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REVIEWS

Source of Ore Fluid in Lode Gold Deposits of Eastern Dharwar Craton: An Intricate Issue

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Abstract | The source of auriferous fluid in late Archean lode gold deposits has long been debated. Among a number of propositions, most of the workers agree upon a metamorphic or magmatic ancestry of ore fluid. With regard to gold deposits in Eastern Dharwar Craton (EDC), a metamorphogenic parentage of ore fluid has been almost exclusively advocated. The generation of ore fluid is attributed to devolatilization reactions during greenschist-amphibolite metamorphism of greenstone rocks. However, at least in Indian context, such a hypothesis warrants further investigation in terms of retention and release of devolatilized fluid from rocks of amphibolite facies. Metamorphism and subsequent fluid production is often tied-up with fault-valve type process in lode gold systems. Yet, we need to ascertain the operation of such a cyclic process and its compatibility with metamorphogenic fluid production in the mineralized domains of EDC. As an alternate to metamorphism, a magmatic model is often postulated, whereby felsic magma is believed to be the source of gold-bearing fluid during late-stage crystallization. Most of the support for this model has come from isotopic composition of gangue minerals in ore zones worldwide. However, the isotope ratios of various elements are not always suggestive of any particular source. This discrepancy in various isotopic datasets possibly manifests fluid-rock interaction or/and varied source for different elemental constituents within ore fluid in question. Recently, in an attempt to testify the magmatic model in parts of EDC, late Archean granitoids proper were considered for detailed investigations. Such studies show that late-magmatic fluid can not only retain precious metal (gold) in appreciable amounts, rather can also carry it for considerable distance along trans-crustal shear zones. However, as of yet, temporal records on ore enrichment processes in EDC are quite poor, which is crucial to link up metallogeny with crustal evolution, and to locate the source of ore fluid as well. Nevertheless, it is challenging to place precise temporal constraints on magmatic-hydrothermal activity, metamorphism, deformation and ore-fluid overprinting processes.

1 Introduction

The late Archean lode gold deposits have been the centre of scientific interest for many decades. Most of the studies in the last century were focussed on categorization and nomenclature of this deposit class (Lindgren, 1933; Emmons, 1937). However, in recent decades, issues related to genesis of lode gold systems have been an important subject of research (Kerrich, 1989; Kerrich and Cassidy, 1994; Groves et al., 1998, 2003). Most of the studies were

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aimed to resolve the complex interplay between deformation, metamorphism and magmatism with regard to ore formation (for review, see Goldfarb et al., 2005). It is generally agreed that ore genetic hydrothermal processes take place during the waning stages of cratonization (Groves, 1993). Yet, there has never been unanimity over the nature of source region (or rocks) for ore-fluid. In fact, defining unifying ore genetic models for lode gold systems has often proved to be a strenuous exercise for economic geologists worldwide. One of the main reasons for this is the wide range of geological environments, in which such deposits can form. Gold-bearing quartz veins are not only hosted by a variety of rocks (e.g., greenstones, granitoids, BIFs etc.) within granite-greenstone ensembles (Groves et al., 2003), but may also form at a wide range of crustal depths (2–20 km, Groves et al., 1998). Thus, the diversity in observed and deduced ore-forming conditions indirectly hampers the interpretations on the source of fluid and metal in such hydrothermal systems. This paper seeks to synthesise and reflect on this issue of source in lode gold deposits of EDC, especially in the light of current perspectives.

2 The Source Problem

In lode gold metallogeny, nature of source(s) for metal and fluid is one of the intricate and long-debated issues (for review, see Ridley and Diamond, 2000). More often than not, the ore fluid is indicated to have a low saline, mixed aqueous carbonic nature, based on fluid inclusion studies. However, more detailed information on fluid chemistry is a prerequisite to resolve the issue of source, to tackle which, stable isotope techniques have been widely employed in the last few decades. The isotope ratio values of ore fluid with respect to some elements (e.g., N, Br, N, Cl, C and H) are perhaps helpful in defining the source, although, are by no means foolproof, as pointed out by Ridley and Diamond (2000). They suggested that not only H isotopes are liable to reset, the $\delta^{13}C$ value is also prone to change in the course of interaction between ore fluid and earlier-formed reservoirs (graphitic rocks or altered carbonates) of carbon. Additionally, for some of the other elements (like N, Br, Cl or Pb), the isotope chemistry for deeper-crustal regions or of probable source rocks is poorly constrained till date. The O and H isotope ratios of gangue minerals are often used to characterize the ore fluid in question. However, the correctness of this approach depends on the weight of other geological evidences as well. In the commonly used $\delta^{18}O$-δD diagram, fields representing metamorphic and magmatic waters show considerable overlap (Sheppard, 1986). It is important to note that extensive fluid pathways are one of the basic features of lode gold systems. It allows interaction of ore fluid with a wide variety of rocks along the whole path from primary fluid source to ore trap. In such a scenario, the isotopic compositions of tracer elements (e.g., O, H, C, N, S, B, Br, Cl, Pb, Sr, Nd) could be imprint of conduit zone rocks or fluid-rock interaction processes. Thus, the extent to which ore fluid reflects the nature of its source remains a contentious issue (Bohlke, 1989; Ridley, 1990). Likewise, there is no agreement on whether the redox conditions of ore fluid are reflective of the buffering reactions during its cooling (Wall, 1987), its source (Cameron and Hattori 1987) or the site of ore enrichment (Lambert et al., 1984; Phillips, 1986). Hence, it is evident that predicting the source for lode gold fluids is an arduous task, particularly in view of the large thickness of heterogeneous crust through which ore fluids traverse.

3 Gold Mineralization in Eastern Dharwar Craton—A Brief Overview

The trinity of granite, gneiss and greenstone rocks is typical of Archean terrains worldwide and Dharwar Craton (DC) is no exception to it. The DC is an assembly of two sub-blocks, namely Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC). As against the western sub-block, eastern one is marked by profuse late Archean calc-alkaline granitoids, mostly of tonalitic, granodioritic or granitic composition. Also, this block is host to a number of N-S (or NNW-SSE to NNE-SSW) trending thin (low width/length ratio) and linear greenstone belts, the major ones among which are Sandur, Kolar, Hutti-Maski and Hungund-Ramagiri schist belts (see Fig. 1). From economic perspective, as evident till date, EDC is better endowed with yellow metal ore, hosted as gold-quartz lodes within a number of schist belts. The mineralization in Kolar and Hutti belts have been the most productive and fall in the 'giant' and 'world class' categories of Laznicka (1999), respectively. In the past century, ~900 t of ore has been mined out from EDC, out of which >800 t has come from Kolar Gold Field (KGF), a profusely mineralized part in the centre of Kolar schist belt (KSB) (Sarkar, 2010). The main ore body in KGF is the Champion reef, which strikes over a length of ~8 km and is a free-milling gold (±calcite) -quartz lode. In KGF, Champion reef accounts for >90 percent of the mineralization, with rest occurring as sulphide-rich lodes (Oriental and McTaggart lodes) in the Nundydroog mine. Presently, the Hutti-Maski schist belt (HMSB) is the only active ore-producing locale in EDC with

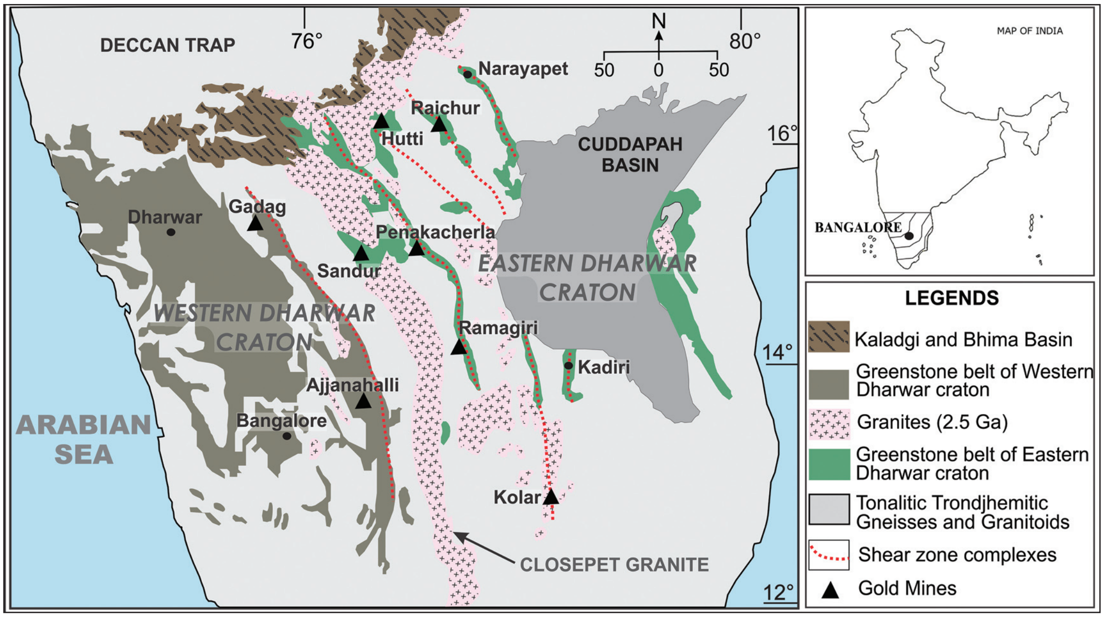

Figure 1: Geological map of the Dharwar Craton showing the distribution of greenstone belts of Western and Eastern Dharwar Cratons along with locations of present and old gold mines (Redrawn after Manikyamba et al., 2004).

promising mineralization at Hutti, Uti and Hira-Buddini. The largest operational mine at Hutti has produced ~72 t of ore from quartz-sulfide lodes (and proximal alteration zone) with >3 t of gold annually. In addition to HMSB and KSB, the Jonnagiri and Ramagiri-Penakacherla schist belts are other notable prospects in this eastern sub-block.

4 Conventional Hypotheses on Source Problem: An Overview

On lode gold deposits, there is no dearth of studies aimed towards exploring the source of ore fluid (for review see Ridley and Diamond, 2000). An outgrowth of the ongoing debate on source has been the proposals on a number of alternate models. Among numerous scenarios proposed, the metamorphic model has been the most prominent, where generation of copious amount of ore fluid is visualized through metamorphic devolatilization of greenstone sequences. Other models involve felsic magmatic devolatilization (Qiu and McNaughton, 1999; McCoy et al., 1997), crystallization of shoshonitic lamprophyres (Rock et al., 1989) and ore enrichment by meteoric waters (Nesbitt, 1989). Involvement of fluids sourced from mantle and those linked with granulitization (driven by influx of CO2) has also been proposed (Cameron, 1988; Card et al., 1989). However, such a hypothesis has been in question based on LIL (Large Ion Lithophile) elemental composition and stable isotope studies by some workers (Kerrich, 1989; Kerrich and Cassidy, 1984). In addition to this, at the end of last century, in an attempt to unify gold deposits formed under widely varied conditions, a 'crustal continuum model' was proposed (Groves, 1993), which has drawn a lot of attention in the last decade (McCuaig and Kerrich, 1998; Goldfarb et al., 2001; Hagemann and Cassidy, 2000; Kolb et al., 2000; and references therein). The central tenet of this model is formation of gold deposits in a wide range of crustal environments ranging from 750 °C to 180 °C, thus favouring the incursion of deeply-sourced fluids. However, this model is also not free of criticism, as some recent studies argue against the migration of fluids above 650 °C (Tomkins and Grundy, 2009; Phillips and Powell, 2009). Nevertheless, out of all such models, most of the workers appeal for generation of ore fluid by either metamorphism (metamorphic model) or felsic magmatism (magmatic model). These two models have been in limelight, in both global and Indian contexts. In the following sections, we discuss these models and related intricacies in perspective of gold metallogeny in EDC.

5 Metamorphism and Ore Fluid

Based on literature review, metamorphic model seems to outnumber the magmatic model in terms of its proponents and adherents worldwide. The metamorphic history of rocks in and around the lode gold camps has been constrained well, based on several investigations involving mineral equilibria calculations (Powell et al., 1991; Elmer et al., 2006; Phillips and Powell, 2009, 2010). In Indian context, this model has been almost exclusively favoured to elucidate the genesis of a number of such deposits in EDC (Mishra, 2010). One of the basic tenets of metamorphic model is the derivation of gold-bearing fluid through devolatilization of greenstone volcano-sedimentary piles at greenschist-amphibolite transition (Powell et al., 1991). The difference in the volatile composition across this facies transition is significant (Fyfe et al., 1978; Elmer et al., 2006). Based on mineral equilibria modelling in the system CaO-MgO-FeO-Al_2O_3-SiO_2-H_2O-CO_2 ($\pm Na_2O$) (CaFMASCH or NCaFMASCH), the devolatilized fluid is suggested to have $X(CO_2)$ varying from 0.2 to 0.3. Poor concentration of chlorine-bearing minerals is predicted to account for the low salinity of devolatilized fluid (Powell et al., 2010). Such originally homogeneous fluids, rich in carbonic component with low salinity, transport gold while being channelized in crustal-scale shear zones. The metal deposition within favourable locales is caused in response to phase separation of ore fluid or its reaction with country rocks. The unmixing or phase separation of mixed aqueous carbonic fluid is attributed to fluctuation in fluid pressure between lithostatic and hydrostatic regimes. The variability in fluid pressure is accounted for by the advection of fluid through large thickness of crust from deeper to shallower levels in response to fault-valve type processes in association with metamorphic dehydration (Sibson et al., 1988; Cox et al., 1991; Sibson, 2001). Recently, in context of Dharwar craton, Chattopadhyay (2010) critically assessed the processes relating to cyclic fault-valve activity. In order to build-up supra-lithostatic fluid pressure resulting in fault-valve processes, presence of an unfavourably oriented fault/shear zones is a prerequisite. For the Hutti gold deposit, Kolb et al. (2004, 2005) suggested D2 fault/shear zone to be favourably oriented for frictional reactivation during D3 event related to mineralization. However, the orientation of maximum principal compressive stress ($\sigma 1$) during D3 was NNE-SSW, which is at low angle to D2 shearzone (N-S to NNW-SSE). Thus, such intricacies demand an accurate rendering of processes related to fluid generation and its release in the framework of metamorphism and deformation. It should be noted that it is a prerequisite to build-up the supra-lithostatic fluid pressure to result in rhythmic fluid activity. However, greenstone rocks would be subjected to reduction in porosity due to compaction during greenschist-amphibolite transition. Thus, the ability of such rocks to regenerate and retain (or accommodate) new aliquots of devolatilized fluid warrants a better understanding. Also, pervasive enhanced porosity or fracturing is vital to drain the devolatilized fluid out of metamorphic rocks, the visible textural traces of which are yet to be reported in EDC.

Recently, Frimmel (2008) pointed out the issue of rate at which fluid can devolatilize out of greenstone sequences. In such rocks, owing to low porosity and permeability, pore-fluid tends to maintain a lithostatic fluid pressure. In view of the regional metamorphism taking place over millions of years (Yardley et al., 1993; Ridley and Thompson, 1985), fluid production must be a slow process in response to endothermic dehydration reactions driven by gradual rate of heat supply. Such fluids, even if with elevated Au contents, need to maintain a focused fluid flow along the same conduits to develop ore veins, which is unlikely as suggested by Frimmel (2008). The protracted fluid flow in conjunction with its generation and escape from source rocks is antithetical to vein development over a short interval of time, as shown for Jeneau veins by Goldfarb et al. (1991b). This incongruity in the rate of fluid production and its consumption (to form ore veins) can be dismissed, if one follows Goldfarb et al.'s (1991) model. They visualized deep ponding of metamorphogenic fluid, which acts as a reservoir and facilitate cyclic pulses of fluids to result in multiple generations of ore veins (Goldfarb et al., 1991b). However, the 'freshest' of metamorphic rocks do not show textural evidence of higher levels of porosity and thus enough storativity during the peak of metamorphism (Yardley and Cleverley, 2014). Also, the possibility of loss of ponded fluids due to retrograde back-reactions (rapid) under favourable P-T conditions remains unattended (Yardley et al., 1993; Yardley and Cleverley, 2014). Any such retrograde loss of fluid can only be avoided, if peak metamorphic conditions are maintained at the source regions (of fluid storage) till the initiation of veining phase, as of yet, the evidence of which have not been shown in EDC. Additionally, during metamorphic devolatilization, solid/fluid partition coefficient of Au and its dependence on varying P-T conditions remains unknown (Ridley and Diamond, 2000). Notably, at times lode gold fluid deviates from its typical composition of low to moderately saline H_2O-$CO_2 \pm CH_4$ composition. For example, in EDC, the Uti deposit within Hutti-Maski schist belt shows absolute absence of carbonic fluids (Mishra, 2010). This was accounted for by loss of deep metamorphogenic H_2O-CO_2 fluid due to lack of shear zone structures, which contradicts with fault-valve processes, suggested to have operated in HMSB (Mishra, 2010). This is because, fault-valve type processes can only occur if fluid is retained in the source region (rather than being lost), which is necessary to build-up the pressure eventually required for development of high angle weak planes.

6 Felsic Magmatism—A Viable Alternative?

Besides metamorphism, one school of thought holds on to a magmatic model and has long been envisaged. In fact, one of the earliest classifications on epigenetic gold systems visualized volcanic and plutonic groups, with latter including the mesothermal and hypothermal gold deposits (Niggli and Parker, 1929). In a number of geological settings, such as in epithermal-type, Carlin-type and porphyry-type deposits, the Au-carrying potential of magmatic fluid has been recognised well. However, the ore-forming ability of such a fluid or its predominance in lode gold systems has been a matter of dispute (Ridley and Diamond, 2000).

Based on studies in granite-related hydrothermal ore systems, magmatic derivation of ore fluid in lode gold settings has drawn some support. The Yilgarn craton in Australia and Superior Province in Canada are host to several magmatic-hydrothermal gold and multi-metal deposits, where mid- to lower-crustal granitic activity is considered to have generated late-magmatic ore fluid (Burrows and Spooner, 1987; Qiu and McNaughton, 1999; Bucci et al., 2002; Hagemann et al., 2006). Yilgarn craton hosts a number of lode gold deposits as well, among which the one at Griffins Find exposes lowest levels of crust in the craton. In this deposit, based on Pb isotope studies, magmatic fluid is believed to be derived from granitoids below the greenstone rocks (Qiu and McNaughton, 1999). In fact, in the past decade, stable isotope studies in lode gold camps of EDC have strengthened the case of processes other than metamorphism (Krienitz et al., 2008; Rogers et al., 2013). For example, the granitoid intrusions in northern part of Hutti-Maski schist belt (HMSB) are considered as a potential source of fluid in Hira Buddini and Hutti gold deposits (Kolb et al., 2005). Studies based on O, H and B isotopes suggest involvement of magmatic fluid in the ore zones of HMSB, with reactivation of ore-fluid plumbing system in response to magma intrusion (Krienitz et al., 2008; Rogers et al., 2013). However, uncertainty still prevails since the stable isotope approach often fails to unequivocally establish the source of ore fluid, as different isotope systems infer distinct sources for corresponding elements in ore fluid. As an example, in Penakacherla schist belt (in EDC), carbon was ascribed a biogenic origin based on $\delta^{13}C$ values of carbonates, while a magmatic (juvenile mantle-derived) origin was suggested for sulphur based on $\delta^{34}S$ of sulphides (Manikyamba et al., 2004). To account for this inconsistency, Manikyamba et al. (2004) interpreted the mixing of fluids sourced from subducting slab and juvenile magmatic rocks. Thus, the exact nature of source for ore-fluid could not be established, rather it was argued to be sourced from anywhere between crust and mantle. It is noteworthy that $\delta^{34}S$ values of sulphides in multiple lode-gold camps within Dharwar craton are consistent (+1.1 to +7.1 per mil), which is a bit puzzling; although these estimates were interpreted to imply an average crustal or magmatic source for sulphur (Mishra, 2010). A $\delta^{34}S$ value of 0 per mil points to magmatic fluid, however, addition of crustal component can lead to greater variability in the sulphur isotope composition of ore fluid. On this premise, the possibility that magmatically derived fluid was an important component in ore fluid regime of EDC, cannot be straightway ruled out.

In the context of late Archean lode gold metallogeny, the viability of magmatic model has been criticised more often than other alternatives. Much of the criticism holds on to lack of close spatial association between granitoids and gold deposits in most of the late Archean terrains (Ridley and Diamond, 2000). This is intriguing considering that granitic magmatism was an integral part of the gold-endowed granite-greenstone terrains in late Archean time (Condie, 1981). It should be noted that often a magmatic parentage of ore fluid is precluded, as late Archean granitoids host a far minor proportion of shear zone-controlled gold deposits. Most of the deposits are hosted in shear zones within metamorphosed volcano-sedimentary rocks of greenschist-amphibolite grade or at their contacts with sheared felsic pluton margins (e.g., Las Cristinas deposit, South America, see Goldfarb et al., 2005). The Superior Province and Abitibi belt in Canada are the only examples, where a considerable amount of gold production has come from ores hosted within felsic intrusions (Colvine et al., 1988). However, it could be just an expression of rheological contrast between granitoids and greenstones during regional deformation, where the latter preferably tends to develop weak (shear/fault) zones, which eventually guide the passage of ore fluids and formation of gold-quartz lodes. Also, mafic and ultramafic rocks have better potential to enhance alteration processes (e.g., carbonate replacement alteration) eventually leading to deposition of gold, which may be due to relatively higher concentration of cations (Fe, Mn, Mg, Ca) in them as against granitic rocks (Kerrich and Fyfe, 1981). Magmatic model cannot be simply dismissed based on inadequate exposures of granitoids around gold camps. The absence of granitoids at the level of ore does not preclude their presence in subsurface, as shown by Wang et al. (1993) for 2.63–2.64 Ga granitoids in Yilgarn block of Australia. Recently, magnetic and gravity anomalies in the region of Archean St. Ives gold camp were attributed to underlying abundant felsic porphyry intrusions (Neumayr et al., 2008). Such granitic intrusions can not only trigger the metal-mobilizing fluid plumbing systems, rather can also release late-magmatic fluid of possible metallogenic potential.

In EDC, although the granitoids do not host any major gold deposit, their close spatial association with ore zones is apparent (Bhattacharya, 2014). This part of Peninsular India witnessed prolific granitic activities during late Archean (Jayananda et al., 2000), representing mixing of multi-pulsed juvenile (mantle-derived) magma with anatectic melts (magma mixing) (Jayananda et al., 1995, 2000; Moyen et al., 2001). This offers a favourable situation to test the magmatic model by investigations on granitoids proper, as most of the support for 'granite-gold connection' has come from isotope data on gangue minerals in the ore zones. Some recent studies in EDC were tempted to understand the implications of late Archean granitic magmatism towards genesis of lode gold deposits (Bhattacharya and Panigrahi, 2011, 2015; Bhattacharya et al., 2014a, b). As shown in Fig. 2, the granitoids bodies (including the Closepet granite body) around auriferous Ramagiri-Penakacherla schist belt (RPSB) were considered for detailed studies (Bhattacharya et al., 2014). These investigations show that between Ramanagaram and Nagasamudram, along a NNE-SSW stretch of ~250 km (Fig. 2a) granitoids were emplaced at pressure-temperature conditions of 4.2–5.6 kbar and 635–749 °C (Fig. 2b). This suggests that mid-crustal depths of ~19 to 14 km were profusely invaded by late Archean granitoids under steeper geothermal gradients (of ~50 °C/km). In view of the prolonged granitic activity in EDC, such conditions could have resulted in a persistent late-magmatic fluid evolution at a low pace (Bhattacharya et al., 2014a). Moreover, fluid inclusion studies confirm abundance of H_2O-$NaCl \pm CO_2$ fluid in the granitic and schistose auriferous domains with variable abundance of CH_4 in the latter. In the granitoid-hosted pegmatites (and veins) around Ramagiri-Penakacherla ore zones, fluid inclusion assemblages (FIA) show predominance of variably saline, aqueous and mixed aqueous carbonic fluids (Fig. 3a, b). On the contrary, heterogeneity in the ore fluid regime has been predicted, based on presence of compositionally variable inclusions within individual assemblages (Fig. 3c, d). Even the inclusion assemblages closely related to gold grains show considerable differences in terms of salinity and CO_2/CH_4 ratios (Fig. 4) (for details, see Bhattacharya and Panigrahi, 2011). The main differences between late-magmatic fluid and the one involved in ore enrichment are in terms of their CH_4/CO_2 and $^{18}O/^{16}O$ ratios. Estimated P-T-fO_2 and halogen fugacity conditions for granitic-hydrothermal system around RPSB favour the metal-carrying efficiency of late-stage fluids (late-magmatic) in concomitance with crystallizing magma (Bhattacharya, 2014). On such basis, up-dip advection of late-magmatic fluid through available conduits (like shear zones) has been visualized (Bhattacharya et al., 2014b). Interaction of such magmatically-derived fluid with meta-volcanosedimentary units within shear zone regime is predicted to cause an increase in its CH_4/CO_2 and $^{18}O/^{16}O$ ratios. As can be seen in Fig. 2c, for carbonic component in late-magmatic fluid, first melting temperature ($TmCO_2$) mostly lies around −56.6 °C, which suggests lack of CH_4 in the system. However, the $TmCO_2$ values for carbonic fluid in Penakacherla and Ramagiri ore zones drops up to −57.0 °C and −64.7 °C respectively. This infers progressively higher CH_4/CO_2 ratios in the ore fluid regime at Penakacherla and Ramagiri, which has been confirmed by Laser Raman studies (Bhattacharya, 2014). On this premise, it has been proposed that in response to incursion of late-magmatic fluid in shear zones followed by fluid-rock interaction, this CH_4-poor fluid entity ($\delta^{18}O_{\text{late-magmatic fluid}} = 6.5 \pm 0.4$ per mil) witnessed an increase in its CH_4/CO_2 and $\delta^{18}O$ values in the shear zone regime at Penakacherla ($\delta^{18}O_{\text{ore fluid}} = 7.3 \pm 0.8$ per mil) and Ramagiri ($\delta^{18}O_{\text{ore fluid}} = 10.0 \pm 1.4$ per mil) (Bhattacharya et al., 2014b). However, such a proposition still demands implications of granite petrogenesis over gold enrichment (cf. Mustard et al., 2006); in addition to detailed characterization of interaction between late-magmatic fluid and different rock units within the shear zone.

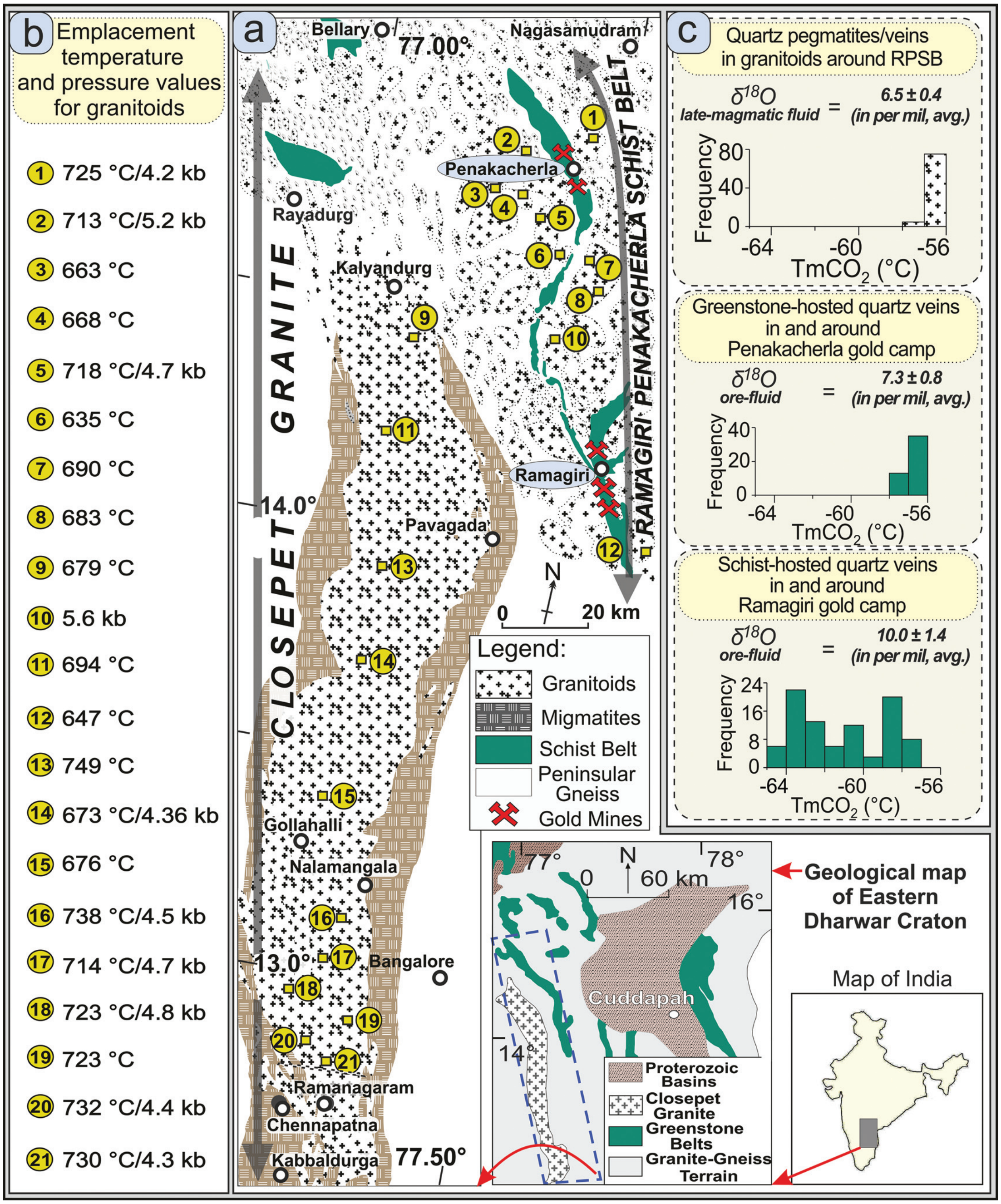

Figure 2: (a) Geological map showing Closepet granite and other granitic bodies around Ramagiri-Penakacherla schist belt (RPSB) along with locations of gold mines. (b) Temperature and pressure values for emplacement of granitic rocks between Ramanagaram and Nagasamudram (for details see Bhattacharya et al., 2014a). (c) The average values of $\delta^{18}O_{bulk\text{-}fluid}$ and histogram plots for $TmCO_2$ for carbonic component of late-magmatic fluid and ore-fluid at Penakacherla and Ramagiri. The $\delta^{18}O_{bulk\text{-}fluid}$ values were shown were calculated assuming a minimum fluid pressure of 2 kbar; (for details, see text and Bhattacharya et al., 2014b).

7 Radiometric Dating—A Challenge

Evaluation of temporal relationship between gold enrichment and evolution of granite-greenstone terrains is crucial to locate the source of ore fluid. However, to put constraints on the entire span of ore forming event(s) is an arduous task. This can be accounted for by the hydrothermal overprinting by multiple phases (or heterogeneity in fluid activity) of fluids altering the isotopic signature of earlier events. Also in radiometric studies, the isotopic systems employed (K-Ar, Rb-Sr, Ar-Ar, Nd-Sm, U-Pb and Re-Os) have hydrothermal properties

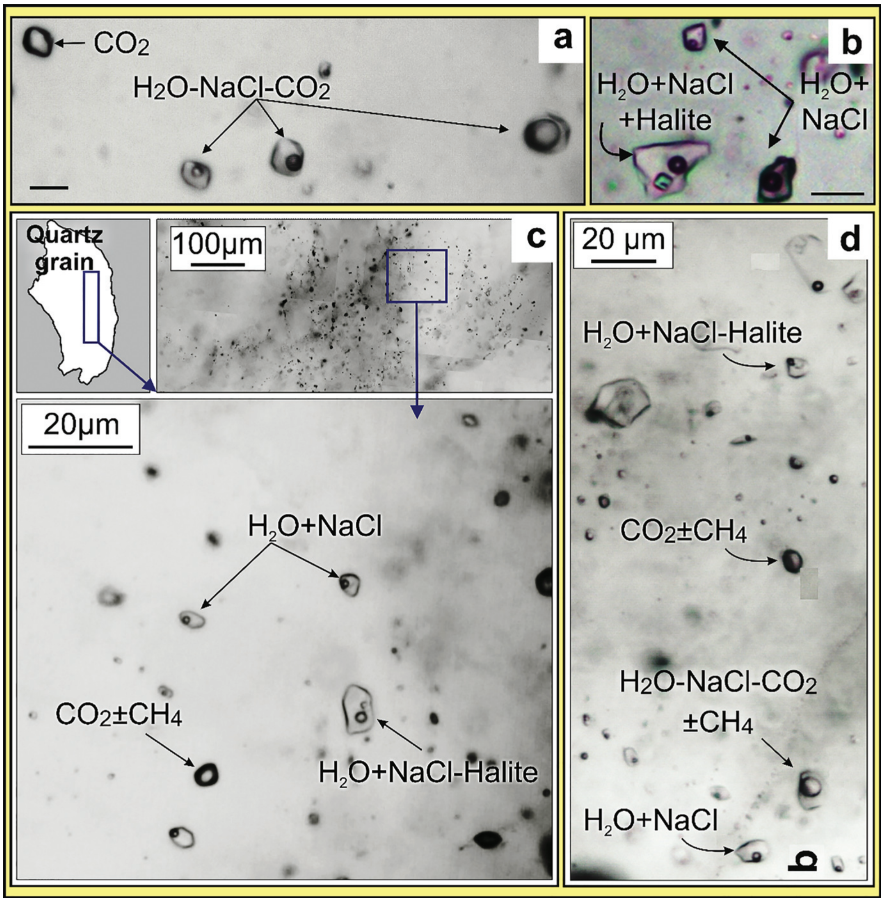

Figure 3: Photomicrographs of fluid inclusion assemblages. (a) Primary assemblage of carbonic and aqueous carbonic inclusions hosted in pegmatites from granitoids around RPSB; (b) primary assemblage of aqueous biphase and halite bearing aqueous inclusions hosted granitic matrix quartz grain; (c) Primary assemblage of aqueous biphase, carbonic and halite-bearing aqueous inclusions hosted in auriferous quartz vein from Ramagiri ore zone; (d) Primary assemblage comprising aqueous biphase, halite-bearing aqueous, carbonic and aqueous carbonic inclusions hosted in auriferous quartz vein from Ramagiri region.

different as against gold (Powell et al., 2010). Thus, the link between such radiogenic elements (mostly of 'hard' nature) and metal-carrying fluid or gold ('soft' metal)—carrying ligand remains equivocal.

In EDC, the time frame of ore forming events has remained poorly constrained with regard to the duration of peak metamorphism and granitic magmatism, although the latter has been well dated (2.65–2.52 Ga) (Jayananda et al., 2000, and references therein). In the Uti deposit within Hutti-Maski schist belt, stage-1 of mineralization has been dated based on a single monazite grain giving a 'preferred age' of 2547 ± 10 Ma (Sarma et al., 2008). This is coeval with U-Pb zircon age of 2545 ± 7 Ma for the proximal Kavital granitoid body, based on which its genetic linkage with ore formation at Uti was suspected (Sarma et al., 2008). The Yellagatti granitoid (2532 ± 3 Ma, Anand et al., 2005) was argued to be linked with stage-2 of mineralization at Hutti deposit, which has not been dated and is presumed to postdate the stage-1 by ~10 Ma (Rogers et al., 2013). The important point, however, is that in the granitic rocks mostly zircon is dated which crystallizes early in the magmatic cooling history. Any genetic linkage between granitoids and mineralization can only be envisaged based on activity of late-magmatic fluids. Thus, rather it is crucial to estimate the span of magmatic-hydrothermal activity in the proximities of gold camps, which must be controlled by conditions of emplacement. For example, a recent study by Zhao et al. (2004) shows that the span of magmatic fluid activity is inherently dependent on the rate of magma emplacement and cooling rate. The activity of ore-forming fluids in response to granitic activity may even lag about 25 to 30 Ma (or more) behind the crystallization of granitic magma. This is not to say that the situation is even more complex in EDC, as this terrain not

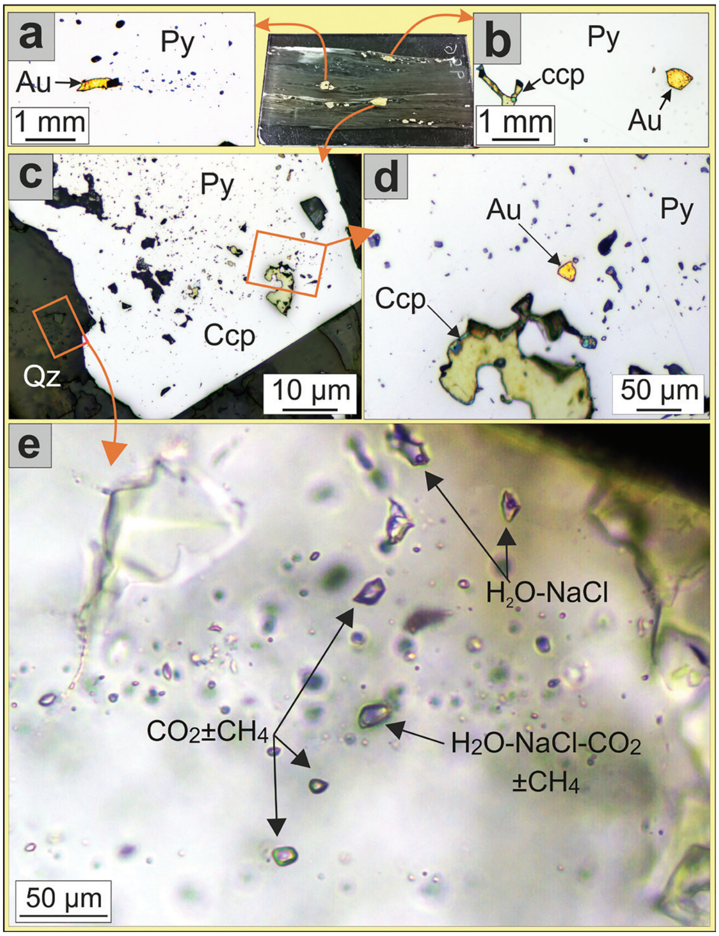

Figure 4: (a, b) Pyrite (± chalcopyrite) enclosing native gold grain, hosted in quartz-sulphide stringers within phyllites; (c) Quartz-sulfide stringer showing pyrite enclosing chalcopyrite and gold; (d) Inset photomicrograph showing Au grain associated with chalcopyrite, both enclosed within pyrite; (e) Inset photomicrograph showing primary assemblage of carbonic (CO_2 $\pm CH_4$), aqueous carbonic (H_2O-CO_2-NaCl $\pm$ CH_4) and aqueous biphase (H_2O-NaCl) inclusions hosted within quartz.

only witnessed granitic activity of multi-pulsed and protracted nature (Jayananda, 2000), rather also a prolonged magmatic-hydrothermal history (Bhattacharya and Panigrahi, 2015, in prep.). It should be noted that late Archean granitoids worldwide show inconsistent temporal links with metallogeny. It can predate, be synchronous with, or postdate the gold-forming events, although mostly occurs over a much broader interval of time than that of lode gold formation (for details, see Goldfarb et al., 2005). On this count, it is clear that any attempt to correlate magmatism (or metamorphism) and ore-formation based on radiogenic dating of minerals formed at different paragenetic stages is a challenging task. Such an approach may only permit us to 'guess' about the chronological relationships between various ore-genetic and associated processes, unless done cautiously.

8 Summary

The wide range of physico-chemical environments in which lode gold deposits occur poses challenges to unequivocally constrain the source of ore fluid. As far as metamorphism is considered, mineral equilibria studies are in support of fluid production through devolatilization of greenstone piles, which is presumed to be the one of metal-enriched nature. Yet, at least in context of EDC, some of the aspects related to release of fluid from source rocks and its storativity in them, needs to be resolved. In EDC, the ore formation has been suggested to postdate the peak metamorphism of immediate host rocks (Mishra, 2010). This corresponds with 'deep-later' type process of Stüwe (1998), whereby deeply generated ore-fluid migrates to shallow crustal depths, which are on their retrograde path. It is evident that in EDC, cooling stages of shallow crustal levels witnessed gold-quartz veining in response to prolonged history of prograde metamorphic devolatilzation at greater depths (Mishra, 2010). It must be noted that in granite-greenstone belts, magmatism and metamorphism seem to be linked processes, where advective heating by rising magma would promote metamorphic processes (Collins and Vernon, 1991; Sandiford and Powell, 1991). Thus, prolific late Archean granitic activity in EDC raises the possibility of 'deep-earlier' type processes, where deeper levels may reach their metamorphic peak early as against relatively shallower depths of crust. However, such a terrain may show 'deep-later' characteristics, if it underwent rapid uplift and erosion, which may allow cooling from above with cooling being progressively later at greater depths. Additionally, granitic magmatism, can also be a vector to pave the way for deep crustal fluids to upper levels; or else, emplaced magma can itself be a source of fluid, which recently has been shown to be of ore-genetic potential around the Ramagiri and Penakacherla gold camps in EDC (Bhattacharya, 2014). Nonetheless, it is notable that data on stable and radiogenic isotope composition of ore fluid, even if may not always be a signature of source rocks, is important to compare it against that of the fluid exsolved from probable source rocks (like granitoids). Such an approach would lead us to trace and characterize the chemical evolution of primary fluids during their interaction with host rocks. Moreover, any radiometric dating approach to work out the timing of metamorphism and granitic-hydrothermal activity should be based on radiometric data on different paragenetic mineral phases. On these lines, it can be surmised that in EDC, the issue of source of auriferous fluid is still open with ample scope to tie-up the records of gold mineralization with that of granitic magmatism, metamorphism and deformation. Use of laser-aided analyzing techniques for trace elements in minerals and fluid/melt inclusions could be useful to fingerprint the source(s) of ore fluid in EDC.

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