DISCUSSION

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Comment on the paper by Schmidt Mumm et al.
High CO$_2$ content of fluid inclusions in gold mineralisations
in the Ashanti Belt, Ghana: a new category of ore forming fluids?
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The recent paper by Schmidt Mumm et al. (1997) discussing the ore-forming fluids in gold deposits of the Paleoproterozoic Ashanti Belt (Ghana) is a welcome addition to the understanding of Paleoproterozoic lode-gold deposits in the Birimian of West Africa. The authors propose on the basis of fluid inclusion studies only, that the gold mineralisation of the Ashanti Belt is probably derived from a CO$_2$-rich, almost water-free fluid. They further imply that the mineralisation in the various gold deposits took place under drastically different temperature (150–440 °C) and pressure (< 1.7 and 5.4 kbar) conditions. I however disagree with their conclusion that the presently available fluid inclusion data indicate a new category of ore-forming fluids. As is outlined later, fluid inclusion evidence from Birimian-hosted lode-gold deposits may very well imply that the mineralising fluid is compatible with H$_2$O-CO$_2$-salt-rich fluids as observed in other lode-gold deposits world-wide. I further feel that the estimation of the *P–T* conditions during the mineralisation of the different deposits of the Ashanti Belt is highly questionable.

The Birimian Supergroup hosts structurally-controlled lode-gold deposits which occur in the transition zones between the volcanic belts and the basin sediments (Leube et al. 1990; Milési et al. 1992). Ore-forming fluids of mineralised quartz veins from the Birimian volcanic belts of Ghana and Burkina Faso were investigated by several workers and are characterised by various significant similarities (see Klemd et al. 1996 and Klemd and Hirdes 1997 for an extensive reference list). As is shown by these studies, some of the gold-bearing quartz veins and quartz pebbles from gold-bearing conglomerates contain more than 80% CO$_2$-rich fluid inclusions without any visible H$_2$O, some of which display a very high density ($\geq$1.0 g/cm^3). H$_2$O-CO$_2$-salt- and H$_2$O-salt-rich inclusions only occur in subordinate amounts. On the other hand, many of these structurally hosted Birimian lode-gold deposits such as Larafella in Burkina Faso (Klemd and Ott 1997), Obuom, Mpesatia, Kubekrom or the Ayanfuri gold deposit in the Ashanti belt (Manu 1993; Schmidt Mumm et al. 1997) have quartz veins which are dominated by H$_2$O-CO$_2$-salt- and H$_2$O-salt-rich fluid inclusions, while CO$_2$-rich inclusions occur only in subordinate amounts. This is even the case in the upper levels of the Ashanti Mine where CO$_2$-rich inclusions comprise just 40% of all observed inclusions (Bowell et al. 1990). This further suggests that a single ore-forming fluid process operated in each of these deposits, instead of a number of processes.

Therefore, if gold mineralisation is due to one common process such as metamorphic devolatilisation or mantle degassing, the CO$_2$-dominated fluid inclusions are unlikely to be unmodified relics of the mineralising fluids as suggested by Schmidt Mumm et al. (1997) and Klemd et al. (1996), respectively. They would appear rather to be the product of selective trapping and/or post-trapping modifications. This is supported by the fact that the high X$_{CO_2}$ of the inclusion fluid is not in thermodynamic equilibrium with the mineral assemblages of the altered wall rock. With decreasing distance from the quartz veins the intensity of chloritisation, sericitisation and epidotisation increases (Schwartz et al. 1992; Manu 1993; Klemd et al. 1997), thus requiring the infiltration of H$_2$O-rich fluids. In contrast, stable isotope studies by Oberthür et al. (1996) indicate equilibration between the CO$_2$ and the hydrothermal alteration assemblage. Furthermore, according to f_{O_2} constraints from fluid-mineral equilibria, the original fluid had to be an H$_2$O-CO$_2$ mixture (Schwartz et al. 1992). Additionally, gold is most likely transported in gold-hydrosulphide or gold-chloride complexes which favour H$_2$O $\pm$ CO$_2$-rich fluids instead of CO$_2$-rich fluids as a transport medium (see Seward 1989). The SiO$_2$-solubility in CO$_2$- rich fluids is also very limited (Walther and Orville 1983), such fluids are consequently unlikely to have been responsible for the precipitation of all the vein-quartz.

In contrast I regard another explanation for the origin of the CO$_2$-rich inclusions to be probable: although only few detailed geothermobarometric studies have been undertaken, recent results show that the rocks of the Ashanti Belt and the Kibi Winneba Belt have undergone epidote-amphibolite- to amphibolite-facies conditions, with peak-metamorphic conditions ranging between 500 and 650 °C at 5 to 6 kbar (Kleinschrot et al. 1994; Hünken 1995; Hünken et al. 1995; John 1997). In the Ashanti Belt ore deposition is interpreted to be largely synmetamorphic (Oberthür et al. 1996), which could be in accordance with the fact that the calculated isochores for the highest density CO$_2$-rich – and H$_2$O-CO$_2$-salt inclusions of almost all gold deposits intersect the *P–T*-range for peak metamorphic conditions, possibly indicating a syn-peak (?)-metamorphic trapping of these fluid inclusions (Hünken 1995; Klemd and Hirdes 1997). However, even if the gold mineralisation occurred during retrograde greenschist-facies conditions at temperatures >350 and <500 °C the vein-quartz will still show recrystallisation features such as grain-boundary migration (e.g. Johnson and Hollister 1995). This is in accordance with the observation, that all investigated quartz veins in the different deposits have undergone ductile deformation (e.g. Manu 1993; Schwartz et al. 1992, personal communication 1997) and recrystallisation during the *retrograde* greenschist-facies overprint (e.g. Manu 1993; Klemd et al. 1997; Klemd and Hirdes 1997). Consequently, most of the CO$_2$-rich inclusions were the result of post-trapping deformation-recrystallisation processes during *retrograde* conditions (Klemd et al. 1997). Grain-boundary migration recrystallisation

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favours the entrapment of CO_2-rich inclusions (Craw and Norris 1993; Johnson and Hollister 1995). The CO_2-rich inclusions thus could have formed from an initially miscible H_2O-CO_2-salt parent fluid as a result of subsequent grain-boundary migration recrystallisation during ductile deformation. This process is supported by fluid inclusion textures and compositions which strongly indicate post-trapping modifications, because inclusions of contrasting compositions and densities were found in the same samples. The quartz veins of the Ashanti Mine usually exhibit features of multistage quartz deposition and recrystallisation with successive events of ductile and brittle deformation (Manu 1993; Schwartz et al. 1992, personal communication 1997). Similar observations were made on quartz veins of the Diabatou gold prospect in Burkina Faso (Klemd et al. 1997). However, CO_2-rich fluid inclusions were also predominantly observed in completely recrystallised, polygonal-clear quartz grains in the Tarkwa Mine (Klemd et al. 1993). Recrystallisation as evidenced by grain-boundary migration of the vein quartz can result in the formation of *primary*, cluster-bound CO_2-rich inclusions in the cores and along the quartz grain boundaries, due to the high-surface energy of CO_2-rich fluids (e.g. Lamb 1993; Johnson and Hollister 1995). Almost identical textural features of CO_2-rich inclusions were observed at Tarkwa and Diabatou (Klemd et al. 1993; Klemd et al. 1997) and possibly at Abosso Damang (Schmidt Mumm et al. 1997; Fig. 1c). Furthermore, the large density range of the CO_2-rich inclusions may be due to re-equilibration-recrystallisation processes during exhumation (Klemd et al. 1993; Klemd et al. 1996; Klemd et al. 1997).

In summary, it is postulated that the presence of primary CO_2-rich inclusions and the relative scarcity of H_2O-CO_2-salt inclusions in some deposits are the result of a grain-boundary migration recrystallisation. Either the CO_2-rich fluids were immiscible during trapping, which would probably only be possible at trapping temperatures below about 350 °C (Duan et al. 1995) or ductile deformation induced selective extraction of H_2O-salt (pipe diffusion) as suggested for similar CO_2-rich inclusions by Bakker and Jansen (1990) and Hollister (1990). CO_2 could only leave the vein quartz via hydrofracturing, while H_2O, due to its strong polarity, wets the quartz surfaces and remains outside the advancing crystal front during growth and recrystallisation and thus, could have been expelled along the grain boundaries (Crawford and Hollister 1986). With decreasing temperatures during ductile deformation H_2O was almost completely removed, since H_2O, due to a lower dihedral angle ($< 60°$) at low temperatures (< 450 °C at 4 kbar), is more mobile along quartz-quartz grain boundaries than CO_2 (Holness 1993).

In the case of the Paleoproterozoic of West Africa it is thus suggested that only those quartz veins which formed during the main deformation event at high P–T conditions (assuring ductile deformation) will display high-density CO_2-rich fluid inclusions. Furthermore, assuming a deformation-continuum the ductile conditions will end with falling temperatures and, consequently, at temperatures below about 300 to 350 °C a brittle deformation-regime will prevail for quartz (White and White 1983). Micro-fracturing during brittle deformation favours the entrapment of aqueous fluids rather than CO_2-rich fluids (Johnson and Hollister 1995). Quartz vein systems which originated in a brittle deformation regime, and hence at higher crustal levels, would consequently contain no high-density CO_2-rich inclusions. Those quartz veins, if not eroded, may or may not be gold-bearing, but would presumably be dominated by H_2O-CO_2- and H_2O-rich inclusions as shown in the samples from the Ayanfuri gold deposit (Schmidt Mumm et al. 1997), the Larafella gold-prospect in Burkina Faso (Klemd and Ott 1997), the Mpesatia and the Kubekrom gold prospects (Manu 1993), and telluride-gold mineralisation at the upper levels of the Ashanti Mine (Bowell et al. 1990).

This conclusion is challenged by the strongly varying P–T estimates (150 to 440 °C at < 1.7 to 5.4 kbar) which were derived for the gold mineralization in different deposits of the Ashanti Belt (Schmidt Mumm et al. 1997). Schmidt Mumm et al. (1997) largely based their P–T constraints on intersecting isochores of CO_2-rich and aqueous inclusions. This method can only be applied to simultaneously trapped fluid inclusions as is correctly pointed out by

Schmidt Mumm et al. (1997). However, these authors fail to demonstrate simultaneous trapping of the two different types of inclusions, in fact Schwartz et al. (1992) showed that at least some aqueous inclusions were trapped later than the CO_2-rich inclusions in quartz veins of the Ashanti Mine. The CO_2-rich inclusions on the other hand, display in almost all deposits a similar density range, with some very high densities of ≥ 1.0 g/cm^3. However, retrograde almost isobaric cooling and subsequent isothermal decompression, as suggested for at least parts of the Ashanti Belt (Kleinschrot et al. 1994), would increase the densities of at least some inclusions, leading to erroneous pressure estimates (see Klemd et al. 1995 for discussion). This is supported by the slope of the highest-density isochores, which give higher pressures (> 6 kbar) than predicted by peak-metamorphic temperatures (e.g. Klemd et al. 1993). Furthermore, at mineralisation temperatures below 250 to 300 °C as suggested by Schmidt Mumm et al. (1997), an H_2O-CO_2-salt rich fluid even with low salinities would have been unevadably immiscible (e.g. Crawford and Hollister 1986; Duan et al. 1995) favouring the entrapment of aqueous fluids rather than CO_2-rich fluids (Johnson and Hollister 1995). Consequently, the determination of P–T conditions using intersecting isochores of non-simultaneously trapped and possibly modified fluid inclusions is questionable. The same can be said for the use of the biotite isograde as an upper pressure estimate. The slope of this reaction boundary strongly depends on the bulk rock composition (e.g. Al-, K-content) and thus, not enough is known of the exact P–T location of this reaction (Spear 1993).

My discussion on the Schmidt Mumm et al. (1997) paper has two main aims. Firstly, it suggests that the study does not account for probable post-trapping modifications which could have been responsible for trapping of the CO_2-rich fluid inclusions in quartz veins of the investigated gold deposits. Secondly, it serves to point out that Schmidt Mumm et al.'s (1997) P–T estimates for the various gold deposits of the Ashanti belt have to be regarded as highly questionable.

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