REE Geochemistry of ore zones in the Archean auriferous schist belts of the eastern Dharwar Craton, south India

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The eastern Dharwar Craton of southern India includes at least three ∼ 2700Ma supracrustal belts (schist belts) which have mesothermal, quartz-carbonate vein gold mineralization emplaced within the sheared metabasalts. In the Hutti and the Kolar schist belts, the host rocks are amphibolites and the ore veins have been flanked by only a thin zone of biotitic alteration; in the Ramagiri belt, however, the host rocks to the veins have been affected by more extensive but lower temperature alteration by fluids. The rare earth element (REE) geochemistry of the host metabasalts, alteration zones, ore veins and the bulk sulfides separated from the ore veins and the alteration zones suggest that

- the REE chemistry of the immediate host rocks has been modified by fluids which added LREE,
- the REE abundance of the ore veins vary with the amount of host rock fragments included in the veins,
- the sulfides formed during mineralization have significant REE concentration with patterns nearly identical to the ore veins and alteration zones and
- therefore the ore fluids involved in gold mineralization here could be LREE enriched.

Because alteration and mineralization involved addition of REE, more LREE compared to HREE, the fluids could be of higher temperature origin. The initial Nd isotope ratios in the host rocks ($\varepsilon_{\mathrm{Nd}}$ calculated at 2700 Ma) showed a large variation (+8 to −4) and a deep crustal source for the fluid REE seems likely. A crustal source for Pb and Os in the ore samples of Kolar belt has previously been suggested (Krogstad *et al* 1995; Walker *et al* 1989). Such a source for ore fluids is consistent with a late Archean (2500Ma) accretionary origin for the terrains of the eastern Dharwar Craton.

1. Introduction

Fluids are amongst the most effective agents for the transport of material in the Earth's crust and possibly in the upper mantle. Aqueous hydrothermal fluids are responsible for the formation of many ore deposits and they play a major role in many metamorphic reactions and magmatic processes. Modern exploration strategies should therefore require a thorough knowledge of metal-bearing fluids which migrate at different levels in the crust, the possible source(s) of the ore fluids and an understanding of the chemical evolution of the fluid. The origin of the fluids that gave rise to Archean mesothermal gold deposits is contentious, and models utilizing isotope systematics, geochemical and petrological constraints propose either metamorphic (Kerrich and Fryer 1979; Crawford 1981; Groves *et al* 1987; Phillips and Powell 1993) or magmatic (Burrows *et al* 1986; Cameron and Hattori 1987) origin for the fluids in these deposits. Compositionally the fluids are reported to be of low salinity (< 2 wt % NaCl equivalent) H_2O-CO_2 fluids with a near neutral or weakly alkaline pH and normally reducing (Phillips *et al* 1986 ; Phillips and Powell 1992), although oxidized fluids (Cameron and Hattori 1987; Cameron 1988) have been recorded.

The source of hydrothermal fluids that gave rise to the Archean lode-gold mineralization has been a topic of debate with ore geochemists the world over suggesting fluids that are either internal or

Keywords. REE geochemistry, Archean, lode gold deposit, eastern Dharwar Craton

Proc. Indian Acad. Sci. (Earth Planet. Sci.), **110**, No. 2, June 2001, pp. 143–159

external to the greenstone belts. Barnicoat *et al* (1991) studied the mesothermal lode gold deposits of western Australia. The oxygen isotope data on ore samples indicated to them that the fluid composition was strongly controlled by the wallrocks traversed. Therefore these authors suggested that it might be difficult to identify the fluid source for gold deposits. Cameron (1988) attributed the Archean lode gold mineralization to the granulitization process which occurred during the principal period of crustal thickening and stabilization circa 2.7 ± 0.2 Ga and suggested that upward streaming of mantle CO_2 along shear zones in the lower crust led to the dehydration of amphibolite grade rocks to form granulite and this process was accompanied by LILE depletion at higher crustal levels. But, Kerrich (1989) did not support the granulitization process as a likely candidate responsible for Archean lode gold deposits. On the basis of variable Pb, C, and O isotope systematics, Kerrich (1989) suggested equilibration of internally or externally derived fluids with compositionally variable crust at low water/rock ratios in transpressive accretionary regimes. Mikucky and Ridley (1993) reviewed the information available on the ore fluid compositions for a wide range of metamorphic conditions from sub-greenschist to lower granulite facies. Based on the alteration zone assemblages and fluid inclusion data, these authors suggested an ore fluid composition that is consistent with derivation from or final equilibration with rocks of intermediate - granitic composition. These authors suggested that the Archean lode-gold mineralization involved either a single fluid moving through the middle and upper crust, or derivation of ore fluids by similar processes at different crustal levels. Ho *et al* (1992), based on the stable and radiogenic isotope data, suggested a multiple source for the ore fluids in the Archean lode gold deposits of western Australia.

Schandl *et al* (1995) have studied the REE geochemistry of hydrothermal alteration in the Volcanogenic Massive Sulfide (VMS) deposits of the Superior Province of Canada, and their study revealed that the host felsic volcanics have undergone extensive LREE depletion and hence can be used as an exploration tool for VMS deposits around the Manitouwadge mining camp. Fleet *et al* (1997) studied the REE geochemistry of the Hemlo gold deposit and their studies indicated that the REE geochemistry remains dominated by the protolith composition and thus cannot be used as a primary tool of exploration. Thus a study of mobility and transport of REE's in the Archean precious metal deposits and the VMS deposits wherein the base metals occur is important in understanding the nature of the hydrothermal fluid responsible for mineralization in these two types of hydrothermal deposits.

The main objective of this article is to elucidate the nature of hydrothermal fluid and the probable source of the ore fluid in the auriferous schist belts of Hutti, Ramagiri and Kolar in the eastern part of the south Indian Dharwar craton with special emphasis on the REE geochemical data on the ore materials from these belts.

2. Regional geology of the Dharwar craton

The cratonic block of south India commonly known as the Dharwar craton, covers an area of $2,38,000\,km^2$ lying between latitudes $12°0'$ and $18°0'$ and longitudes $74°0'$ and $80°0'$ (figure 1). The cratonic block has been divided into two parts on the basis of a central N-S trending belt of late kinematic plutonic granitoid rocks known as the Closepet Granite. The present study is confined to the lode-gold deposits in the three major auriferous schist belts at Hutti, Ramagiri, and Kolar in the eastern subblock of the Dharwar craton, occurring to the east of the central Closepet Granite. All the three belts consist dominantly of mafic metavolcanic rocks of predominantly tholeiitic composition, except in Kolar where subordinate amounts of komatiitic rocks occur (Rajamani *et al* 1985, 1989). These belts also include subordinate amounts of felsic metavolcanic rocks and banded iron formations (BIF). Only the Ramagiri schist belt has a few mappable units of serpentinite which probably represent the obducted pieces of Archean oceanic lithosphere (Zachariah *et al* 1996).

The metavolcanic rocks of the schist belts are $\sim$ 2700 Ma and are surrounded by 2700–2500 Ma granitic gneisses with a record of distinct geological histories (Balakrishnan *et al* 1999). The contact between the schist belts and the gneisses are commonly tectonic. However, in the Hutti and Ramagiri schist belts, an intrusive relation between a late phase granite and the supracrustal rocks is seen. The entire eastern subblock of Dharwar craton is thought to have been an accreted terrane and the schist belts represent terrane boundaries. The assembly of the different terranes and their final collision with the western subblock nucleus were thought to have occurred at $\sim$ 2500 Ma (Krogstad *et al* 1989; Balakrishnan *et al* 1999). The geological setting of these three auriferous belts are described in the following paragraphs.

2.1 *Geology of the auriferous schist belts*

2.1.1 *Hutti Schist Belt*

The Hutti Schist Belt is one of the northernmost auriferous schist belts in the eastern Dharwar cra-

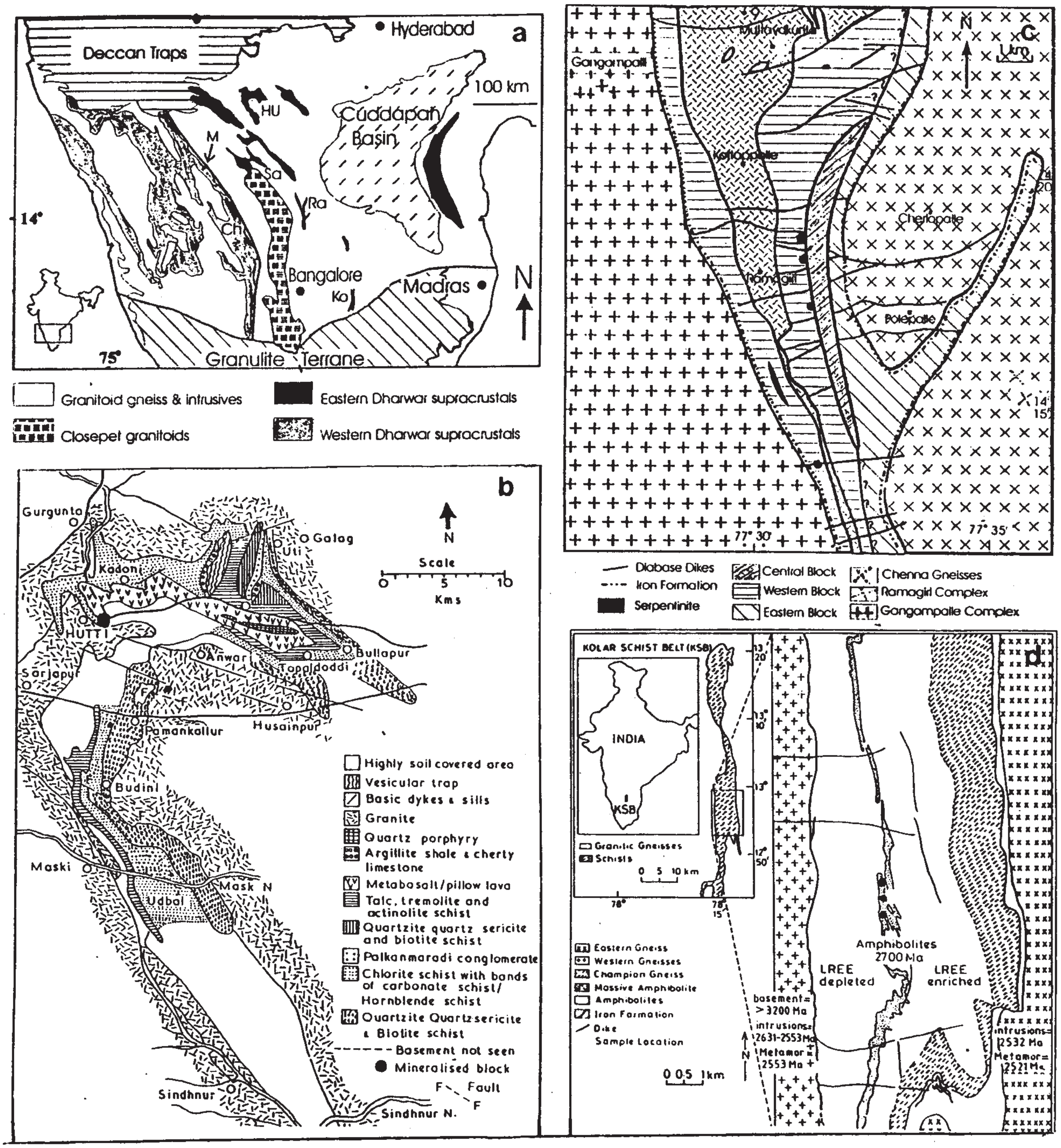

Figure 1. **(a).** Geological map of southern India. Dharwar Craton is bound by Deccan Traps, Granulite Terrane and Cuddapah Basin. The eastern and western parts of the Dharwar Craton are considered to have had distinct evolutionary histories. **Ra** = Ramagiri, **Ko** = Kolar, **Sa** = Sandur, **Hu** = Hutti and **Ch** = Chitradurga schist belts. **M** = mylonitized zone on eastern margin of the Chitradurga schist belt. Inset shows location of the Dharwar Craton. **(b).** Geological map of the Hutti-Maski schist belt (redrawn after Biswas *et al* 1985). **(c).** Geological map of the Ramagiri schist belt U-Pb ages of Zircons from felsic volcanics from the central block, Chenna Gneiss, Ramagiri and Gangam Complexes are 2707 ± 18, 2650 ± 7, 2613 ± 6 and 2528 ± 1 Ma, respectively. **(d).** Geological map of the Kolar schist belt. In all the three belts, the mineralized areas are indicated by filled-circles.

ton located 80kms west of Raichur town. It is a hook shaped schist belt ∼65 kms in length and ∼ 8 kms in width consisting predominantly of metavolcanic rocks and subordinate metasedimentary rocks. Pillow-bearing tholeiitic metabasalts dominate the volcanic suite followed by acid volcanics. The belt is surrounded by granitoid rocks which show intrusive relationship at places such as Madriankota and Uti in the northern part. Available whole rock-K feldspar Pb-Pb isochron data for a granite phase suggest an age of ∼ 2600 Ma (Krogstad, unpublished data). The last phase of igneous activity in the Hutti belt is represented by dykes of pegmatite, dolerite and gabbro (Biswas *et al* 1985). Structural studies by Roy (1979), revealed the presence of three phases of deformation (F_1, F_2 and F_3) in the Hutti belt. Riazullah *et al* (1996) studied the mineral assemblages and their chemistry in the metabasalts and suggested a metamorphic grade transitional between greenschist and amphibolite facies. Giritharan and Rajamani (1998) studied the geochemistry of the host tholeiitic metavolcanics in the Hutti belt and suggested their derivation from melt-metasomatized mantle sources by different extents of partial melting probably in an island arc tectonic setting.

The gold-quartz-carbonate-sulphide mineralization in the Hutti belt is hosted predominantly by the metabasalts, which is confined to narrow but laterally and vertically persistent tabular bodies in the NNW-trending shear zones. The auriferous lodes of the Hutti belt consist largely of altered wallrock with quartz and carbonate in the form of veins, veinlets and stringers impregnated with sulfide minerals, native gold and scheelite. Apart from native gold in the quartz vein, gold also occurs as inclusions within the sulphide minerals such as arsenopyrite, pyrite and pyrrhotite within the altered wallrocks enveloping the quartz veins (Raju 1996).

2.1.2 *Ramagiri schist belt*

The Ramagiri schist belt is one of the important gold producers in the eastern Dharwar craton located in the Anantapur district of Andhra Pradesh. It is a volcanics dominated trident shaped late Archean schist belt about 50kms in length and about 3 kms in width at the central part where the present gold mining activity is concentrated. The schist belt consists of two major arms (western and central) and a minor impersistant eastern arm. Detailed geochemical and geochronological information of the Ramagiri schist belt are available in Zachariah *et al* 1995, 1997. Gold mineralization in the Ramagiri belt occurs in a zone of chlorite-carbonate-quartz-sericite phyllites within the western subblock amphibolites along with minor sulfide minerals such as pyrite and chalcopyrite. Quartz - Carbonate veinlets are localized within the extremely altered (retrogressed) broad phyllitic zones within the amphibolites. Rao *et al* (1989) reported anomalously abundant native gold and scheelite in association with quartz veins in sericite-chlorite phyllites.

2.1.3 *Geology of the Kolar schist belt*

This is the southernmost N-S trending belt and till recently the most productive auriferous schist belt in the Dharwar craton consisting predominantly of tholeiitic amphibolites. Komatiitic amphibolites, BIF, graphitic schists and felsic schists commonly known as the Champion Gneiss are the other rock types that occur in minor amounts. In the central part of the belt where there is extensive gold mineralization (Kolar Gold Fields) a massive, fine-grained, tholeiitic amphibolite unit occurs about which the belt is divided into an eastern part and western part. The central zone where gold-quartz vein mineralization is intense appears to be a tectonic contact zone between the two suites of metavolcanics. Krogstad *et al* (1989) based on a detailed geological, geochemical and geochronological study suggested that the Kolar schist belt is a late Archean suture (∼2500Ma), representing the boundary between at least two distinct late Archean gneissic terranes and that the inferred tectonic setting for the Kolar area is analogous to that proposed for the Mesozoic-Cenozoic margin of the north American Cordillera where fault-bounded allochthonous terranes apparently were accreted by plate convergence.

The Kolar belt includes two distinct types of gold mineralization; an amphibolite-hosted quartz-carbonate veins type (Archean lode gold) which is economically the most important and a BIF-hosted stratiform sulfide type. The lode gold mineralization occurs in the central part of the belt as several parallel sets of veins within the shear zones in the eastern LREE enriched tholeiitic amphibolites. A detailed study on geology, geochemistry and isotopic systematics of the stratiform sulfide type by Siva Siddaiah and Rajamani (1989) and Siva Siddaiah *et al* (1994) revealed a syngenetic volcanic exhalative origin for these deposits and are distinctly different from those of epigenetic vein quartz deposits.

Samples of ore veins from the four main Reefs viz., the Oakley's Reef, Middle Reef, Zone-I Reef and Strike Reef in the underground mine at Hutti and wallrock alteration zone immediately adjacent to the ore veins in the first three Reefs and unaltered host rock at a distance of 5–6 metres on either side of the fourth Reef were collected for geochemical and petrographic studies. In the Ramagiri

Table 1. *Salient features of gold deposits in the three schist belts of the eastern Dharwar craton.*

	Kolar schist belt	Ramagiri schist belt	Hutti schist belt
Host rock	LREE enriched amphibolites and felsic schists known as the Champion Gneiss.	LREE depleted to flat metabasalts represented by amphibolites.	Slightly LREE enriched to flat tholeiitic amphibolites.
Wallrock alteration	Narrow zones of intense alteration with biotitization, albitization, sulfidation and carbonatization.	A wider zone (∼ 200 mts) of not so intense alteration with sericitization, saussuritization, carbonatization and sulfidation of the host rock.	Narrow zones of intense alteration with biotitization, albitization, carbonatization and sulfidation of the host schistose amphibolite.
Ore vein	Epigenetic Au-quartz carbonate vein with varying amounts of host rock fragments and minor sulfides.	A broad zone of chlorite-carbonate phyllites with sericitization and sulfidation.	Epigenetic Au- quartz-carbonate veins with varying amounts of host rock fragments and minor sulfides.
Mode of occurrence	Fracture filled veins with disseminations of sulfides; gold occurring in native form in the quartz vein within the shear zones.	Fracture filling veins in the host actinolite-chlorite schists with minor sulfides. Gold occurs as free milling type within quartz vein and as inclusions in sulfides.	Fracture filling veins in the host amphibolite with minor sulfides. Gold occurs as both free milling gold in quartz and as inclusions in sulfides.
Sulfides	Pyrrhotite ± pyrite ± arsenopyrite.	Dominantly pyrite ± chalcopyrite.	Dominantly arsenopyrite ± pyrite ± pyrrhotite.

belt diamond drill core samples from the western block of the central arm of Ramagiri belt which includes samples from ore horizons, wallrock alteration zones and unaltered host rocks along with a few samples of host rock from the surface outcrops were collected for geochemical and petrographic studies. In the case of Kolar schist belt, the information available in Siva Siddaiah *et al* (1990) is used for comparison with the data of Hutti and Ramagiri belts. The details of the nature of host rock, wallrock alteration zone and ore vein in these three auriferous schist belts of eastern Dharwar craton are described below and summarised in table 1.

2.2 *Host rocks*

The unaltered host mafic metavolcanics in the auriferous schist belts are represented by different textural varieties of amphibolites viz., **(1)** the coarse grained spotted variety, **(2)** medium grained schistose variety and **(3)** the fine grained massive variety, all of them having a similar geochemical and mineralogical composition. Mineralization is hosted by the schistose amphibolites which are Fe-rich tholeiite in composition and are characterized by flat to LREE enriched rare earth patterns. Major and trace element modeling of the host tholeiitic metavolcanics from the Hutti schist belt as well as in the Kolar and Ramagiri belts suggests that they were formed from melt enriched mantle sources by different extents of partial melting at pressures ∼ 25 kbars (Rajamani *et al* 1989). A critical analysis of the host metavolcanics from all the three belts indicated that the process of formation of Fe-rich tholeiites, their metamorphism to amphibolites and their emplacement along terrane boundaries have provided a favourable geochemical environment for gold mineralization in these three belts. The textural features of the host tholeiitic metavolcanics indicate that they have been subjected to different episodes of shearing, the final one being relatively more brittle.

2.2.1 *Ore veins*

The ore vein in these three belts is a dilational feature in the country rock metabasalts, consisting predominantly of quartz, varying amounts of country rock fragments and minor amounts of carbonates and sulfides (table 1). The ore vein generally runs either parallel to the schistosity of the metabasalts or cutting the dominant foliation in the country rock at small angles. In the Kolar and Hutti schist belts, the contacts of the ore vein with the host rock is commonly sharp excepting for a thin, a few centimeter thick, bleached and biotitized wallrock alteration zone, and only in the Ramagiri schist belt, the contact of the ore vein with the host is somewhat gradational characterised by a wider wallrock alteration zone.

2.2.2 *Wallrock alteration*

As stated above, the wallrock alteration zone in the auriferous schist belts of Hutti and Kolar are similar and are characterized by a thin zone of bleached country rocks which have undergone biotitization, carbonatization, albitization and sulfidation of the host metatholeiites due to addition of Na, K, CO_2, S and H_2O. The thickness of this zone in these two schist belts varies from less than a centimeter to about a meter and is inferred to be dependent on the fluid/rock ratio apart from other factors such as permeability and composition of protoliths and physicochemical conditions of fluids. The lesser the thickness of this wallrock alteration zone, the higher is the intensity of alteration which means a stronger focusing of the ore bearing fluid (high water : rock ratio locally). In both Kolar (Champion Reef) and Hutti (Zone-I Reef) belts such zones are associated with higher gold tenor (personal communication from mine geologists). In the case of Ramagiri schist belt, the elements added to the host rocks are similar to those at Kolar and Hutti belts indicating the involvement of fluids of similar composition but the minerals precipitated from the hydrothermal fluids are different which can be attributed to the relatively lower temperature of the fluid. In the Ramagiri belt, the potassic alteration is represented by the formation of sericite, instead of biotite which is a higher temperature phase and is common in the Kolar and Hutti belts. Moreover, the sulfidation in Ramagiri is represented by the formation of abundant pyrite which has a larger stability field in the system Fe-As-S compared to phases such as pyrrhotite and arsenopyrite which are restricted mainly to higher temperatures.

3. Analytical methodology

Finely powdered (−200 mesh) and homogenised host rock samples, ore veins and wallrock alteration zone samples from the Hutti schist belt and the diamond drill core samples comprising host metatholeiites, ore zone and wallrock alteration zone from the western block of the central arm of Ramagiri schist belt were analysed for major and trace elements following a modified digestion procedure of Shapiro and Brannock (1962) using HF, HNO_3, and $HClO_4$ and analysed by a Labtam 8440 ICP-AES. SiO_2 was determined using a Spectronic −20 Bausch & Lomb spectrophotometer. Rare earth elements on these samples along with the bulk sulfide separates from the ore veins and wallrock alteration zone in the Hutti and Ramagiri belts were determined by a polychromator in the Labtam 8440 ICP – AES. Standardization for majority of the major and trace elements (excluding REE) were based on USGS rock standards STM-1, RGM-1, W-2 and DNC-1 and in-house rock standards developed at JNU from the samples of Kolar schist belt. For REE determination on the bulk ore veins, wallrock alteration and unaltered host rocks, the procedure given in Giritharan and Rajamani (1998) was followed. Bulk sulfides from the ore veins and wallrock alteration zone samples were handpicked, finely powdered and used for REE determination. 1–2 g of this finely powdered bulk sulfide samples were dissolved initially in 10–20 ml of 6N HNO_3 and then with concentrated acid, and the solution was allowed to evaporate on a hot plate. It was observed that few undissolved particles were present at the bottom of the teflon beakers used for drying and their examination under a binocular microscope revealed that they were made up mainly of quartz and few amphibole grains and did not have any accessory minerals such as zircon, sphene etc. which would otherwise have an impact on the nature and abundances of REE patterns. This undissolved material was weighed and used for calculating the final abundances of REE in the sulfides. The dried residue of the bulk sulfide samples were then dissolved in 25–30 ml of 1N HCl and loaded on to the HCl quartz columns packed with the same cation exchange resin (AG50W-X8), since iron is the only major matrix element to be removed. The loaded solution was eluted with 60ml of 1.7 N HCl and the REEs were collected with 240ml of 6N HCl and dried. The column separation procedure was repeated 2–3 times till all the iron was removed and a colourless final cut obtained. Standardization for REEs was done with metal standards obtained from Johnson Mathey Inc and in-house rock standards (a basalt and a monzodiorite) which were analysed by isotope dilution method at S.U.N.Y., Stony Brook, USA. Calibration of the cation exchange resin columns for the complete recovery of REEs were done by mixing pure metal standards with other major cations and the abundances of these elements in the eluted solution in every 10 ml intervals were determined by ICP-AES. Except for a higher Er value which is due to Zr interference for this Er line (326.478 nm), the values of all other rare earth elements were comparable to that obtained by the isotope dilution method. The precision of our REE analysis is better than 5% for HREE and better than 10% for LREE, for basaltic rocks with about 10 – 20 x chondrite abundance for LREE.

Table 2. *Major and trace element data of Hutti ore samples.*

	Oakley's Reef			Middle Reef			Zone-I Reef			Strike Reef		
	Ore Vein	Alteration Zone		Ore Vein	Alteration Zone		Ore Vein	Alteration Zone		Ore Vein	Weakly Altered	
	HO–1	HO–2	HO–3	HO–4	HO–5	HO–6	HO–7	HO–8	HO–9	HO–10	HO–11	HO–12
S_iO_2	85.15	61.00	53.87	91.38	48.93	49.86	83.88	57.19	48.29	94.68	54.30	54.31
T_iO_2	0.22	0.49	0.68	0.06	0.83	0.85	0.22	0.72	0.96	0.04	0.97	1.02
Al_2O_3	3.96	9.47	10.60	2.90	14.13	13.64	5.80	13.80	13.00	1.42	13.10	14.70
FeO(t)	3.20	6.21	8.99	1.12	10.05	11.30	3.26	7.75	11.50	0.60	12.10	10.80
MnO	0.06	0.14	0.14	0.01	0.18	0.21	0.04	0.12	0.21	0.01	0.18	0.17
MgO	1.98	3.97	5.89	0.34	5.34	6.72	1.05	3.17	5.99	0.31	6.35	5.12
CaO	3.49	7.06	7.42	0.54	10.18	11.63	2.08	5.44	10.00	0.39	9.77	9.17
Na_2O	1.03	3.14	1.90	1.14	1.99	1.22	1.17	4.44	2.21	0.07	1.78	2.68
K_2O	0.43	1.10	1.80	0.37	0.40	2.40	1.24	1.60	1.40	0.60	1.80	1.05
P_2O_5	0.04	0.08	0.12	0.24	0.39	0.20	0.28	0.21	0.13	0.01	0.14	0.13
TOTAL	99.56	94.41	90.40	98.10	92.42	97.73	99.02	94.44	93.68	98.12	100.49	99.14
Ni	37	80	104	24	137	489	34	27	109	2	111	97
Cr	73	165	154	88	266	194	100	23	129	5	126	135
Ba	15	38	63	27	182	186	182	398	66	18	32	40
Sr	25	63	67	24	111	79	76	385	116	4	126	137
Zr	2	33	56	16	99	48	45	122	44	-	38	44
Y	6	15	20	2	21	-	10	31	24	1	23	26
Ce	2.88	10.71	15.92	12.18	9.35	11.20	14.41	46.97	12.40	0.68	11.14	13.00
Nd	1.76	4.05	7.34	4.77	6.46	7.17	8.30	25.90	7.87	0.31	7.50	8.41
Sm	0.51	1.40	2.00	0.86	2.12	2.36	2.02	5.87	2.22	0.08	2.37	2.40
Eu	0.19	0.43	0.64	0.21	0.79	0.85	0.61	1.66	0.83	0.04	0.93	0.90
Gd	0.69	1.76	2.41	0.79	2.80	3.33	2.13	5.99	3.04	0.12	3.51	3.40
Dy	0.90	2.09	2.66	0.41	3.02	3.03	1.90	5.79	3.78	0.15	3.87	4.05
Er	0.63	1.75	2.18	0.47	2.27	2.60	1.44	3.84	2.75	0.11	3.12	2.95
Yb	0.53	1.18	1.64	0.18	1.90	2.02	1.19	3.29	2.27	0.09	2.44	2.39

4. Results

4.1 *Hutti schist belt*

The major and trace element data including rare earth element data of samples of host rock, wall-rock alteration zone and ore veins collected from the underground mine at Hutti is given in table. 2. In Hutti as well as in the other two schist belts ore zone samples studied come from a single lithology, metabasalts, possibly with some differences in their metamorphic history. The binary plot of least mobile major elements such as Al_2O_3 and TiO_2 (figure 2a) of the Hutti ore samples shows a positive correlation suggesting that **(a)** Al and Ti remained immobile during hydrothermal alteration as suggested by MacLean and Kranidiotis (1987) and that **(b)** the ore samples can be characterized by two end member composition, the metabasalts and the major ore vein mineral quartz (figure 2b and c). The variation seen in Fe, Mg and Ca can also be explained by the two end members to a large extent. Because of carbonate addition, the behaviour of Ca is less regular compared to Fe and Mg. Similarly K_2O shows a large non-systematic variation because of varying extents of alteration of amphibole to biotite.

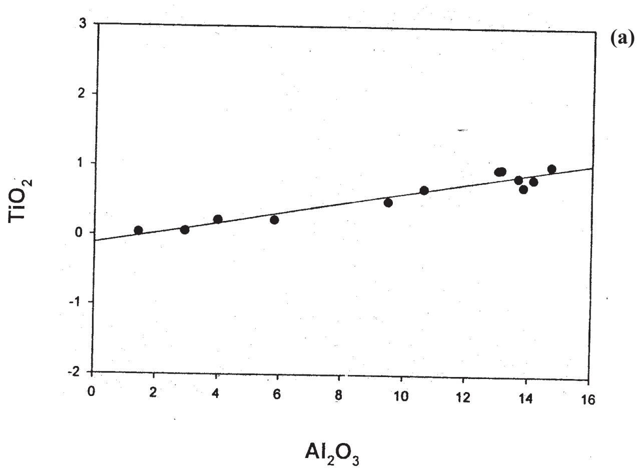

Figure 2(a). Binary plot of TiO_2 vs Al_2O_3 in the Hutti ore samples.

The variation observed in the trace elements of Hutti ore samples is much irregular compared to the major elements. Zr, Cr, Ni and Ce show increasingly irregular variation when plotted against Ti. Interestingly the sample with the highest degree of biotitic alteration such as sample #8 from the Zone-I Reef, seemed to have lost Ni and Cr, but gained Ba, Sr, Zr and Y.

The rare earth elements (REE) in the Hutti ore samples as a group behaved more irregularly than those of the other trace elements as well as major

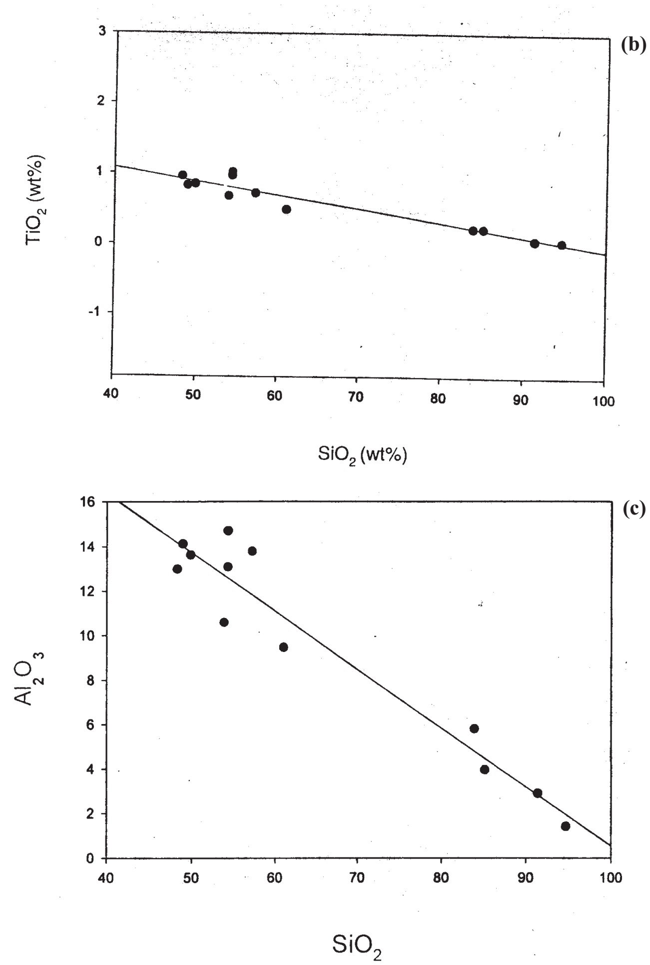

Figure 2(b). Binary plot of **(b)** TiO_2 vs SiO_2 of Hutti ore samples, and **(c)**. Al_2O_3 vs SiO_2 plot of Hutti ore samples.

elements. In the unaltered host amphibolites, the REE patterns are slightly LREE enriched to flat patterns and the abundances vary between 10x and 20 x relative to chondrite. Among the samples from the wallrock alteration zone those with least alteration in terms of biotitization and carbonatization have REE patterns and abundances very similar to that of the host amphibolite. In sample (# 8) which has been extensively biotitized, the REE pattern became more fractionated with the abundance of light rare earths increasing to a greater extent than the heavy rare earths. In the present situation, wallrock alteration involved addition of rare earth elements to the metabasalts and the LREEs seem to have been added more than the heavy rare earths.

The ore vein samples show a large variation in terms of rare earth abundance and patterns. This is because of at least two observed factors such as **(i)** relative proportion of quartz vein and rock fragments and **(ii)** the intensity of alteration of the included rock fragments. The ore samples associated with the intensely altered wallrock (compare

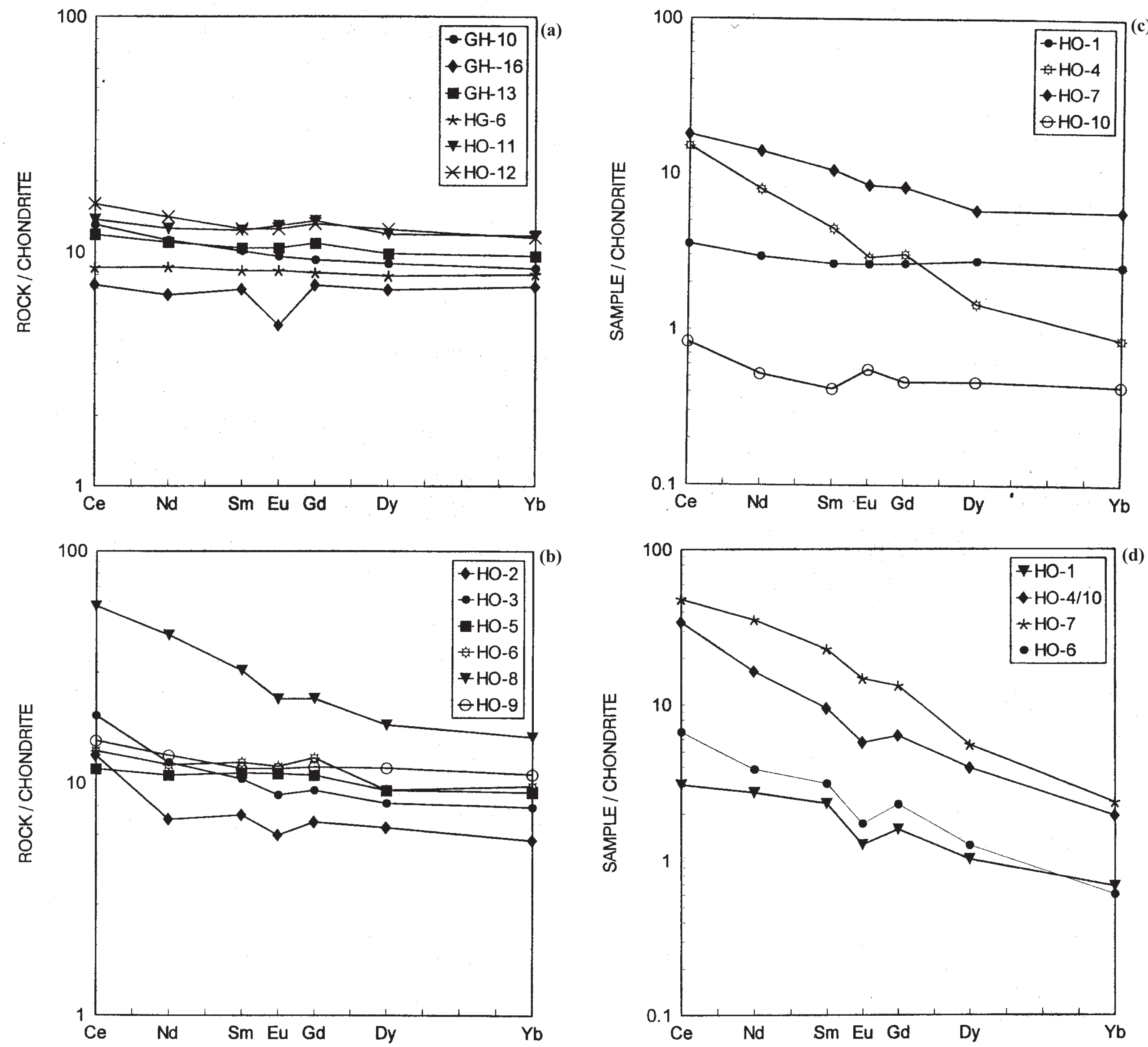

Figure 3. Chondrite normalized REE patterns of Hutti samples. **(a)** Host rocks **(b)** Wallrock alteration zone samples **(c)** Ore veins and **(d)** Bulk sulfide separates from the ore veins and wallrock alteration zone.

samples No. 8 and 7 in figures 3b and c) show similar REE patterns. However the vein sample (No. 7) has much lower REE abundances than the wallrock alteration zone sample (No. 8). Ore vein sample #4 with a very high abundance of silica in it also has a pattern with LREE enrichment. These observations suggest that the alteration and ore vein formation resulted in a change in the REE patterns, particularly through addition of light rare earths (figure 3d). It appears that the fluids responsible for alteration of the wallrock and precipitation of quartz, carbonate and sulfides were enriched in LREE relative to HREE. This inference is further corroborated by the REE chemistry of the sulfide separates from the ore samples.

The sulfides show LREE enriched and HREE fractionated patterns with different extents of negative Eu anomaly. The sulfide separates from those ore veins which are associated with relatively higher degrees of alteration, have greater abundances of REE (sample #4 and #7 in figure 3e). The ore sample with the least amount of rock fragments (#4) and the sulfide separated from them have parallel REE patterns with sulfides having relatively higher amounts of REE than the ore vein. In ore samples with higher proportions of included country rock fragments the parallelism between the ore veins and the sulfide separated from them is absent (for example #7) and the ore vein has higher abundances of HREE relative to the sul-

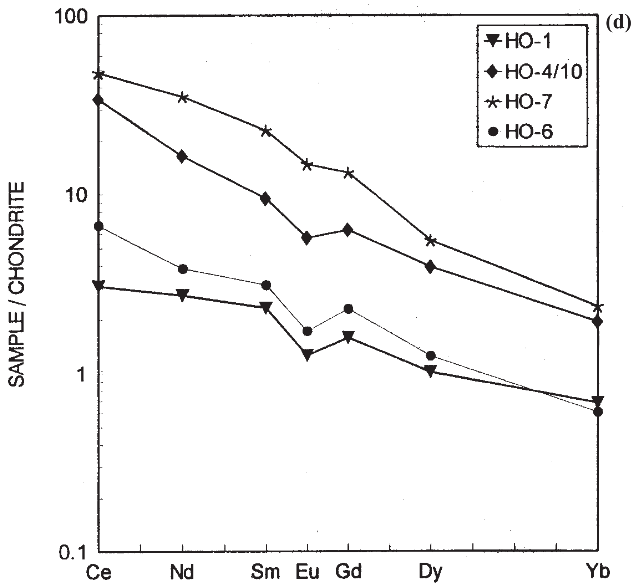

Figure 3. (e) Typical host lithology normalized REE patterns of ore samples from the Hutti belt.

fides because of the presence of amphibole rich rock fragments in the ore vein. Even here, sulfides are significantly enriched in LREE relative to the bulk ore sample.

The similarity of the REE patterns of the bulk sulfide separates from all the ore samples suggests that the sulfide REE patterns could be reasonable proxies to those of the fluids from which the sulfides were precipitated. Although we do not have much information on the selective uptake of REE from ore solutions, available data suggest that sulfides do not fractionate REE (Siva Siddaiah *et al* 1994). Also we observe that sulfides to some extent determine the REE abundance of the ore samples as well as the alteration samples. These observations are quite different from those reported from the Hemlo deposit (Fleet *et al* 1997) where hydrothermal alteration of the protoliths resulted in the depletion of REE in general, and greater depletion of LREEs in particular. The secondary minerals added to the ore samples such as quartz, pyrite, barite and carbonates resulted in the dilution of REE contents. Obviously the nature of the fluids involved in the two geological settings could be different. In the present case, if the sulfides provided only active surfaces for the REE as complexes to be adsorbed, then there probably was no fractionation of the rare earths. Siva Siddaiah *et al* (1994) studied the REE geochemistry of the whole ore and sulfide separates from the BIF hosted Mallappakonda gold sulfide deposit and their study indicated a lack of fractionation of REE by the mineralising fluids. Graf (1977) also suggested that chemical precipitation processes do not commonly fractionate the REE to any significant extent. In the absence of significant evidence for the fractionation of REE by the fluids, the sulfide rare earth patterns could be a good proxy for the REE patterns of the fluids. The abundances in the sulfides could of course be determined by the **(i)** temperature of the fluids **(ii)** the amount of sulfide precipitated and **(iii)** the grain size of the sulfide minerals precipitated. If in case, sulfides provided suitable structural position for the rare earths, the abundance would also depend on the distribution coefficient between the sulfides and the fluids ($K_d^{\mathrm{mineral/fluid}}$).

Although we have not analysed the samples for gold, from the available ore grade information, the gold tenor of the ore zones depends on the intensity of alteration. The ore samples from the Zone - I Reef, #7 and #8 represent the highest intensity of alteration with the highest abundance of rare earths in them. This reef is known to have the highest grade of ore in the Hutti mine (personal information from mine geologists).

4.2 *Ramagiri schist belt*

Drill core samples representing unaltered host rock, wallrock alteration and ore zone were collected from the Ramagiri schist belt and were analysed for major and trace elements including REE (table 3). In this auriferous belt also, the ore samples belong to a single lithology, metabasalt, as at Hutti. However, the host metabasalts in this belt are metamorphosed only up to upper greenshist facies as evidenced by the mineral assemblage with ubiquitous presence of chlorite. The fluid alteration in the Ramagiri schist belt is represented by a wider zone of (~200 metres) less intense, lower temperature alteration and this is exemplified by a virtually undisturbed major element chemistry of the ore samples. The ore horizon in this belt is a broader zone of chloritic, sericitic and carbonate alteration with minor sulfidation within the massive metabasalts and the contact between the ore samples and unaltered host is gradational. The ore samples in this auriferous belt cannot be characterised by two end member compositions in a binary plot of immobile major elements such as Al and Ti as in the case of Hutti schist belt although in this binary plot (figure 4a and b) the Ramagiri ore samples show a linear array suggesting that both these elements remained relatively immobile as at Hutti. Fe, Mg and Ca when plotted against TiO_2 also show a somewhat linear arrangement of sample points but are less regular compared to similar plots of Hutti ore samples. Trace elements such as Ni, Cr, and Ba show little or no correlation when plotted against TiO_2.

The wallrock alteration zone in the western block of the Ramagiri schist belt is characterized by acti-

Table 3. *Major and trace element data of Ramagiri Drill Core samples.*

	Unaltered Host Rock		Weakly Altered Host			Ore Zone	Weakly Altered Host			Weakly Altered Host			Alt.Zone
	88-11	88-17	4-4	4-5	4-6	4-7	4-10	4-11	4-14	4-15	4-16	4-17	4-19
S_iO_2	48.30	48.20	46.07	43.07	43.71	56.56	46.42	44.99	48.68	42.80	44.28	43.56	51.31
T_iO_2	0.77	0.88	0.39	0.75	0.83	0.70	0.84	0.89	0.74	0.70	0.96	0.76	1.61
Al_2O_3	15.00	15.30	12.10	13.88	14.10	14.77	14.63	13.63	14.35	13.77	15.20	13.60	13.9
FeO(t)	10.20	11.50	11.86	10.86	11.23	13.50	10.40	8.33	8.96	8.51	8.95	8.64	11.6
MnO	0.16	0.18	0.15	0.22	0.22	0.05	0.18	0.15	0.13	0.14	0.14	0.15	0.18
MgO	6.11	8.26	7.89	6.86	6.98	3.20	5.18	4.78	4.70	4.48	4.58	4.85	4.43
CaO	13.10	10.13	8.18	10.86	11.64	1.10	9.55	10.06	10.35	9.66	9.07	8.35	6.04
Na_2O	1.27	1.42	1.95	2.19	2.23	1.53	2.56	3.37	1.53	1.61	2.13	3.45	5.25
K_2O	0.08	0.10	0.40	0.12	0.20	1.05	0.30	0.23	0.43	1.10	0.53	0.30	0.37
P_2O_5	-	-	-	0.39	0.43	0.43	0.39	0.14	0.14	0.14	0.20	0.15	0.28
TOTAL	94.99	95.97	88.99	89.20	91.57	92.89	90.45	86.37	90.01	82.91	86.04	83.81	94.97
Ni	157	175	168	152	162	188	169	125	138	117	144	118	84
Cr	274	250	261	296	316	375	326	224	235	215	266	214	145
Ba	39	41	26	9	18	55	26	31	45	186	42	27	48
Sr	122	101	86	88	81	53	89	98	102	70	88	105	53
Zr	34	45	46	96	42	76	118	88	74	72	76	87	94
Y	19	21	12	-	-	4	8	5	7	7.4	7	6	34
Ce	6.67	7.03		8.00		10.82	10.42			14.20		9.81	28.86
Nd	5.44	5.61		5.83		8.29	6.98			7.40		6.17	17.24
Sm	1.86	1.94		1.90		2.83	2.28			2.30		1.87	5.23
Eu	0.78	0.75		0.79		0.90	0.84			0.75		0.69	1.43
Gd	2.53	2.56		2.58		4.13	3.36			3.15		2.55	6.48
Dy	3.22	3.48		2.91		5.05	3.90			2.70		3.07	7.40
Er	2.12	2.19		2.12		3.79	3.36			2.20		2.34	4.60
Yb	2.05	2.19		1.86		3.11	2.41			1.73		1.92	4.20

Table 4. *REE data of bulk sulfide separates from the ore veins and wallrock alteration zone in the Hutti and Ramagiri schist belts.*

	HO–1	HO–4/10	HO–7	HO–6	4–19
Ce	2.495	27.806	39.273	5.450	4.104
Nd	1.631	9.753	21.175	2.301	1.450
Sm	0.446	1.811	4.370	0.598	0.424
Eu	0.091	0.411	1.057	0.124	0.136
Gd	0.411	1.635	3.412	0.595	0.540
Dy	0.331	1.277	1.795	0.407	0.570
Er	0.193	0.610	0.696	0.210	0.524
Yb	0.142	0.404	0.492	0.126	0.380

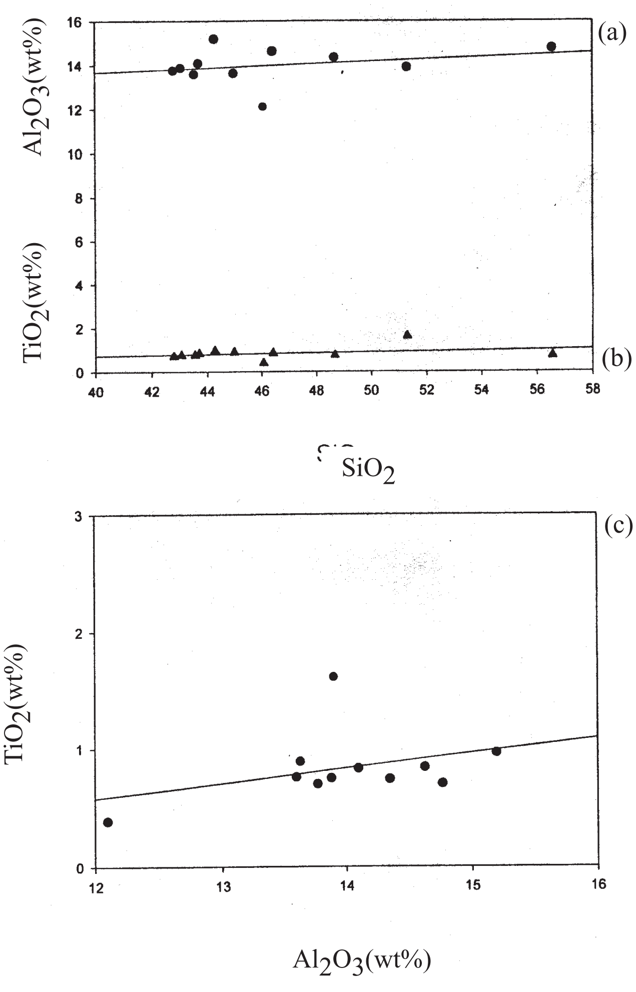

Figure 4. Binary plot of Ramagiri ore samples showing **(a)** SiO_2 vs Al_2O_3, **(b)** SiO_2 vs TiO_2 and **(c)** Al_2O_3 vs TiO_2.

nolite ± chlorite ± albite ± calcite ±sericite ± quartz with minor sulfides which include mainly pyrite. Typical wallrock alteration zone (#4–19) in the Ramagiri belt is characterised by higher contents of Si, Ti, Na, K, Ba, Sr and Zr and lower concentrations of Ca, Fe, Ni and Cr than the unaltered host rock. The sample studied shows a similarity to the wallrock alteration zone of the Hutti belt. Ore sample # 4–7 has the highest silica (56. 6 wt % only) and Ni, Cr contents among the drill core samples studied but this sample has the lowest CaO content and is characterised by silicification and sericitization of the host lithology. Wallrock sample # 4–15 which has undergone sericitization, has the highest K_2O and Ba, Sr contents and is moderately enriched in REE.

The chondrite normalised REE patterns obtained on the unaltered host rock, alteration zone and ore zone drill core samples of the western block is shown in the figures 5a to 5d. The REE as well as other trace elements in Ramagiri ore samples behaved more regularly than those of the Hutti ore samples indicating that the fluid alteration did not affect the chemistry significantly. In the unaltered host lithology from the western block of the central arm of the Ramagiri belt the REE pattern is slightly LREE depleted (Ce_N/ Yb_N = 0.7) to flat pattern. The wallrock alteration samples (# 4–19 and # 4–15) on the other hand have slightly LREE enriched (Ce_N/Yb_N = 1.76) and slightly fractionated HREE patterns (Gd_N/Yb_N = 1.23, figure 5b), but with a higher REE abundance than the unaltered host rocks. Just as in the Hutti schist belt, here also the fluid alteration has resulted in the addition of REE, more so of LREE than HREE. As at Hutti, the alteration related REE addition is highly variable.

The bulk sulfides separated from the wallrock alteration sample # 4–19 in the Ramagiri belt have a lower abundance of REE than the host sample # 4–19, but has a more pronounced LREE enrichment and a slightly fractionated HREE pattern (figure 5d). This has similarity to the bulk sulfide pattern from the wallrock alteration of Hutti belt (# HO-6) in terms of LREE enriched nature but the HREE fractionation is more in the bulk sulfides from the wallrock in Hutti belt than in the Ramagiri belt.

Apart from the addition of rare earths by hydrothermal fluid alteration, albitization of the wallrock also appears to be a characteristic feature of both these auriferous belts.

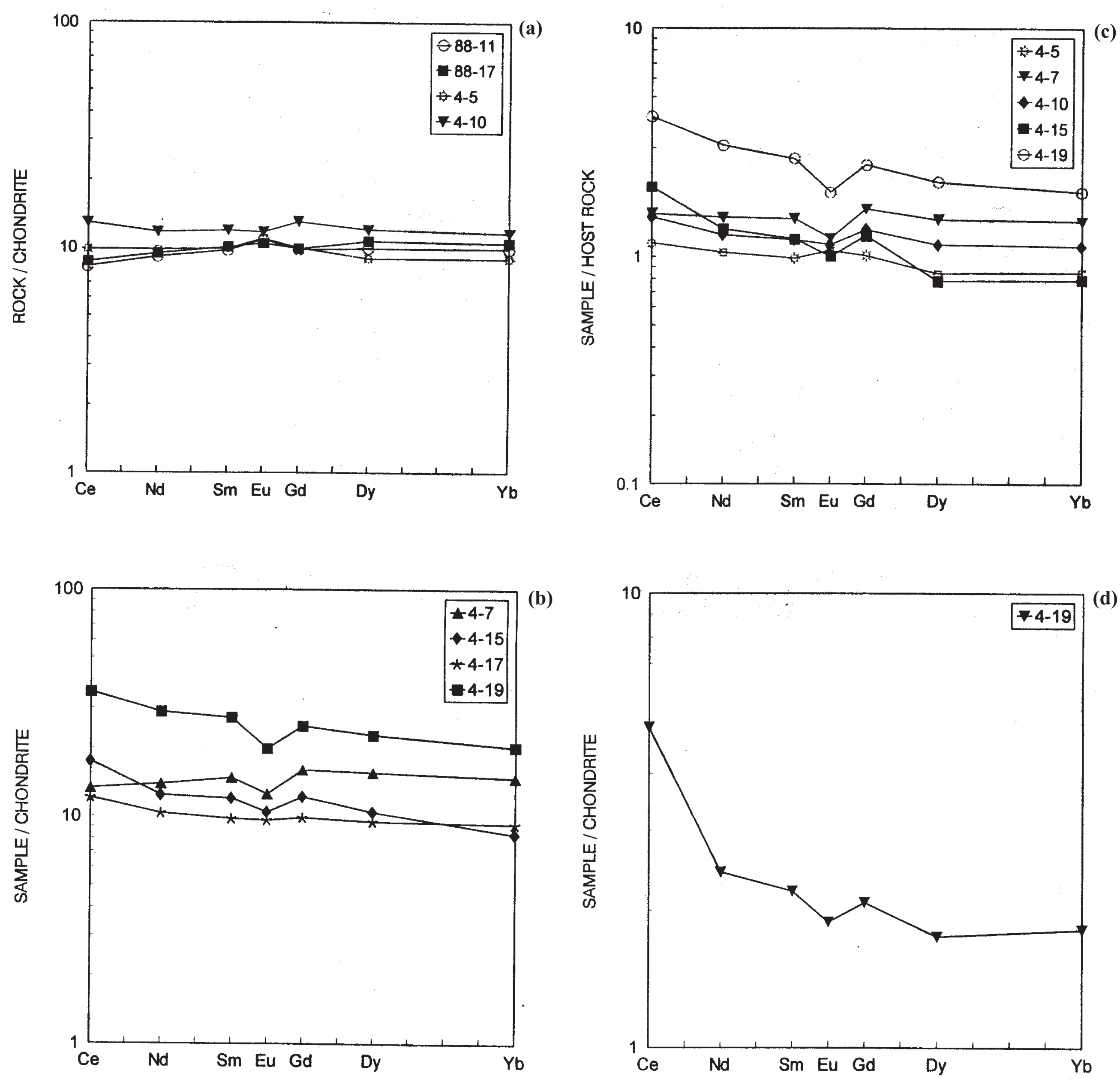

Figure 5. Chondrite normalized REE patterns of Ramagiri samples. **(a)** Host rock, **(b)** Wallrock alteration and ore zone, **(c)** Typical host rock normalized REE pattern of Ramagiri ore samples, **(d)** Bulk sulfide separates from wallrock.

4.3 *Fluid alteration in the Kolar schist belt*

Sajid (1987) studied the chemistry of wallrock alteration samples associated with the gold-quartz-carbonate veins from the Oriental and McTaggart lodes in the Kolar mine. A comparison of the same with the unaltered host metatholeiites collected from surface outcrops indicated that the chemistry of wallrock samples does not differ significantly from that of the unaltered host amphibolites. This study also revealed the absence of any systematic change in the chemistry of wallrock between the contact zones and the one away from it barring small scale changes in the chemistry in a thin zone (few cms) of bleached wallrock adjacent to the ore vein. This zone is characterised by extensive biotitization and the biotite seems to have resulted from reactions involving diopside, hornblende, titanite and K- bearing fluids (Siva Siddaiah *et al* 1990).

Siva Siddaiah *et al* (1990) characterised the REE chemistry of the ore veins, wallrock alteration zone and unaltered host amphibolites in the Kolar schist belt (figure 6). These authors reported that the ore veins in this belt are characterised by variable abundances of REEs but similar LREE enriched and HREE fractionated patterns. The abundances of REE in the ore vein samples vary at least by two orders of magnitude and appears to be controlled

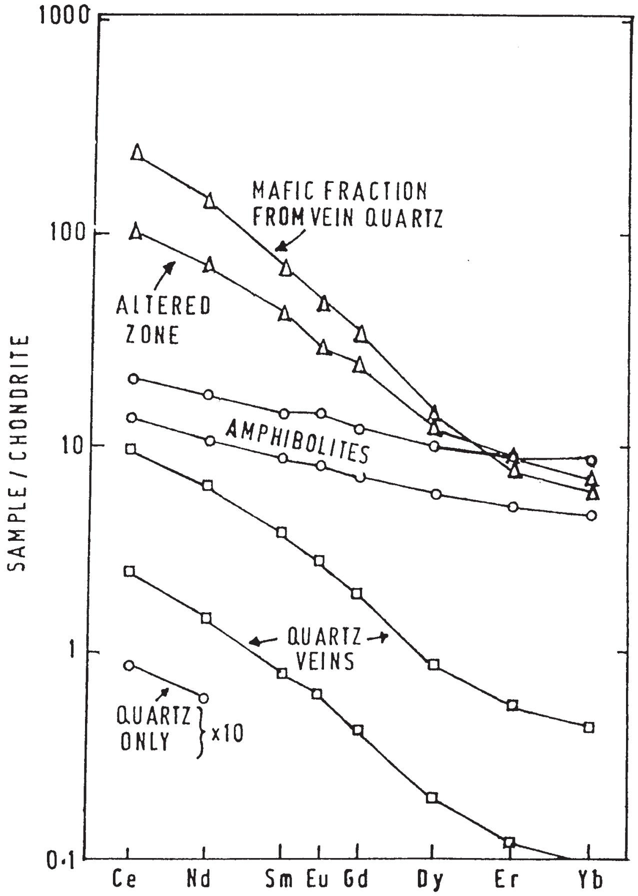

Figure 6. REE patterns of host amphibolites, wallrock alteration zone, ore veins and mafic fraction from ore veins in the Kolar schist belt (after Siva Siddaiah *et al* (1990a)).

by the proportion of rock fragments in the veins, as seen in the Hutti ores. Samples rich in fragments of amphibolite have higher abundances of REE. The wallrock alteration zones adjacent to the ore vein in the Kolar belt have patterns that are similar to the ore veins but dissimilar to the host rock REE pattern indicating that the REE chemistry of the immediate host has been modified by the fluids. REE, more so LREE, have been added to the wallrock just as seen in the Hutti ores. Thus in the Kolar belt, the fluid has imposed it's signature on the immediate host rock, indicating a higher fluid /rock ratio at least locally within the shear zone. The metamorphic grade of the host rock and alteration zone mineralogy are similar to that of the Hutti belt and are indicative of high temperature of the fluids. The only notable difference between the two schist belts (Hutti and Kolar) arises from the sulfide mineralogy of the ore vein and wallrock alteration zone. The abundant sulfide in the ore veins of the Kolar schist belt is pyrrhotite, whereas that in the Hutti belt is arsenopyrite.

5. Discussion

The mobility of a particular group of REE in hydrothermal solutions has been shown to depend on **(a)** the physicochemical conditions of the host environment, most importantly the temperature, fO_2 **(b)** pH of the fluid and **(c)** the water/rock ratio (Michard and Albarede 1986; Shenberger and Barnes 1989; Sanjuan *et al* 1988 and Michard 1989. Michard and Albarede (1986) showed that the seafloor hydrothermal fluids are preferentially enriched in the lighter REE and Eu^{2+} and depleted in HREE. These authors concluded that the preexisting REE concentrations in rocks remain relatively unchanged unless the water/rock ratios are very high ($>10^6$). These authors also suggested that the high temperature fluids can mobilize more of LREE than HREE and the low temperature CO_2 rich fluids can mobilize more HREE relative to LREE.

The addition of rare earths by fluids, especially the light rare earths, to the host lithology as seen in the case of auriferous zones of the three schist belts of eastern Dharwar craton can occur only if the fluids were of high temperature and that the fluids were not acidic at the time of interaction with the host rocks. The abundance of REEs in the fluids as indicated by the bulk sulfide REE abundance from the ore zones in the Hutti, Ramagiri and Kolar schist belts and their REE patterns indicate that fluids were not mantle derived H_2O-CO_2 fluids, since such fluids are reported to have very high REE abundance ($\sim$ 6000x chondritic abundance of Ce, Hanson 1981). Therefore it is possible that the fluids were H_2O dominated, crustally-derived fluids probably related to the granulitization of the lower crust, similar to that reported by Cameron (1988).

Although the fluids involved in the Archean lode gold deposits at Hutti, Kolar and Ramagiri of the eastern Dharwar craton are broadly similar, in terms of temperature and source(s) of the ore fluid, there appears to be some localised differences between the Ramagiri belt and the other two belts as indicated by the mineral assemblage in the wallrock alteration zone. The potassic alteration in the Ramagiri belt is manifested in the formation of sericite instead of biotite which is common in the Kolar and Hutti belts and saussuritization of plagioclase is seen only in the Ramagiri belt. As mentioned in the preceding paragraphs this could be due to a relatively lower temperature of the hydrothermal fluid in the Ramagiri belt. The predominance of pyrite in the Ramagiri belt over high temperature sulfide minerals such as pyrrhotite and arsenopyrite which is seen in the Kolar and Hutti belts respectively also supports the idea of a relatively lower temperature of the fluid in the

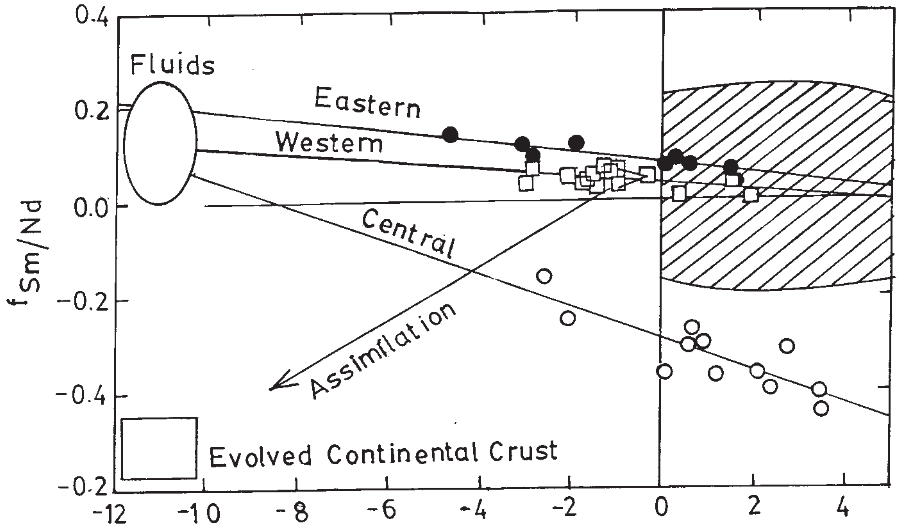

Figure 7. $f_{Sm/Nd}$ vs. ε_{Nd} diagram showing host rock amphibolites from the three different blocks of the Ramagiri schist belt. For mantle derived basaltic rocks, negative ε_{Nd} values are anomalous. This and the trends shown by the three suites of rocks indicate that their Nd isotopic systematics were disturbed by interaction with crustally derived fluids (after Zachariah *et al* 1997b). The hatched area at the right shows the field for Kolar amphibolites.

Ramagiri belt. Zachariah *et al* (1995) attributed the preservation of distinct Nd isotope composition in closely spaced samples of metabasalts of Ramagiri schist belt to low temperature fluid interactions. The gold tenor of the Ramagiri ore is less compared to that of Kolar and Hutti belts. It is possible that low grade alteration mineralogy in the ore zones, almost negligible addition of REE and low gold tenor of the ore are related features resulting from low temperature of the ore fluids and/or low fluid/rock ratios. In the Hutti mine also, ore zones with least change in REE have lowest gold tenor.

The REE abundance of typical wallrock alteration zone samples of Hutti and Ramagiri belts when normalized against the REE abundance of unaltered host rock in the respective schist belts also supports the LREE enriched nature of the fluid (figure 3d and figure 5c). The host rock normalized pattern for the Hutti samples is much more fractionated with relatively higher enrichment of LREE relative to Ramagiri samples. This is perhaps a result of localised differences in the temperature of mineralizing fluids in the Hutti and Ramagiri belts. It has been noted earlier that the REE pattern of hydrothermal fluids is to a large extent determined by the temperature of fluids. The host rock normalized pattern of the Ramagiri alteration zone shows a very sharp negative Eu anomaly. This could be due to the interaction of the fluid with a calcic plagioclase dominated lithology of granodioritic/dioritic composition on its path, which could have resulted in the selective depletion of Eu relative to other REE.

A detailed study of the Sm – Nd isotopic systematics of all varieties metabasalts in the Ramagiri belt indicated a post-magmatic disturbance of the Nd isotopic system (Zachariah *et al* 1995 and 1997). Because ϵ_{Nd} at 2700 Ma showed a large range from +3 to −4 for mantle derived magmas (figure 7), their Sm – Nd systematics were modelled to suggest interaction of these metabasalts after their emplacement (2700 Ma) but before 2480 Ma with crustally derived fluids ($\epsilon_{Nd} \sim -8$ to -10). Similarly the Kolar amphibolites also showed a large range of ϵ_{Nd} at 2700Ma, from +8 to ~ 0, which could also possibly be due to interaction with crustally derived fluids (Balakrishnan *et al* 1990; Zachariah *et al* 1997).

In the Kolar belt, compelling evidence for the involvement of crustal fluids in ore formation is provided by evolved signatures of Os and Pb isotopic data for samples of ore zones (Walker *et al* 1989; Krogstad *et al* 1995). Pb isotopic data for quartz samples from the ore veins of Ramagiri and Hutti belts, however, are less radiogenic and are similar to the associated metabasalts (Zachariah *et al* 1997). Thus ore forming hydrothermal fluids must have evolved and / or interacted with older crustal lithologies in addition to the host metabasalts during the late Archean crustal growth.

The eastern Dharwar craton was thought to have formed by accretion and collision of different continental, island arc and oceanic terranes in the time interval between 2510 and 2450Ma (Krogstad *et al* 1989; Balakrishnan *et al* 1999). This period of accretion and collision coincides with the granulite formation now occurring at the southern and southeastern margins of the craton (Peucat *et al* 1993a). Although we do not have any age data for the ore veins in the three belts, at Kolar, a 2465Ma pegmatite dyke crosscuts the gold-quartz-carbonate ore veins in the amphibolite. The processes of cratonization, granulite formation and gold mineralization along terrane boundaries are possibly related both temporally and spatially. And in the Dharwar craton of southern India, it seems to have occurred around 2500Ma, unlike in other shield areas where the same events are reported to be somewhat older (Balakrishnan *et al* 1999).

6. Summary

The three gold mineralised schist belts in the eastern Dharwar craton show evidence of varying extents of REE addition, more so LREE, to the host rocks immediately adjacent to the ore veins. The magnitude of REE addition seems to depend on the temperature of alteration as inferred from the alteration zone mineralogy. Sulfide minerals formed from the ore fluids all have LREE enriched REE patterns, variable abundances and negative Eu anomaly. It is inferred that fluids responsible for gold mineralization could have had LREE enriched REE chemistry resulting from higher temperature source regions. Available initial Nd isotope data (ϵ_{Nd} at 2700 Ma) for the host amphibolites point to their interaction with crustally derived fluids after their magmatic crystallization. Because the mineralised belts are considered to be terrane boundaries (not greenstone belts), and the ore fluids are likely to be deep-seated with multiple sources, the model of transpressive tectonic regime for gold mineralization seems applicable to these late Archean gold deposits.

Acknowledgements

This paper forms a part of the Ph.D. dissertation work of T S G during which J.N.U. provided a Research Fellowship. Financial assistance from CSIR in the form of Research Associateship to T S G is gratefully acknowledged. This research was also supported by NSF Grants INT 9322645 to V R and Prof. G. N Hanson of S.U.N.Y., Stony Brook, USA. We thank Dr. R H Sawkar and Dr. K K Raju of the Hutti Gold Mines Limited for the logistic support during the field work and for providing the ore samples from the underground mine at Hutti.

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MS received 3 January 2000; revised 16 November 2000