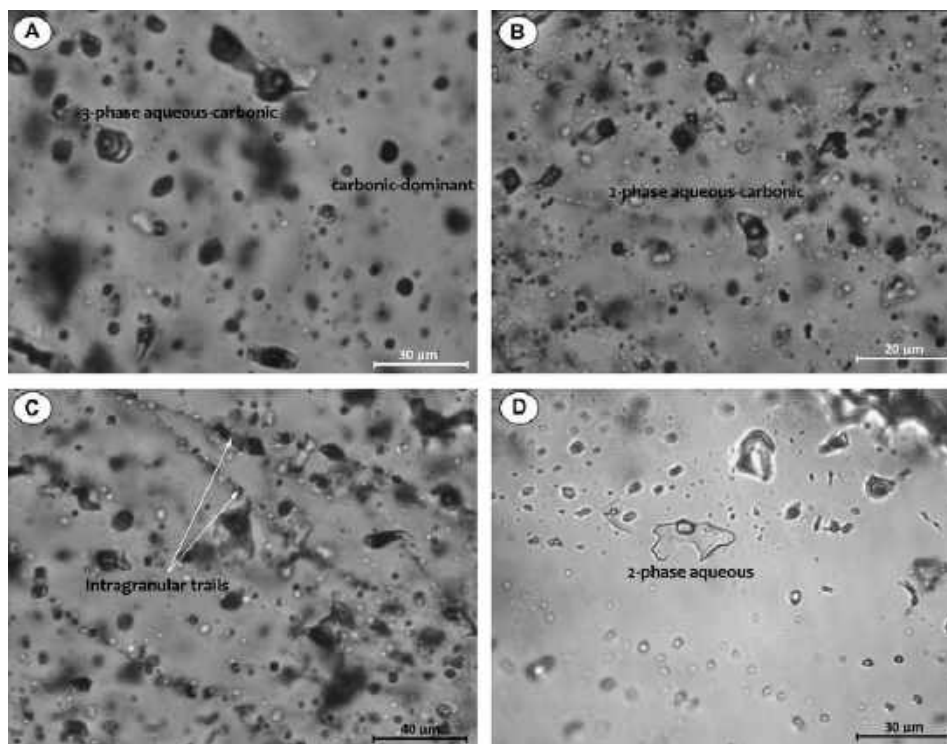


Fig. 11. (A) Variably-shaped, isolated and trail-bound aqueous-carbonic and carbonic-dominant inclusions in mineralised quartz veins from the Abu Marawat gold deposit. (B) Randomly-distributed, clustered aqueous-carbonic and carbonic-dominant inclusions in mineralised quartz veins. (C) Intragranular inclusion trails in mineralised quartz veins. (D) Irregular-shaped aqueous inclusions in clear (recrystallised) quartz.

Table 4

Characteristics and microthermometric data of the fluid inclusion types in the Abu Marawat auriferous quartz lodes.

Aqueous-carbonic inclusions ($\text{H}_2\text{O}-\text{NaCl}-\text{CO}_2 \pm \text{CH}_4$)	Carbonic-dominant inclusions ($\text{CO}_2 \pm \text{CH}_4 \pm \text{H}_2\text{O}$)	Aqueous inclusions ($\text{H}_2\text{O}-\text{NaCl}$)
Abundance: ~75% of the bulk inclusions population	Abundance: ~15%	Abundance: ~10%
Shape: irregular, rounded, elongate and negative crystals	Shape: negative crystals, elongate	Shape: irregular, rounded, ellipsoid
Size: 5–30 μm	Size: 2–10 μm	Size: 5–30 μm
DF = 30–80%	DF = 0–10%	Vol.% H_2O vapour = 5–10
$T_{\text{mCO}_2} = -56.6$ to -57.6 $^{\circ}\text{C}$	$T_{\text{mCO}_2} = -56.6$ to -57.1 $^{\circ}\text{C}$	$T_{\text{m ice}} = -0.7$ to -3.2 $^{\circ}\text{C}$
$T_{\text{m Clath}} = 6.4$ – 9.3 $^{\circ}\text{C}$	$T_{\text{m Clath}} = 8.8$ $^{\circ}\text{C}$ (one measurement)	$T_{\text{h total}} = 147.1$ – 238.3 $^{\circ}\text{C}$
$T_{\text{h CO}_2} = 21.6$ – 30.7 $^{\circ}\text{C}$ (into liquid)	$T_{\text{h CO}_2} = 17.6$ – 26.4 $^{\circ}\text{C}$ (into liquid)	Salinity = 1.2–5.3 wt.% NaCl eq.
$T_{\text{h total}} = 284$ – 378 $^{\circ}\text{C}$ (commonly into liquid)	$T_{\text{h CO}_2} = 28.2$ – 29.7 $^{\circ}\text{C}$ (into liquid)	Molar volume = 20.3–24.7 cm^3/mol
Salinity = 1.4–6.7 wt.% NaCl eq	$T_{\text{h total}} = 299$ – 386 $^{\circ}\text{C}$ (into vapour; hardly observable)	Bulk density = 0.99–1.03 g/cm^3
$\text{XCO}_2 = 5$ –42 mol.%	Salinity = ~2.5 wt.% NaCl Eq. (7)	
Molar volume = 21.5–35.1 cm^3/mol	$\text{XCO}_2 = 77$ –100 mol%	
Bulk density = 0.84–0.91 g/cm^3	Molar volume = 51.1–77.4 cm^3/mol	
	Bulk density = 0.29–0.65 g/cm^3	

within individual groups and trails compared to those in different trails or different grains. Daughter minerals have not been found in any of the fluid inclusions studied.

Microthermometric data were collected from inclusions in the less deformed quartz. The collected data, including temperatures of total homogenisation ($T_{\text{h total}}$), partial melting of CO_2 (T_{mCO_2}), clathrate melting and final melting of ice ($T_{\text{m ice}}$), are summarized in Table 4. Thermometric data were interpreted in terms of composition and density of the trapped fluids. Molar volumes, compositions and densities were calculated using the 'BULK' 'ISOC' software packages (Bakker, 2003). Salinities from ice melting were obtained using the equation given by Bodnar (1993). Isochors were calculated applying the equation of state of Zhang and Frantz (1987).

The melting temperature of CO_2 (T_{mCO_2}) is close to the CO_2 triple point (-56.6 $^{\circ}\text{C}$) with a few measurements ranging down to

-57.6 $^{\circ}\text{C}$ (Fig. 12A). Homogenisation of the carbonic phase (T_{hCO_2}) occurred commonly to liquid, at temperatures ranging from 17.6 to 26.4 $^{\circ}\text{C}$ and from 21.6 to 30.7 $^{\circ}\text{C}$ for carbonic-dominant and aqueous-carbonic inclusions, respectively (Fig. 12B). Clathrate melting ($T_{\text{m clath}}$) data could be obtained from many aqueous-carbonic inclusions using the double freezing technique outlined by Collins (1979), which allowed recognizable clathrate melting in the absence of ice. In all measurable aqueous-carbonic inclusions, clathrate melting ($T_{\text{m Clath}}$) occurred at 6.4–9.3 $^{\circ}\text{C}$ with a mode at 7.6 $\pm$ 0.8 $^{\circ}\text{C}$ (salinities between 1.4 and 6.7 wt.% eq. NaCl; Fig. 11C). These values correspond to CO_2 densities of 0.80–0.69 g/cm^3 and 0.76 to 0.55 g/cm^3 , respectively. Few carbonic-dominant inclusions showed CO_2 homogenisation into vapour at 28.2–29.7 $^{\circ}\text{C}$, corresponding to CO_2 densities of 0.29–0.36 g/cm^3 . The aqueous-carbonic inclusions display total homogenisation temperatures ($T_{\text{h total}}$) between 274 and 378 $^{\circ}\text{C}$ with a peak at 330 ± 40 $^{\circ}\text{C}$

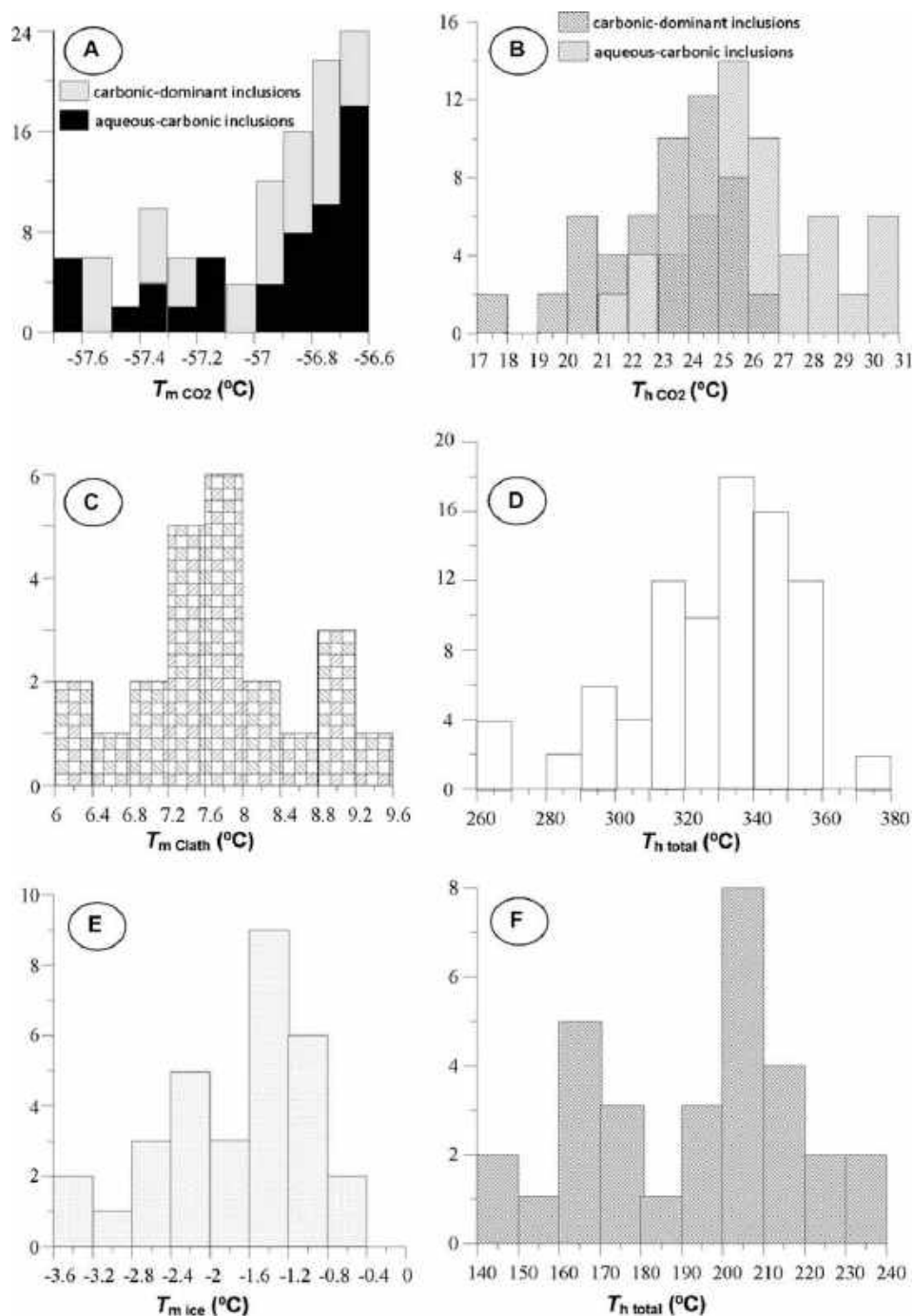


Fig. 12. Histograms of the microthermometric data of Abu Marawat auriferous quartz veins: (A) Melting temperature of CO₂ ($T_{m\text{ CO}_2}$) in aqueous-carbonic and carbonic-dominant inclusions. (B) Homogenisation of the carbonic phase ($T_{h\text{ CO}_2}$) in aqueous-carbonic and carbonic-dominant inclusions, commonly into liquid. (C) Clathrate melting ($T_{m\text{ clath}}$) data of the aqueous-carbonic inclusions. (D) Total homogenisation temperatures ($T_{h\text{ total}}$) of the aqueous-carbonic inclusions. (E) Final ice melting temperatures ($T_{m\text{ ice}}$) for aqueous inclusions. (F) Total homogenisation temperatures ($T_{h\text{ total}}$) of the aqueous inclusions isolated and along trails.

(Fig. 12D). Homogenisation to the vapour phase has been observed in a few cases, where $T_{h\text{ total}}$ was difficult to be obtained. The aqueous inclusions display initial ice melting temperatures close to the eutectic melting temperatures for the system NaCl–H₂O (–21.2 °C). Final ice melting temperatures for aqueous inclusions ($T_{m\text{ ice}}$) range from –3.2 to –0.7 °C with a mode at 6–1.4 °C (Fig. 12E). Total homogenisation occurred to the liquid phase at 147–238 °C (Fig. 12F). Homogenisation temperatures of aqueous inclusions along transgranular trails are comparable with those occurring as isolated or clusters in clear quartz grains (recrystallised quartz?).

5.2. Fluid entrapment mechanism and gold deposition

The carbonic-dominant and aqueous-carbonic inclusions may be related to heterogeneous entrapment of an originally immiscible aqueous-carbonic fluid with a wide range in carbonic gas content (c.f. Ramboz et al., 1982). This is consistent with the fact that these two inclusion types were observed together within all selected samples and inclusion assemblages. Microthermometric measurements corroborate this hypothesis, as indicated by the similarity of CO₂ melting and homogenisation data for both inclusion types, the aqueous inclusions and the aqueous-carbonic inclu-

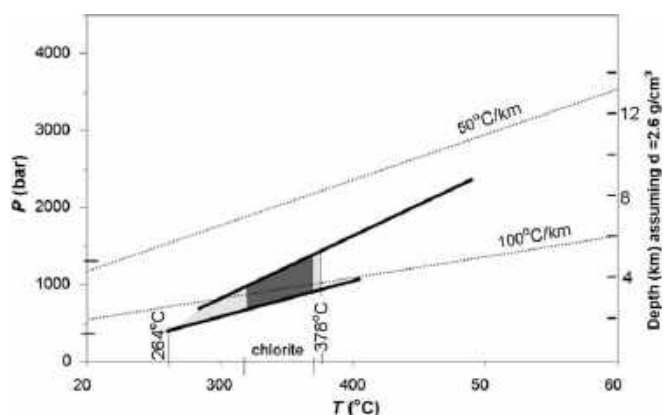


Fig. 13. Isochors for the highest and lowest bulk density aqueous-carbonic inclusions in Abu Marawat gold deposit. The hatched area resulted from intersection of these isochors with maximum and minimum total homogenisation temperatures of the aqueous-carbonic inclusions (378 and 264 °C) and chlorite thermometry (322–370 °C) refers to quartz-gold mineralisation formation conditions. Depths calculated on basis of rock density of 2.6 g/cm³, geothermal gradients of 50 and 100 °C/km are given.

sions occurring in the same assemblage. In addition, salinities and homogenisation temperatures of the aqueous and aqueous-carbonic inclusions are not in the same range. Therefore, it is not likely that the aqueous inclusions represent the water-rich end member of the immiscible aqueous-carbonic fluid. Instead, the aqueous inclusion may represent a different fluid, mostly probably circulated during recrystallisation and grain boundary migration. Fluid phase separation has been attributed to fluid pressure fluctuations triggered by fracture opening during cyclic fault movement (e.g. [Sibson et al., 1988](#); [Hagemann and Cassidy, 2000](#); [Sibson, 2001](#)). Given the evidence of structural control during formation of the quartz veins, it is possible that a similar process took place during gold mineralisation at the Abu Marawat area. [Mikucki \(1998\)](#) noted that heat loss and fO_2 and pH increase during fluid immiscibility can act to inhibit gold deposition, and the change in sulphur activity (e.g. sulphidation of iron oxides) favours gold precipitation.

5.3. P–T conditions of gold deposition

As heterogeneous trapping of immiscible fluids was suggested by the data, the entrapment temperature is given by the homogenisation temperature of the aqueous-carbonic inclusions (e.g. [Diamond, 1994](#)). Since the aqueous-carbonic inclusions are therefore representative for the ore fluid, pressure–temperature conditions of the fluid must lie along the isochors for these fluid inclusions. [Fig. 13](#) shows representative isochors covering the density range of the aqueous-carbonic inclusions. The temperature estimates are based on chlorite selvages in mineralised quartz veins as well as the $T_{h \text{ total}}$ range of the aqueous-carbonic inclusions (264–378 °C). The pressures obtained range from ~0.4 to ~1.2 kbar. Assuming that lithostatic pressure prevailed during fluid entrapment, a range of depth of formation between about 2.5 and 5 km can be estimated. Depth–temperature estimates may reflect a high geothermal gradient (50–150 °C/km) prevailed while the fluid system was active.

6. Discussion

Structural synthesis of the Abu Marawat area indicates that the ductile deformation in the area was terminated with development of nearly N–S fracture/shear fabrics post-dating S_3 crenulation cleavage. Analysis of the N–S faults, shear zones and their associ-

ated structures elsewhere in the Eastern Desert indicates that this structural trend is complicated due the presence of superimposed ductile and brittle structures, slip lineations, compressional and extensional fabrics (e.g. [Akawy, 2003](#)). [Akawy \(2007\)](#) suggested that the N–S striking faults in the Eastern Desert formed during two stages. The first was mainly ductile and resulted in development of upright N–S oriented folds and right-lateral strike-slip faults. The effect of this phase attenuates northwards. The second stage was mostly brittle and resulted in reactivation of the older faults as left-lateral strike-slip faults with an extension component (transtension). In the study area, the abundant slickensides, shearing and brecciation along the mineralised shear zone may refer to formation as fault breccias, however, the abraded or highly rounded shape of the clasts implies attrition during fluid circulation. This leads to the assumption that the N–S shear zone and related quartz veining/gold mineralisation is related to the second stage of [Akawy \(2007\)](#). Hydrothermal alteration includes pervasive silicification, pyritisation, sericitisation, carbonatisation confined to a delicate set of quartz veins and shear planes, in addition to a more widespread propylitic alteration assemblage (quartz + chlorite + pyrite + calcite ± epidote). Alteration is intense at and close to the intersection of the N–S shears with the NW- and NE-trending fault segments. Fixation of H₂O during the shear zone development is manifested by abundant chlorite and epidote within and adjacent to the shear zones. Presence of H₂O during deformation enhances the crystal plasticity and induces ductile deformation although the host shear zone is mainly brittle.

In accordance with results of [El-Mezayen et al. \(1995\)](#), the present work confirms the epigenetic nature of the investigated gold deposits. Features indicative of the epigenetic genesis of the Abu Marawat gold deposit include: (a) gold-sulphide-bearing quartz veins and associated symmetric hydrothermal alteration overprint the host metavolcanic rocks and related BIF and (b) no stratiform sulphide mineralisation have been observed at any scale.

Hydrothermal fluids, probably originating from granitic intrusions, ascended along the channelways and first percolated through the iron-rich host rocks. Fluid/wallrock interaction produces sulphur-rich fluids with distinctly reducing Eh, which would be able of transporting gold bi-sulphide complexes (e.g. [Borg et al., 1990, and references therein](#)). Replacement of magnetite by pyrite destabilized the Au complexes by reducing ligand availability, and led to variations in the aH_2S and fO_2 conditions, thereby drastically lowering gold solubility (e.g. [Borg et al., 1990, and references therein](#)). A further drive to Au precipitation would be the loss of sulphur that took place during fluid phase separation due to preferential partitioning of H₂S into the effervescent CO₂ phase (c.f. [Andrianjakavah et al., 2007](#)).

[El-Mezayen et al. \(1995\)](#) indicated that the Abu Marawat metavolcanics show erratic contents of Cu, Zn, Pb and Ba, especially in the un-altered meta-andesites and their tuffaceous equivalents (from 40 to 1148 ppm Cu, from 126 to 3396 ppm Zn, from 52 to 63 ppm Pb and from 91 to 297 ppm Ba). This may evoke for the Abu Marawat basic metavolcanics as potential source for base metals (and gold?).

7. Conclusions

Based on the field, microscopic and fluid inclusion studies, the Abu Marawat gold deposit formed as a result of interaction between iron-rich host rocks and structurally focused hydrothermal fluids under mesothermal conditions. The nature and mechanism of the ore fluids and formation conditions of the Abu Marawat gold deposit are similar to those of the Archaean BIF-hosted mesothermal lode-gold deposits (e.g. [Phillips and Powell, 1993](#); [Hagemann and Cassidy, 2000](#)). The presence of refractory gold in pyrite and

chalcopryrite may evoke similarity to the orogenic gold deposits in the Eastern Desert and elsewhere (c.f. [Mumin et al., 1994](#); [Hilmy and Osman, 1989](#); [Osman and Dardir, 1989](#); [Saha and Venkatesh, 2002](#); [Zoheir et al., 2008](#), and many others).

Based on the fluid inclusion data and the high geothermal gradient, gold mineralisation and the related hydrothermal alteration have been concurrent with an active volcanism. The structural evolution of the area leads to assume a genetic link between gold mineralisation and the post-Hammamat felsites intrusions (a potential fluid source) in view of their communal relationship with the N–S fault/shear trend (c.f. [Essawy and Abu Zeid, 1972](#)).

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