Acta Geochim (2024) 43:555–570
https://doi.org/10.1007/s11631-023-00661-3

ORIGINAL ARTICLE

# Geochemistry and depositional environment of fuchsite quartzites from Sargur Group, western Dharwar Craton, India

**C. S. Sindhuja[1] · G. Harshitha[1] · C. Manikyamba[1] · K. S. V. Subramanyam[1]**

Received: 31 July 2023 / Revised: 4 November 2023 / Accepted: 12 November 2023 / Published online: 13 December 2023


**Abstract** Meso-Neoarchean fuchsite quartzites are present in different stratigraphic positions of Dharwar Craton including the oldest ($\sim$ 3.3 Ga) Sargur Group of western Dharwar Craton. The present study deals with the petrographic and geochemical characteristics of the fuchsite quartzites from the Ghattihosahalli belt to evaluate their genesis, depositional setting and the enigma involved in the ancient sedimentation history. Their major mineral assemblages include quartz, fuchsite, and feldspars along with accessory kyanite and rutile. The geochemical compositions are characterized by high $SiO_2$, $Al_2O_3$, low MgO, CaO, strongly enriched Cr (1326–6899 ppm), Ba (1165–3653 ppm), Sr (46–210 ppm), V (107–868 ppm) and Zn (11–158 ppm) contents compared to the upper continental crust (UCC). The UCC normalized rare earth element (REE) patterns are characterized by depleted light REE $[(La/Sm)_{UCC} = 0.33–0.95]$ compared to heavy REE $[(Gd/Yb)_{UCC} = 0.42–1.65)]$ with conspicuous positive Eu-anomalies ($Eu/Eu^* = 1.35–18.27$) characteristic of hydrothermal solutions evidenced through the interlayered barites. The overall major and trace element systematics reflect a combined mafic-felsic provenance and suggest their deposition at a passive continental margin environment. The comprehensive field, petrographic, and geochemical studies indicate that these quartzites are infiltrated by Cr-rich fluids released during high-grade metamorphism of associated ultramafic rocks. The Sargur and the subsequent Dharwar orogeny amalgamated diverse lithounits from different tectonic settings, possibly leading to the release of Cr-rich fluids and the formation of fuchsite quartzite during or after the orogeny. These findings suggest a pre-existing stable crust prior to the Sargur Group and the link between orogenic events and various mineral deposits in the Dharwar Craton.

**Keywords** Dharwar Craton · Ghattihosahalli · Fuchsite quartzite · Provenance · Depositional setting

## 1 Introduction

The clastic sedimentary rocks represent natural archives offering clues about their geological history of formation, sedimentation styles, and composition of exposed continental crust during the geological past (Taylor and McLennan 1985; Gao and Wedepohl 1995). Archean sediments, predating $\sim$3.0 Ga are of paramount significance as they offer invaluable insights into the ancient crust and sedimentary processes (Dhiume et al. 2012; Chowdhury et al. 2021). One such Archean clastic sedimentary rock is fuchsitic quartzite which is often overlooked and considered petrologically unusual, but holds a significant place in Earth's history due to its occurrence in Archean greenstone belts of numerous cratons of the world, signifying probably the earliest sedimentation processes on the Earth. Fuchsite

✉ C. Manikyamba
cmaningri@gmail.com

C. S. Sindhuja
sindhujachalla29@gmail.com

G. Harshitha
gangulalitty@gmail.com

K. S. V. Subramanyam
ksvsubramanyam@yahoo.com

1 CSIR (Council of Scientific and Industrial Research)-National Geophysical Research Institute (NGRI), Uppal Road, Hyderabad 500007, India

[$K(Al,Cr)_3Si_3O_{10}(OH)_2$] is a Cr, K-rich mineral variety of muscovite mica with a green-coloured tint occurring commonly in metasomatized ultramafic rocks (Whitmore et al. 1946; Brigatti et al. 2001; Ferenc et al. 2016; Austrheim et al. 2021). Fuchsites usually form by substitution of Cr which is mobilized from chrome-spinel or chromium-bearing silicates in ultramafic host rocks; and when K is introduced through hydrothermal fluids in muscovite (Hall and Zhao 1995; Sleep et al. 2011; Haugaard et al. 2021). They show mineralogical association with corundum, aluminum–silicate polymorphs such as kyanite and andalusite (Whitmore et al. 1946) and are stratigraphically associated with ultramafic lithologies within Archean greenstone belts (Nutman et al. 2009; Treloar 1987; Cui et al. 2018). They are also found interlayered with cherts (de Wit et a1. 1982), quartz-carbonate assemblages (Pearton 1981), and metasediments of volcaniclastic origin (Naqvi et al. 1981). As Cr is one of the most immobile elements, its transportation is restricted to a limited distance and therefore, its occurrence as a detrital grain indicates a very proximal source (McLeod 2001). The chromite characteristically crystallizes in mafic–ultramafic magmatic complexes. However, globally the occurrence of chromite in the form of detrital grains in phyllosilicates, spinels, and micas hosted in various metasedimentary lithologies has also been reported (Challis et al. 1995). As Chromite has a higher resistance to weathering compared to silicate minerals, detrital chromites in metasedimentary rocks have been reported to occur as relicts within the fuchsitic micas (Haugaard et al. 2021). However, the origin of fuchsite is an entrancing debate and has two schools of thought, namely hydrothermal alteration (Morata et al. 2001) and metamorphism of chromium minerals in the parent rock (Argast 1995). Fuchsite shows four main litho-mineralogical associations within Archean supracrustal belts, corundum-aluminosilicate-quartz assemblage as found in Barberton greenstone belt, South Africa and Yilgarn craton of Western Australia; chert association representing silicification of komatiites in Barberton greenstone belt; carbonate-quartz association together with Au, As and Ag as found in various greenstone belts of South Africa, Canada, and western Australia; fuchsite occurring in clastic, volcanoclastic and chemical metasediments of western Australia and India (Staddon et al. 2021; Martyn and Johnson 1986).

In India, fuchsite quartzites have been reported from the Archean Bastar, Singhbhum and Dharwar cratons. Randive et al. (2015) have reported the paragenesis of Cr-rich micas and associated chlorites in the fuchsite quartzites which occur as enclaves of the Amagaon Group within the Amagaon Gneissic Complex at the Saigaon–Palasgaon area of Bastar Craton. The bimodal source of origin of Cr-bearing quartzites which are a part of Mahagiri quartzite of Iron-Ore Group of Singhbum craton has been reported by Das et al. (2021). Sadashivaiah and Karisiddaiah (1976) have studied the optical properties and mineral chemistry of fuchsite quartzites from Nemakallu of the Bellary area, Sandur schist belt of western Dharwar Craton (WDC). Khanna and Sai (2018) have reported fuchsite quartzites from the Velligallu schist belt of Eastern Dharwar Craton (EDC) and suggested a hydrothermal origin for enrichment of Cr in the micas and felsic provenance for these rocks. Fuchsite quartzites from Sargur Group of Supracrustal rocks have been reported from Hunasehalli, Bettadabidu of Mysore area (Raase et al. 1983); Banavara (Maibam et al. 2021) and Belavadi (Raase et al. 1983) of Hassan area and Holenarsipur (Naqvi et al. 1983), Ghattihosahali schist belts (Devaraju and Murthy 1978). The fuchsite quartzites of the Sargur Group are very significant as they are the oldest sediments in the Dharwar Craton which may provide valuable insights into the preservation of ancient sedimentation history and the effects of subsequent metamorphism and hydrothermal activity which in general are attributed to rich mineral heritage. Most of the studies on fuchsite quartzites are restricted to mineral chemical data and the whole rock geochemistry is very meager to understand the provenance, its relationship with the associated rocks, and subsequent effects of metamorphism. The present study supplements the available mineral chemical data with the whole-rock geochemistry and petrography of fuchsite quartzites from the Ghattihosahalli schist belt and aims to understand their paleoweathering, provenance, and depositional setting.

## 2 Geological setting

The volcano-sedimentary units of the greenstone belts and tonalite-trondhjemite-granodiorite (TTG) granitoid complexes are well preserved in the Dharwar Craton of southern peninsular India, (Swami Nath and Ramakrishnan 1981; Rogers 1986; Chadwick et al. 2000; Manikyamba and Ganguly 2020) which is divided into western, eastern, and central provinces based on the lithology, crustal thickness, and isotope geochronology (Peucat et al. 2013). The western Dharwar craton (WDC) is demarcated from the eastern Dharwar Craton (EDC) by the ~2.5 Ga Closepet Granite and is divided into older supracrustal formations named the Sargur Group of rocks (3.25–3.1.3 Ga) and younger overlying Dharwar Supergroup of rocks (2.9–2.6 Ga; Friend and Nutman 1992). The Ghattihosahalli greenstone belt of WDC is situated towards the western-most boundary of the Chitradurga greenstone belt and is surrounded by 3.1 Ga TTG peninsular gneisses in the eastern and northern peripheries (Jayananda et al. 2008; Fig. 1). This belt extends for 25 km from Mayankonda in the west to Talya in the east with ESE–WNW to SE–NW trend (Paranthaman 2005) and is reported to have undergone multiple deformation events, tectonism, granite intrusions and amalgamation. Hence, the establishment of a coherent stratigraphic sequence is complicated (Sengupta et al. 2020). The Sargur supracrustal rocks of the Ghattihosahalli belt are represented by ultramafic rocks such as komatiites, serpentinites, amphibolites, and metasedimentary rocks including quartzites and barytes (Radhakrishna and Sreenivasaiah 1974). The Sargur Group and the basement peninsular gneissic complex of this belt form a synformal keel which is together folded into an antiform plunging towards the north (Paranthaman 2005), and the impersistence and discontinuity in the lithounits of the belt are evidenced through the diverse structural trends in the volcano-sedimentary lithounits. Besides the deformation events, the Dharwar orogeny appears to have also affected the Sargur Group of rocks in the Ghattihosahalli belt. The detrital zircons from the conglomerates of the Ghattihosahalli belt have yielded a U–Pb age of 3467 ± 18 Ma and those from the fuchsite quartzites of the Bababudan belt are dated at 3382 ± 16 Ma. The ultramafic rocks of Ghattihosahalli and surrounding Sargur complexes including Banasandra, Nuggihalli, JC Pura, and Kalyadi yielded a Sm–Nd whole-rock isochron age of 3352 ± 110 Ma (Jayananda et al. 2008). Given that the depositional age of the Sargur Group supracrustals has been broadly constrained between 3.3 and 3.1 Ga, and the ultramafic rocks associated with the fuchsite quartzites were emplaced at ∼ 3.35 Ga, the depositional age of the fuchsite quartzites has been inferred at ∼3.2 Ga. Tungsten, barium, and SEDEX-type of base metal mineralization have been reported from the amphibolites of this belt (Srinivasaiah et al. 2015). The strontium isotopic data ($^{87}Sr/^{86}Sr = \sim 0.7018$) of barytes indicates buffered interaction of fluids with komatiitic-basaltic crust (Deb et al. 1990). The sulfur isotopic compositions ($\delta^{34}S = -12.2‰$ and $-1.4‰$; $\Delta^{33}S = -0.79‰$ and $-0.19$ ‰; $\Delta^{36}S = -0.8‰$ and $+0.9$ ‰) of pyrite occurring in the barytes associated with fuchsite quartzites indicate bacterial sulfate reduction (Muller et al. 2017). The mineral chemistry and petrography of Ba–Cr micas in the quartzites suggested the volcanic exhalative origin of Barium (Raase et al. 1983; Devaraju et al. 1999). According to Raith et al. (2014), Ba–Cr micas of Ghattihosahalli originated from pre-existing clay minerals such as illite, which have adsorbed metallic Cr, Ba derived from hydrothermal exhalatives as well as weathered constituents of associated komatiites. Although the nature and composition of Cr bearing micas have been discussed by earlier workers, the whole rock geochemical compositions to understand the depositional environment and the processes involved in the enrichment of Cr in these quartzites have not been paid much attention. Therefore, their petrographic and whole rock geochemical studies have been attempted in this study to decipher the source of Cr in the genesis of these rocks.

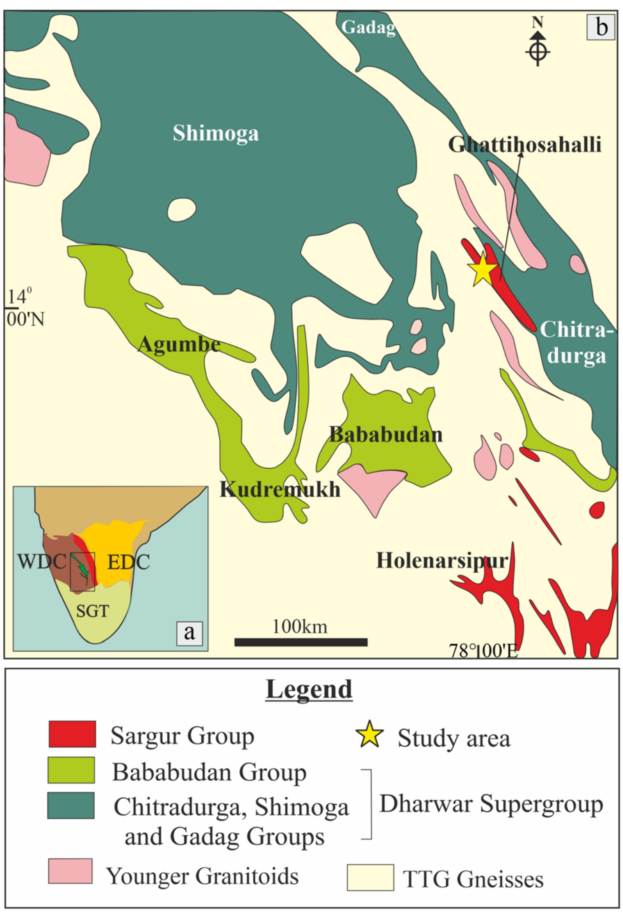



**Fig. 1** **a** Map of the southern peninsular India showing the location of western and eastern Dharwar Craton (WDC, EDC), **b** Simplified geological map showing western Dharwar Craton and sample location from Ghattihosahalli area of Chitradurga greenstone belt (modified after Ravindran et al. 2023)

## 3 Analytical techniques

The fuchsite quartzites of the Ghattihosahalli belt are spatially associated with the ultramafic rocks of the Kumminagatta area. For the present study, nine green-micaceous fuchsite quartzite samples were collected from fresh outcrops (N13°59′21″, E76°17′09″), where, the fuchsite quartzite beds gradually grade into micaceous quartzites. These samples are intercalated with barytes and are underlined by ultramafic rocks, predominantly komatiitic. The samples for the present study have been collected randomly in the mine area avoiding the barytes and micaceous quartzite beds. The collected samples are powdered to ∼240 mesh by using agate mortar for whole-rock geochemical studies. The major element analysis was conducted by using pressed pellets following the method of Krishna et al. (2007) by X-Ray Florescence Spectrometer (XRF; Phillips MAGIX PRO Model 2440). The trace element analysis was performed using the closed digestion method by High-Resolution Inductively Coupled Mass Spectrometer (HR-ICP-MS; Nu Instruments Attom, UK). SARM-49 has been used as an international standard for the analysis of these rocks where precision and accuracy are within 3–5 % (Table 1). High resolution scanning electron microprobe (SEM) images and respective EDS spectra are obtained from Hitachi S-3400 N SEM at CSIR-NGRI.

## 4 Results

### 4.1 Petrography

The fuchsite quartzites of the present study predominantly consist of quartz with subordinate amounts of muscovite (Fig. 2c). Most of the quartz grains are colourless to grey in colour, sub-rounded to sub-angular in shape and display wavy extinction. They exhibit mosaic texture with distinct grain boundaries and some of them show amoeboidal and serrated boundaries suggesting deformation and metamorphism. Tiny flakes of muscovite occur as randomly oriented grains within the quartz matrix (Fig. 2d). The fuchsite quartzites display characteristic green colour under plane-polarized light and they exhibit high order interference colours ranging from deep green to bluish green under crossed nicols due to the presence of green micaceous mineral, fuchsite along a preferred orientation. Chromite grains are occasionally found enclosed in the fuchsites indicating metamorphism and leaching from underlying ultramafic rocks (Fig. 2e and f). They are isotropic in nature, subhedral to sub-rounded in shape and display high relief (Fig. 2g). Rutile is the major accessory mineral associated with kyanite (Fig. 2h).

### 4.2 Geochemistry

The results of the major and trace element geochemistry of the fuchsite quartzites from the studied Ghattihosahalli greenstone belt are given in Table 2. They contain high $SiO_2$ (52.01–91.50 wt%), $Al_2O_3$ (4.18–34.7 wt%), very low $TiO_2$ (0.07–0.23 wt%) and $K_2O$ (0.1–0.92 wt%) when compared to Upper Continental Crust (UCC; Taylor and McLennan 1985). The average compositions of major elements from the present study are analogous with the Cr-rich metasediments from Parapara Inlet Cr-quartzites, New Zealand and Jowet Well Quartz-Andalusite-Fuchsite rocks of Australia along with Cr- rich quartzites of Holanarsipur and Veligallu greenstone belts of WDC and EDC respectively (Fig. 3a). The trace and REE compositions of the fuchsite quartzites have been normalized with Upper Continental Crust (UCC; Taylor and McLennan 1985). The UCC normalized REE patterns of the studied samples are characterized by depleted LREE contents $[(La/Sm)_{UCC} = 0.33–0.95]$ compared to HREE $[(Gd/Yb)_{UCC} = 0.42–1.65)]$ with conspicuous positive Europium anomalies (Eu/Eu* = 1.35–18.27; Fig. 3b; $Eu/Eu^* = (Eu)_{cn}/[(Sm)_{cn} \times (Gd)_{cn}]^{0.5}$). They have highly enriched contents of Cr (1326–6899 ppm), Ba (1165–9437 ppm) and V (106–868 ppm) compared to UCC (Fig. 3c) and are depleted in Nb (0.51–3.87 ppm) and Ta (0.04–0.7 ppm). The enrichment of Cr in these quartzites can be attributed to the presence of fuchsite, i.e., Cr-mica, while high barium and vanadium contents are due to the intercalated fine layered barite seams.

## 5 Discussion

### 5.1 Paleo-weathering conditions

The chemical compositions of sedimentary rocks are influenced by numerous factors such as sediment supply, sorting, transportation, intensity of weathering and post-depositional alteration (McLennan 1993; Nesbitt and Young 1982; Cullers 2000). To quantify the degree of weathering, various alteration indices such as chemical index of alteration (CIA), chemical index of weathering (CIW), index of compositional variation (ICV) and plagioclase index of weathering (PIA) have been proposed (Nesbit and Young 1982; Harnois 1988). Recently, Cho and Ohta (2022) have formulated a robust weathering index for sediments that have biogenic and authigenic material. In the relationship between Mafic (M)-Felsic (F)-Robust Weathering (RW; Fig. 4a), the studied samples plot close to RW apex suggesting intense weathering. The relationship between CIA and ICV of fuchsite quartzites indicates moderate weathering conditions (CIA = 66–81; Fig. 4b; $CIA = [Al_2O_3/(Al_2O_3 + Na_2O + CaO^* + K_2O)] \times 100$, calculated in molar proportions and CaO* corresponds to CaO from silicates excluding CaO from carbonates, sulfates and phosphates) which collectively suggest moderate to intense weathering conditions. Further, ICV $< 1$ indicates compositionally mature sediments while ICV $> 1$ suggests immature sediments. The fuchsite quartzites of the present study are characterized by ICV $< 1$ [0.25–0.62; $ICV = Fe_2O_3 + K_2O + Na_2O + CaO + MgO + MnO + TiO_2)/Al_2O_3$] suggesting matured nature of sediments.

**Table 1** Analytical data, standard deviations (SD) of GSR-4 and JG-2 obtained by HR-ICP-MS in the present study and reported values from Govindaraju (1994) and GEOREM (http://georem.mpch-mainz.gwdg.de)

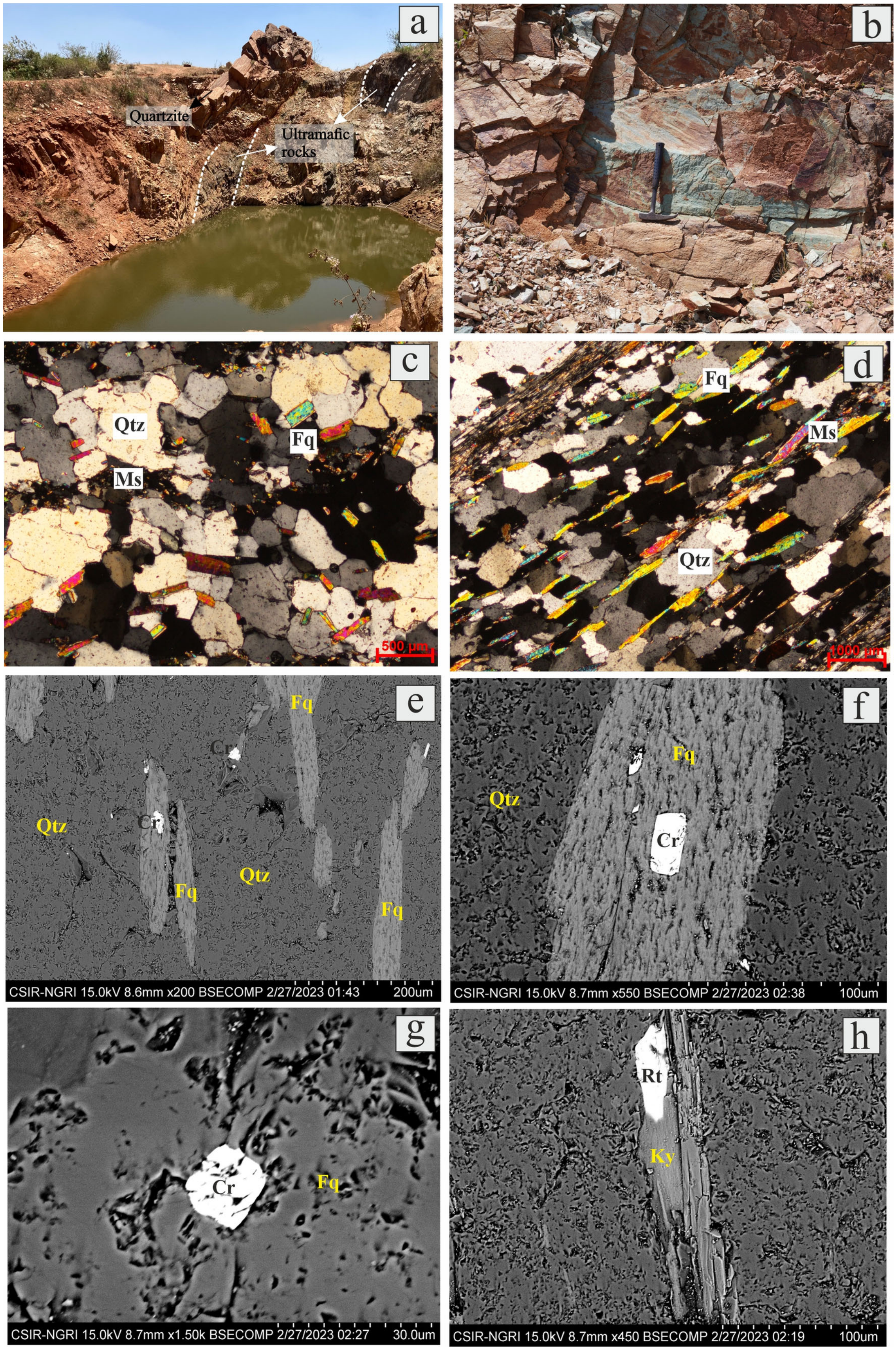
| Analyte | mass No | GSR-4 | | | | JG-2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | A | B | SD | %RSD | A | B | SD | %RSD |
| Sc | 45 | 4.256 | 4.200 | 0.023 | 0.54 | 2.489 | 2.470 | 0.0042 | 0.168 |
| V | 51 | 32.979 | 33.000 | 0.160 | 0.48 | 3.133 | 3.000 | 0.0289 | 0.921 |
| Cr | 53 | 20.031 | 20.000 | 0.115 | 0.58 | 7.770 | 7.600 | 0.0368 | 0.474 |
| Co | 59 | 6.403 | 6.400 | 0.034 | 0.54 | 4.402 | 4.300 | 0.0222 | 0.503 |
| Ni | 60 | 16.302 | 16.600 | 0.072 | 0.44 | 2.146 | 2.100 | 0.0100 | 0.467 |
| Cu | 63 | 18.902 | 19.000 | 0.091 | 0.48 | 0.409 | 0.400 | 0.0020 | 0.492 |
| Zn | 66 | 19.856 | 20.000 | 0.094 | 0.47 | 13.022 | 12.700 | 0.0698 | 0.536 |
| Ga | 71 | 5.419 | 5.300 | 0.032 | 0.58 | 19.630 | 19.000 | 0.1363 | 0.694 |
| Rb | 85 | 29.131 | 29.000 | 0.142 | 0.49 | 300.159 | 297.000 | 0.6839 | 0.228 |
| Sr | 88 | 58.263 | 58.000 | 0.274 | 0.47 | 16.406 | 16.000 | 0.0878 | 0.535 |
| Y | 89 | 21.634 | 21.500 | 0.094 | 0.43 | 90.409 | 88.200 | 0.4783 | 0.529 |
| Zr | 90 | 214.701 | 214.000 | 0.927 | 0.43 | 103.586 | 101.000 | 0.5599 | 0.540 |
| Nb | 93 | 5.937 | 5.900 | 0.032 | 0.54 | 15.330 | 15.000 | 0.0714 | 0.466 |
| Cs | 133 | 1.835 | 1.800 | 0.010 | 0.52 | 2.139 | 2.096 | 0.0092 | 0.431 |
| Ba | 137 | 146.004 | 143.000 | 0.923 | 0.63 | 68.739 | 67.000 | 0.3765 | 0.548 |
| La | 139 | 21.425 | 21.000 | 0.117 | 0.55 | 20.483 | 20.100 | 0.0828 | 0.404 |
| Ce | 140 | 48.944 | 48.000 | 0.322 | 0.66 | 50.534 | 49.500 | 0.2239 | 0.443 |
| Pr | 141 | 5.474 | 5.400 | 0.032 | 0.58 | 6.144 | 6.010 | 0.0291 | 0.473 |
| Nd | 146 | 21.437 | 21.000 | 0.129 | 0.60 | 26.287 | 25.800 | 0.1054 | 0.401 |
| Sm | 147 | 4.805 | 4.700 | 0.035 | 0.73 | 7.866 | 7.720 | 0.0317 | 0.403 |
| Eu | 153 | 1.023 | 1.020 | 0.006 | 0.62 | 0.090 | 0.090 | 0.0001 | 0.087 |
| Gd | 157 | 4.643 | 4.500 | 0.035 | 0.75 | 7.251 | 7.100 | 0.0328 | 0.452 |
| Tb | 159 | 0.814 | 0.790 | 0.005 | 0.67 | 1.529 | 1.500 | 0.0063 | 0.414 |
| Dy | 163 | 4.177 | 4.100 | 0.032 | 0.77 | 11.753 | 11.500 | 0.0548 | 0.466 |
| Ho | 165 | 0.762 | 0.750 | 0.006 | 0.76 | 1.433 | 1.400 | 0.0072 | 0.505 |
| Er | 166 | 2.036 | 2.000 | 0.013 | 0.66 | 5.076 | 4.950 | 0.0272 | 0.536 |
| Tm | 169 | 0.332 | 0.320 | 0.003 | 0.96 | 0.712 | 0.700 | 0.0026 | 0.369 |
| Yb | 172 | 1.990 | 1.920 | 0.021 | 1.07 | 7.535 | 7.340 | 0.0423 | 0.561 |
| Lu | 175 | 0.304 | 0.300 | 0.002 | 0.58 | 1.248 | 1.220 | 0.0061 | 0.488 |
| Hf | 178 | 6.684 | 6.600 | 0.048 | 0.72 | 5.520 | 5.360 | 0.0347 | 0.628 |
| Ta | 181 | 0.430 | 0.420 | 0.004 | 0.93 | 1.926 | 1.900 | 0.0056 | 0.293 |
| Pb | 208 | 7.803 | 7.600 | 0.060 | 0.77 | 33.750 | 32.800 | 0.2056 | 0.609 |
| Th | 232 | 7.134 | 7.000 | 0.041 | 0.58 | 30.097 | 29.700 | 0.0859 | 0.286 |
| U | 238 | 2.167 | 2.100 | 0.015 | 0.70 | 12.867 | 12.500 | 0.0794 | 0.617 |

A—values from ICP-MS (average of 3 values)

B—values from Govindaraju (1994) and GEOREM (http://georem.mpch-mainz.gwdg.de)

### 5.2 Geochemical characteristics and provenance

Fuchsite quartzites that are hosted in Archean greenstone belts are enriched in Cr and are characterized by distinctive metamorphic mineral assemblages, geochemical characteristics, and complex depositional conditions, with fuchsite being formed either as a reaction product of detrital chromite grains (Schreyer 1982) or through hydrothermal alteration of pre-existing chrome-spinels (Morata et al. 2001). Hence, understanding the elemental association of Cr is important to decipher their source and tectonic framework. The fuchsite quartzites of the present study show a negative relationship with $SiO_2$ and a non-linear relationship with MgO (Fig. 5a, b). Though the studied samples are closely associated with ultramafic rocks, they are extremely depleted in MgO and display very low $MgO/K_2O$ ratios (0.009–0.01). This reflects that the ultramafic rocks have not provided the volcaniclastic input for the studied rocks, though they were within the Sargur basin. $Al_2O_3$, $K_2O$, and $Na_2O$ show a strong positive correlation with Cr suggesting the detrital origin for the quartzites, as commonly observed (Fig. 5c, d, e). Cr and Ni are typically



a
Quartzite
Ultramafic rocks
b
c
Qtz
Fq
Ms
500 µm
d
Fq
Ms
Qtz
1000 µm
e
Fq
Cr
Cr
Qtz
Qtz
Fq
Fq
CSIR-NGRI 15.0kV 8.6mm x200 BSECOMP 2/27/2023 01:43 200um
f
Fq
Qtz
Cr
CSIR-NGRI 15.0kV 8.7mm x550 BSECOMP 2/27/2023 02:38 100um
g
Cr
Fq
CSIR-NGRI 15.0kV 8.7mm x1.50k BSECOMP 2/27/2023 02:27 30.0um
h
Rt
Ky
CSIR-NGRI 15.0kV 8.7mm x450 BSECOMP 2/27/2023 02:19 100um

◀ **Fig. 2** **a** Field photograph showing the contacts between the fuchsite quartzite and associated ultramafic rocks, **b** close-up view of fuchsitic quartzite with greenish tint; **c**, **d** photomicrographs of the studied fuchsite quartzites showing serrated quartz grains with sutured contacts along with fuchsite and muscovite in a preferred orientation; **e** parallelly oriented grains of fuchsite in quartz matrix; **f** chromite grain enclosed in fuchsite mica; **g** Subhedral to subrounded chromite in fuchsite mica; **h** kyanite grain enclosing rutile

enriched in Archean sedimentary rocks compared to their post-Archean counterparts (Taylor and McLennan 1985; Condie 1993). However, Arora and Naqvi (1993) reported that the quartzites of the Bababudan belt are characterized by the enrichment of Cr without an increase in Ni. The samples in the present study show similarity to the above-mentioned rocks and improper correlation between Cr and Ni (Fig. 5f) suggests that their composition is independent of each other. Similarly, Cr also shows a strong positive correlation with Zr implying the retention of resistant detrital minerals and their subsequent accumulation along with the quartzites (Fig. 5g). The lack of a linear relationship between Zn and Cr in the studied fuchsite quartzites indicates the non-concurrent enrichment of Zn during the late-stage hydrothermal remobilization (Fig. 5h).

In order to decipher the provenance of the sedimentary rocks, immobile trace elements such as Ti and Zr are widely used as proxies (Floyd et al. 1989; Hayashi et al. 1997). In the relationship between $TiO_2$ and Zr (Fig. 6a), the fuchsite quartzites indicate mafic provenance and occupy the field of Sargur ultramafic rocks which would have been inherited due to the contribution of Cr-rich fluids. However, the predominant felsic source for the genesis of these rocks cannot be ignored keeping in view of the presence of quartz, feldspars, and mica. Generally, mafic rocks are depleted in La, Th and enriched in Sc, Co contents compared to felsic rocks (Cullers 2000). In La/Sc and Th/Co relationship, the studied samples again attest to mafic provenance and depict similarities with the Holenarsipur Cr-rich metapelites (Fig. 6b). The influence of mafic–ultramafic rocks in the formation of these fuchsite quartzites is further corroborated by the ternary relationship between the V–Cr–Th followed by the binary relationship between Y/Ni versus Cr/V and Cr/Th versus Th/Sc (Fig. 6c, d, e). The studied samples depict greater influence of ultramafic source compared to Holenarsipur counterparts, but, the Veligallu fuchsite quartzites from eastern Dharwar Craton indicate the influence of felsic source (Fig. 6d). However, the felsic provenance for the studied quartzites cannot be overruled, as the PGC basement is reported to be already formed by ~3.2 Ga (Ravindran et al. 2023). As derived from the $TiO_2$, Zr and La/Sc and Th/Co relationships, had the studied quartzites originated from mafic/ultramafic provenance, their concentrations of MgO, $Fe_2O_3$ Ni, Co, and other mafic elements would have been notably higher. This is also evidenced through the lack of detrital chromite which collectively indicates the absence of volcaniclastic input to these quartzites. Hence, the provenance of the fuchsite quartzites in the Ghattihosahalli belt is attributed to a mixed felsic-mafic source involving the basement PGC and a predominant infiltration of Cr-rich fluids from the associated volcanic rocks. This indicates that the ultramafic rocks were either emplaced later than the deposition of quartzites, or the detrital wear-off of the already emplaced ultramafic rocks was not operative during their deposition. It even reflects on the distal nature of the ultramafic rocks within the basin which could have attained its proximity after the Sargur orogeny that imparted Cr-rich fluids into the quartzites.

### 5.3 Depositional environment

The fuchsite quartzites of the present study show a unique geological association with Archean pyritiferous barytes and ultramafic rocks. Muller et al. (2017) have reported sulfur isotopic systematics of Ghattihosahalli pyritiferous barytes and suggested that the spatial variations in $\delta^{34}S$, $\Delta^{33}S$ and $\Delta^{36}S$ have been preserved despite of the high-grade metamorphism and ductile deformation. Furthermore, they suggested that the S-isotope compositions in the pyrites occurring in barytes were produced by bacterial sulfate reduction along with thermal reduction of associated sulfate. According to McLennan (1989), REEs are immobile and are not susceptible to fractionation during sedimentary processes. All the individual LREE from the studied samples exhibited a positive correlation with the HREE (figures not shown) reflecting their immobile nature. In the Sm versus Dy plot (Fig. 7a), the positive correlation in the studied samples is analogous with their counterparts from the Mesoarchean (Naharmagra Quartzites, Aravalli Craton; Raza et al. 2010), Neoarchean (Keonjhar Quartzite, Singhbhum Craton; Ghosh et al. 2016) and Neoproterozoic era (Somanpalli Sandstone, Pranahita-Godavari valley; Rao et al. 2018). The REE and high-field strength elements (HFSE) are typically considered to be immobile during weathering and diagenetic processes (Pearce 1996; Taylor and McLennan 1985). In the relationship between La and Th (Fig. 7b), the fuchsite quartzites of the present study plot in the field of Archean sediments indicating that the REE signatures were not much disturbed during their deposition, despite their moderate to intense weathering. This is also evidenced through the preservation of positive Eu anomaly which appears to have been inherited either from the TTG source or from hydrothermal fluids. Based on the mineral chemistry and mineral paragenesis, earlier workers have suggested volcanic-exhalative origin for the

**Table 2** Major and trace element compositions of the studied fuchsite quartzites from Ghattihosahalli, Chitradurga greenstone belt, Dharwar Craton, India

| wt% | B-1 | B-2 | B-3 | B-4 | B-5 | B-6 | B-7 | B-8 | B-9 |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 85.78 | 70.90 | 85.08 | 69.75 | 78.08 | 52.01 | 83.96 | 85.27 | 91.50 |
| Al2O3 | 8.77 | 22.89 | 10.98 | 21.46 | 14.20 | 34.72 | 9.30 | 9.67 | 4.18 |
| TiO2 | 0.66 | 0.32 | 0.39 | 0.52 | 0.47 | 0.45 | 0.36 | 0.47 | 0.30 |
| Fe2O3 | 0.004 | 0.005 | 0.003 | 0.004 | 0.004 | 0.001 | 0.004 | 0.001 | 0.004 |
| MnO | 0.13 | 0.02 | 0.05 | 0.03 | 0.06 | 0.01 | 0.03 | 0.08 | 0.06 |
| MgO | 0.014 | 0.003 | 0.002 | 0.002 | 0.001 | 0.006 | 0.001 | 0.001 | 0.001 |
| CaO | 0.38 | 0.36 | 0.30 | 0.77 | 0.55 | 1.05 | 0.37 | 0.36 | 0.25 |
| $Na_2O$ | 2.16 | 2.53 | 1.71 | 4.81 | 3.22 | 8.25 | 1.48 | 1.59 | 0.96 |
| $K_2O$ | 0.24 | 0.47 | 0.23 | 0.45 | 0.33 | 0.92 | 0.16 | 0.23 | 0.10 |
| P2O5 | 0.004 | 0.017 | 0.010 | 0.006 | 0.004 | 0.007 | 0.003 | 0.003 | 0.003 |
| LOI | 1.0 | 2.0 | 1.0 | 2.0 | 2.0 | 1.0 | 4.0 | 1.0 | 1.0 |
| Sum | 99.13 | 99.53 | 99.76 | 99.80 | 98.91 | 98.42 | 99.66 | 98.69 | 98.35 |
| Cr | 1785 | 3042 | 1378 | 3072 | 3459 | 6899 | 1516 | 2747 | 1326 |
| Co | 5.23 | 8.37 | 9.86 | 2.89 | 6.49 | 3.60 | 2.83 | 4.21 | 2.95 |
| Ni | 23.74 | 14.72 | 27.89 | 15.33 | 32.56 | 21.78 | 12.21 | 16.77 | 16.30 |
| Rb | 72.75 | 100.48 | 47.31 | 167.07 | 102.49 | 265.79 | 56.00 | 63.45 | 35.60 |
| Sr | 56.05 | 51.37 | 55.29 | 100.49 | 103.61 | 210.85 | 45.96 | 81.95 | 70.33 |
| Cs | 8.67 | 6.42 | 2.83 | 10.64 | 5.54 | 15.94 | 3.59 | 5.86 | 2.54 |
| Ba | 2809 | 1165 | 1475 | 2948 | 4760 | 9438 | 1173 | 7171 | 1935 |
| Sc | 5.21 | 7.22 | 5.27 | 10.52 | 16.93 | 61.58 | 11.05 | 3.57 | 2.52 |
| V | 204.31 | 336.26 | 156.82 | 318.88 | 309.21 | 868.56 | 179.27 | 191.03 | 106.85 |
| Ta | 0.08 | 0.17 | 0.05 | 0.21 | 0.05 | 0.70 | 0.06 | 0.04 | 0.10 |
| Nb | 0.84 | 1.60 | 0.65 | 1.61 | 0.67 | 3.87 | 0.56 | 0.51 | 1.12 |
| Zr | 31.12 | 24.85 | 22.79 | 31.48 | 30.75 | 95.30 | 18.53 | 18.01 | 17.25 |
| Hf | 1.29 | 1.10 | 0.80 | 1.35 | 1.24 | 3.61 | 0.71 | 0.80 | 0.58 |
| Th | 0.56 | 0.76 | 0.45 | 0.44 | 0.42 | 0.26 | 0.24 | 0.13 | 0.18 |
| U | 0.43 | 0.72 | 0.31 | 0.21 | 0.20 | 0.25 | 0.10 | 0.15 | 0.13 |
| Y | 4.78 | 10.68 | 4.31 | 10 | 2.14 | 6.97 | 4.01 | 0.67 | 0.84 |
| La | 2.24 | 3.75 | 1.65 | 1.58 | 2.47 | 0.82 | 1.01 | 0.81 | 1.20 |
| Ce | 5.16 | 7.74 | 3.63 | 3.88 | 4.98 | 1.57 | 2.17 | 1.42 | 2.30 |
| Pr | 0.58 | 1.38 | 0.48 | 0.50 | 0.58 | 0.22 | 0.32 | 0.17 | 0.27 |
| Nd | 2.22 | 6.05 | 2.00 | 2.08 | 2.23 | 1.01 | 1.28 | 0.61 | 0.99 |
| Sm | 0.52 | 1.65 | 0.51 | 0.65 | 0.47 | 0.37 | 0.32 | 0.13 | 0.20 |
| Eu | 0.30 | 0.50 | 0.22 | 0.41 | 0.43 | 0.78 | 0.21 | 0.48 | 0.16 |
| Gd | 0.63 | 1.75 | 0.57 | 0.95 | 0.43 | 0.61 | 0.42 | 0.12 | 0.17 |
| Tb | 0.13 | 0.35 | 0.12 | 0.22 | 0.06 | 0.15 | 0.09 | 0.01 | 0.03 |
| Dy | 0.84 | 2.07 | 0.70 | 1.49 | 0.36 | 1.09 | 0.62 | 0.07 | 0.14 |
| Ho | 0.17 | 0.39 | 0.15 | 0.34 | 0.07 | 0.25 | 0.14 | 0.02 | 0.03 |
| Er | 0.50 | 1.08 | 0.43 | 1.03 | 0.20 | 0.76 | 0.42 | 0.04 | 0.07 |
| Tm | 0.08 | 0.17 | 0.07 | 0.17 | 0.03 | 0.13 | 0.07 | 0.01 | 0.01 |
| Yb | 0.53 | 0.98 | 0.44 | 1.13 | 0.20 | 0.84 | 0.47 | 0.04 | 0.08 |
| Lu | 0.08 | 0.16 | 0.07 | 0.18 | 0.03 | 0.14 | 0.08 | 0.01 | 0.02 |
| Cu | 27.37 | 9.60 | 19.67 | 10.48 | 24.16 | 9.55 | 7.70 | 18.61 | 18.63 |
| Pb | 11.09 | 6.48 | 12.98 | 8.38 | 31.93 | 9.27 | 5.03 | 7.57 | 14.02 |
| Zn | 61.14 | 20.61 | 66.16 | 27.05 | 157.94 | 19.83 | 11.10 | 33.16 | 52.50 |
| CIA | 66 | 81 | 75 | 69 | 68 | 68 | 74 | 73 | 66 |
| ICV | 0.63 | 0.25 | 0.38 | 0.49 | 0.52 | 0.49 | 0.40 | 0.44 | 0.62 |
| La/La* | 0.99 | 0.91 | 1.02 | 0.96 | 1.08 | 1.34 | 0.90 | 1.09 | 0.02 |

**Table 2** continued

| wt% | B-1 | B-2 | B-3 | B-4 | B-5 | B-6 | B-7 | B-8 | B-9 |
|---|---|---|---|---|---|---|---|---|---|
| Y/Y* | 0.08 | 0.18 | 0.07 | 0.18 | 0.03 | 0.09 | 0.08 | 0.01 | 0.12 |
| Th/Co | 0.11 | 0.09 | 0.05 | 0.15 | 0.06 | 0.07 | 0.09 | 0.03 | 0.06 |
| La/Sc | 0.43 | 0.52 | 0.31 | 0.15 | 0.15 | 0.01 | 0.09 | 0.23 | 0.48 |
| $MgO/K_2O$ | 0.0586 | 0.0064 | 0.0087 | 0.0044 | 0.0031 | 0.0066 | 0.0064 | 0.0043 | 0.0097 |
| Cr/Th | 3182 | 3990 | 3060 | 6909 | 8232 | 26,788 | 6262 | 20,577 | 7312 |
| Th/Sc | 0.11 | 0.11 | 0.09 | 0.04 | 0.02 | 0.00 | 0.02 | 0.04 | 0.07 |
| Cr/V | 8.74 | 9.05 | 8.79 | 9.63 | 11.19 | 7.94 | 8.46 | 14.38 | 12.41 |
| Y/Ni | 0.20 | 0.73 | 0.15 | 0.65 | 0.07 | 0.32 | 0.33 | 0.04 | 0.05 |

fuchsites of the present study (Raase et al. 1983; Devaraju et al. 1999; Raith et al. 2014). On the basis of the isometric log-ratio transformations of major and trace element concentrations, Verma and Altrin (2016) distinguished the active and passive margin sediments and the studied samples indicating their passive margin origin (Fig. 7c, d). The occurrence of > 3.0 Ga sedimentary rocks and the corresponding evidence of shallow marine sedimentation in a craton indicate the operation of terrestrial subaerial erosion of the Paleo-Mesoarchean felsic crust. This indirectly throws light on the existence of the cratonic crust before the widely accepted ~ 2.5 Ga rapid continental emergence above the sea level (Bindeman et al. 2018; Chowdhury et al. 2021). Chowdhury et al. (2021) proposed that the magmatic-sedimentary evolution of the Singhbhum Craton was accompanied by the ~3.3–3.2 Ga continental emersion by the > 3.0 Ga crustal emergence of the Kaapvaal craton. Consistent with this, the evidence of passive continental margin sedimentation indicated by the fuchsite quartzites in this study sheds light on the continental emersion in the Dharwar Craton as early as ~3.2 Ga, supporting the subsequent deposition of later supracrustal sequences of the Dharwar Supergroup.

### 5.4 Source of Cr-bearing fluids for the fuchsite quartzites

The studies on the mafic–ultramafic lithounits formed at different geological settings indicated the mobility of Cr through hydrothermal fluids at temperatures of ~500–800 °C (Johan et al. 2017). Aqueous $Cr^{+3}$ is highly soluble in water at near neutral pH and experimental investigations pertaining to Cr solubility have indicated that mafic–ultramafic fluids could transport large concentrations of Cr at Cl-rich or reducing conditions (Huang et al. 2019). Keeping in view of the nature of the chromite and the geochemical evidence of fuchsite quartzites and their close association with the mafic–ultramafic rocks, it is suggested that the Cr-bearing fluids of these fuchsite quartzites are sourced from the associated volcanic rocks. Mantle-derived ultramafic rocks are usually thermodynamically unstable under near-surface environments and are easily prone to serpentinization and carbonation in contact with aqueous fluids (McCollom and Bach 2009). These mechanisms lead to a series of reactions and products including listvenite, carbonate minerals such as magnesite, calcite and fuchsite as the end product of silicification. Austrheim et al. (2021) recorded the sequence of the stages of transformation of peridotite to fuchsite quartzite in a serpentinised peridotite body from southern Norway along the Caledonides. They have demonstrated the transformation through serpentinization and carbonation of mantle peridotites through $CO_2$-rich fluid influx forming soapstone and listvenite which has subsequently undergone elimination of Mg and enrichment of Si resulting in the gradation to pure fuchsite quartzite. Similar sequences were also reported from an ultramafic ophiolite of eastern Iran (Boskabadi et al. 2020), and Neoproterozoic ophiolite from northern Nubian shield (Moussa et al. 2021) reporting the carbonation and serpentinization mechanisms of ultramafic mantle sections for the formation of fuchsite quartzites. Emam and Zoheir (2013) suggested the Cr mobilization from primary Cr-spinels during metasomatism through $CO_2$ rich hydrothermal fluids. However, Argast (1995) opines that the fuchsite bearing quartzites of western Dharwar Craton including those from Nuggihalli, Holenarsipur, Javanahalli, Bababudan and Chitradurga belts are the products of clastic sedimentation where chromites are derived through ultramafic clastic debris. It is speculated that the origin of fuchsite is either detrital or as a result of later metamorphism. As the fuchsite quartzites of Ghattihosahalli belt are not spatially associated with the listvenite sequences of carbonates and soapstone, their formation through the process of carbonation and listvenitisation is overruled in the present scenario. In the Ghattihosahalli belt, the

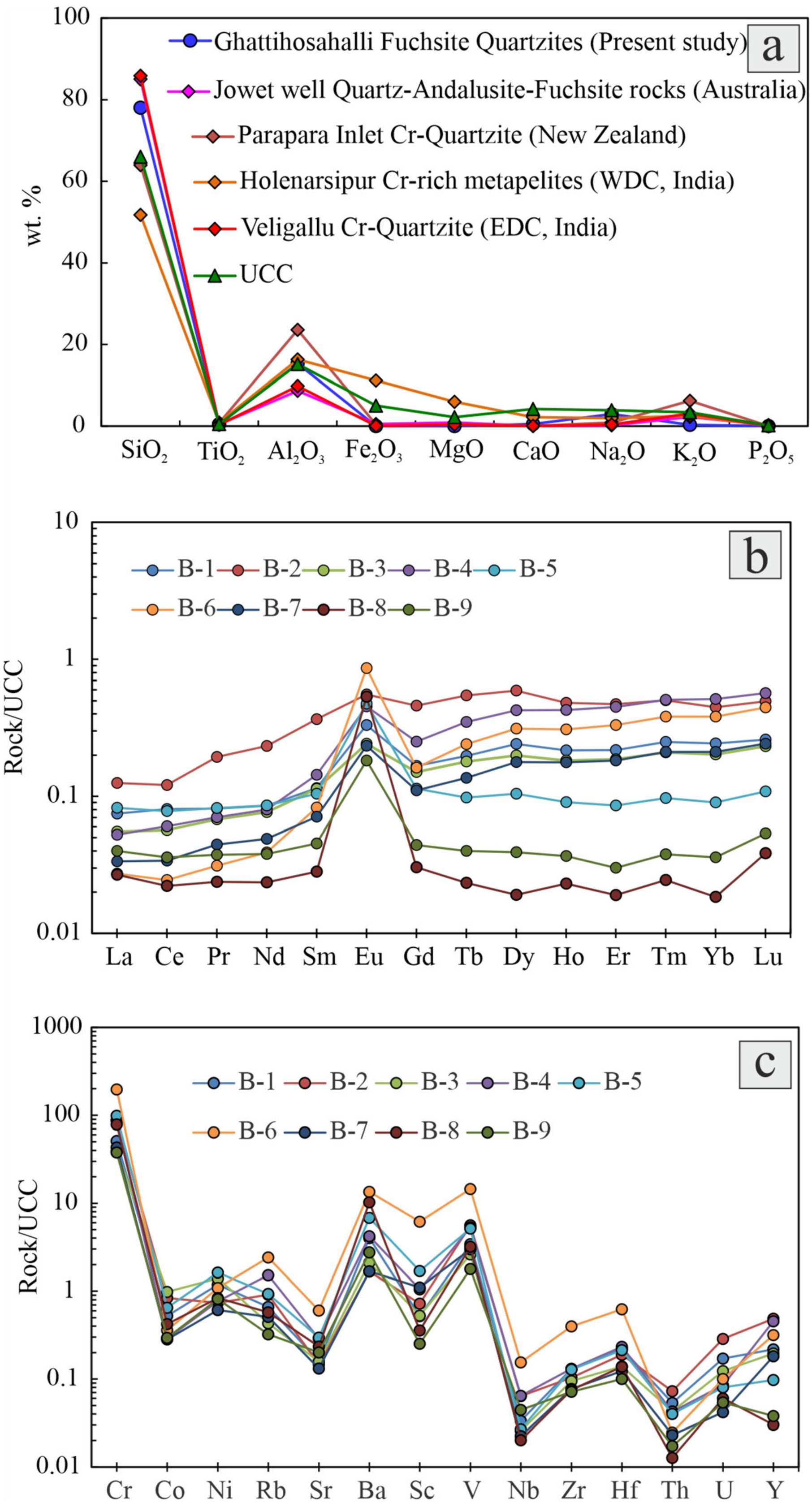



**Fig. 3** **a** UCC normalized major elements of fuchsite quartzites from the present study analogous to Cr-rich quartzites and metapelites from Holenarsipur and Veligalli belts of WDC and EDC respectively (Naqvi et al. 1983; Khanna and Sai 2018), Jowet Well, Menzies greenstone belt of western Australia (Martyn and Johnson 1986) and Parapara inlet quarry of New Zealand (Challis et al. 1995); **b** UCC normalized REE patterns of fuchsite quartzites showing conspicuously positive Europium anomalies; **c** UCC normalized trace element patterns of fuchsite quartzites displaying strong positive anomalies of Barium and Vanadium. Normalized values are from Taylor and Mc Lennan (1985)

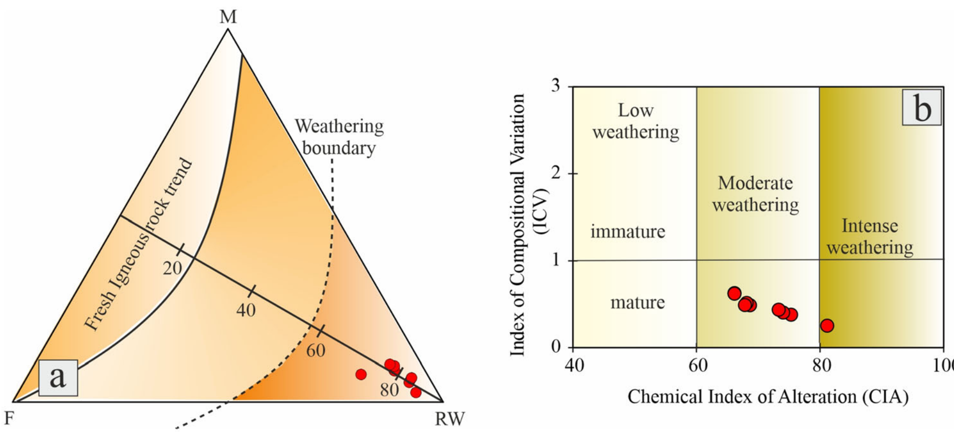



**Fig. 4** **a** Mafic-Felsic-Robust Weathering (RW) index ternary diagram displaying high weathering intensity away from fresh igneous rock trend for the studied fuchsite quartzites [after Cho and Ohta 2022; Mafic apex = exp.(m)/(exp.(m) + exp.(f) + exp.(rw), Felsic apex = exp.(f)/(exp.(m) + exp.(f) + exp.(rw), RW apex = exp.(rw)/(exp.(m) + exp.(f) + exp.(rw), where, $m = 0.051 \times \ln(TiO_2)–0.120 \times \ln(Al_2O_3)- + 0.018 \times \ln(Fe_2O_3) + 0.33 \times \ln(MgO) + 0.193 \times \ln(Na_2O)–0.392 \times \ln(K_2O) + 0.330$; $f = -0.204 \times \ln(TiO_2)–0.000 \times \ln(Al_2O_3)–0.166 \times \ln(Fe_2O_3)–0.177 \times \ln(MgO) + 0.311 \times \ln(Na_2O) + 0.236 \times \ln(K_2O) + 0.176$ and $rw = 0.152 \times \ln(TiO_2) + 0.198 \times \ln(Al_2O_3)- + 0.148 \times \ln(Fe_2O_3)–0.152 \times \ln(MgO)–0.503 \times \ln(Na_2O) + 0.156 \times \ln(K_2O)–0.506$)]; **b** index of compositional variability (ICV) and chemical index of alteration (CIA) relationship after Cox et al. (1995) indicating moderate to intense weathering domain

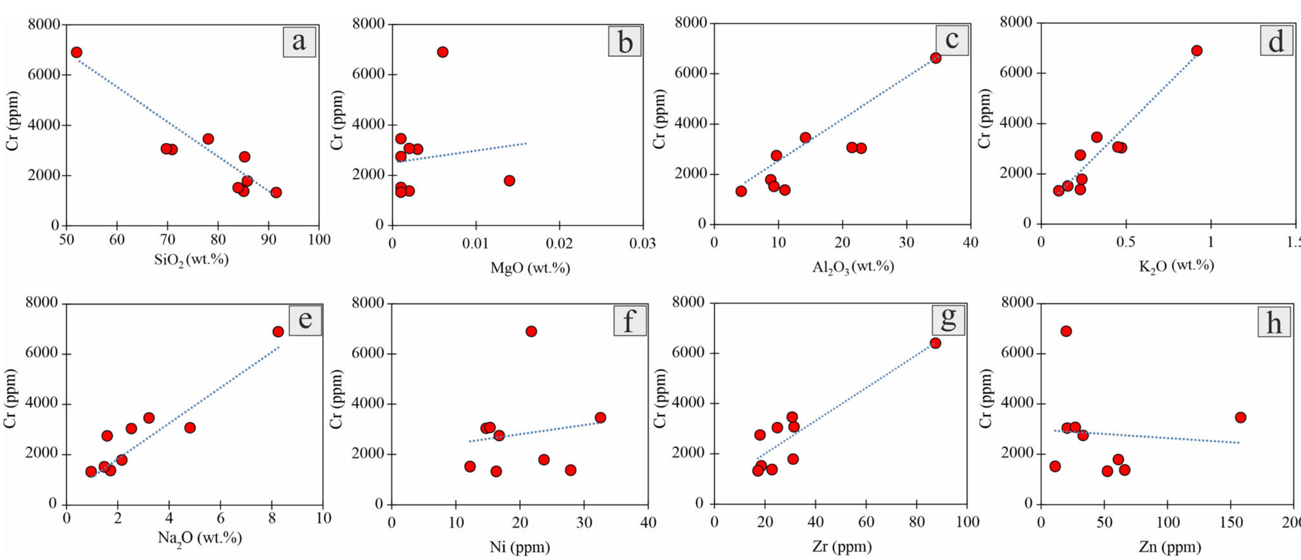



**Fig. 5** **a–h** Binary plots showing the inter-relationship of Cr with selected major and minor elements

association of ultramafic rocks along with barites, quartzites and fuchsite quartzites comprehend multiple processes involving mantle plume magmatism, volcano-exhalative processes, and the influence of hydrothermal fluids. The komatiites of WDC including those from the Ghattihosahalli belt originated through a mantle plume beneath an oceanic crust (Jayananda et al. 2008). All these lithounits along with the passive margin quartzites are suggested to be eventually subjected to high-grade metamorphism which is evidenced with the presence of kyanite-chromite-fuchsite mineral assemblages along with recrystallized quartz that resulted in the formation of interlayered fuchsite quartzite. These associated volcanic rocks appear to have released the Cr-bearing fluids due to metamorphic reactions during the high-grade metamorphism. These fluids which permeated into the quartzite have preferentially reacted with the muscovite and replaced the $Al^{+3}$ with $Cr^{+3}$ forming fuchsite. In addition, considering the absence of precise stratigraphic sequence and the intense metamorphism of this Sargur Group of metavolcanic and metasedimentary rocks, it is suggested that the Archean volcano-exhalative processes responsible for the chemical precipitation of barites might be synchronous with the passive margin sedimentation which is reflected in the high

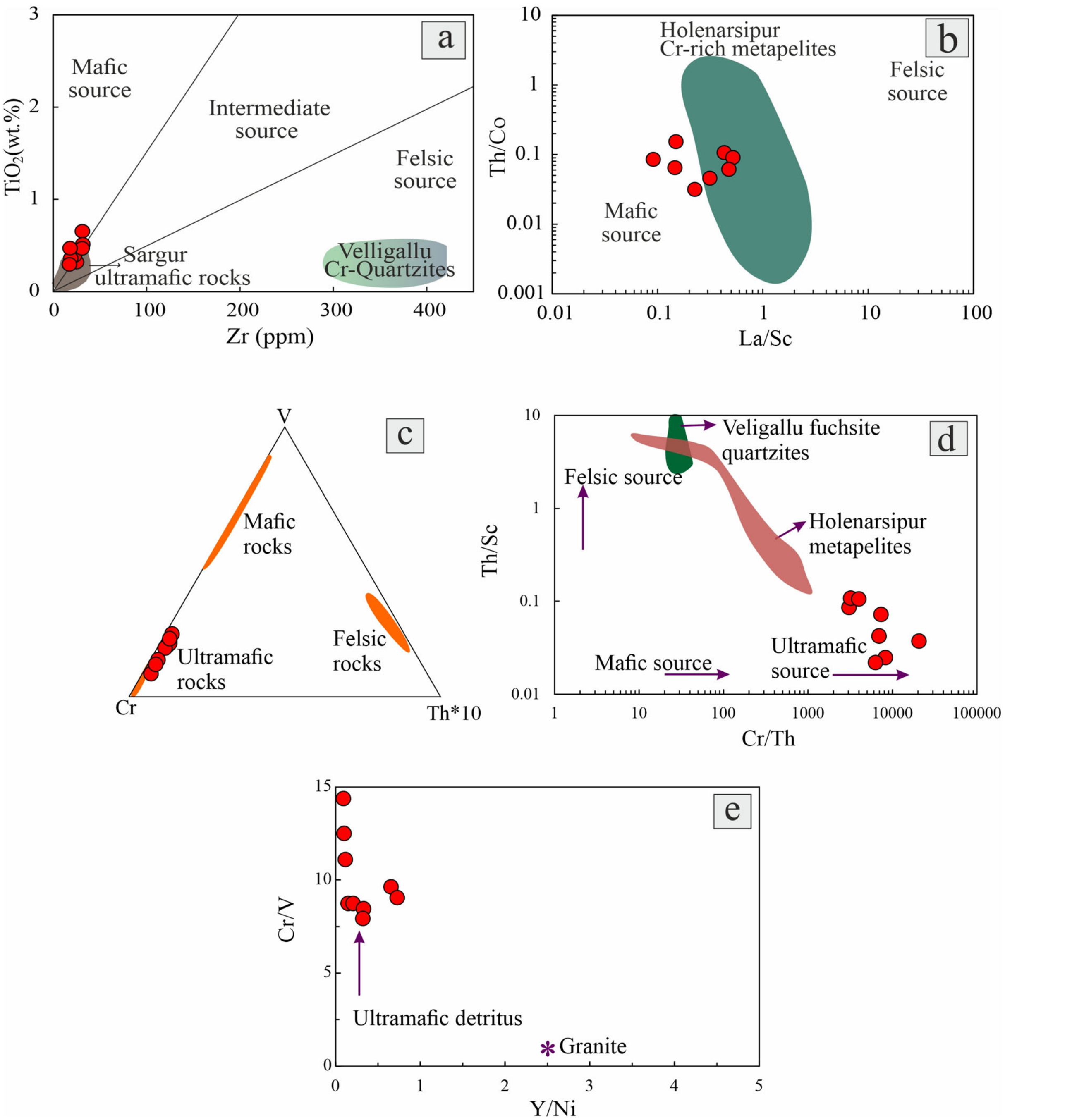



**Fig. 6** **a** Zr versus $TiO_2$ binary plot after Hayashi et al. (1997) indicating the influence of mafic to ultramafic provenance for the studied rocks; **b** La/Sc versus Th/Co plot (after Cullers 2000) attesting to the mafic provenance and displaying similarities with Holenarsipur meta-pelites (Naqvi et al. 1983); **c** V–Cr–Th*10 ternary plot for source rock discrimination; **d** cross plot of Cr/Th versus Th/Sc after Condie and Wronkiewicz (1990) and **e** Y/Ni versus Cr/V plot after McLennan et al. (1993) altogether indicating the influence of ultramafic rocks in the provenance of the studied fuchsite quartzites

concentrations of Ba in the fuchsite quartzites. Therefore, it is suggested that the quartzites in the Ghattihosahalli belt are originated from a combined felsic-mafic provenance, deposited in a passive margin setting of an Archean continental margin. The Sargur orogenic event of ~3.0 Ga followed by the Dharwar Supergroup orogeny appears to have brought the lithounits of Sargur basin proximal which also contributed for the release of Cr-rich fluids from the ultramafic rocks. Subsequently, the infiltration of Cr-bearing fluids and selective addition and substitution of Cr into the muscovite micas from the associated ultramafic rocks are responsible for the formation of these studied fuchsite

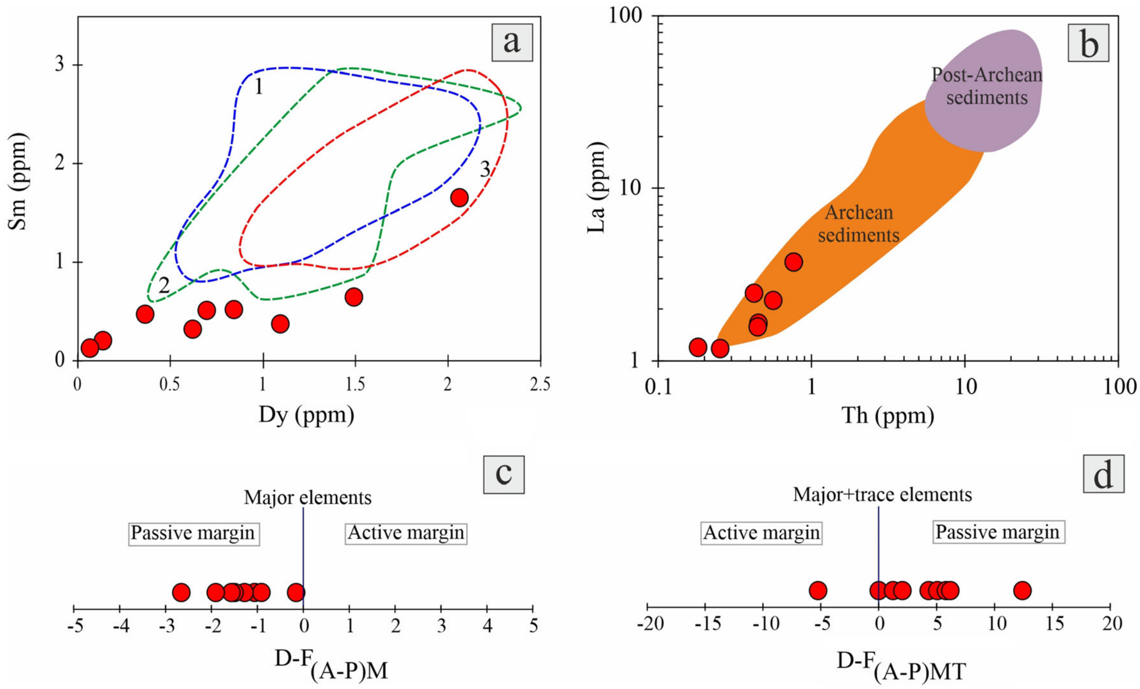



**Fig. 7** **a** Dy versus Sm binary plot showing a positive correlation similar to the quartzites of 1-Mesoarchean (Naharmagra Quartzites, Aravalli Craton; Raza et al. 2010), 2-Neoarchean (Keonjhar Quartzite, Singhbhum Craton; Ghosh et al. 2016) and 3-Neoproterozoic era (Somanpalli Sandstone, Pranahita-Godavari valley; Rao et al. 2018); **b** Th versus La source rock discrimination diagram after McLennan (1989) indicating their pristine nature and preservation of REE signatures and **c**, **d** Multidimensional discriminant function diagrams based on major and selected trace elements after Verma and Amstrong-Altrin (2016) indicative of passive continental margin depositional setting for the Ghattihosahalli fuchsite quartzites. Discriminant functions were calculated using revised equations published in the corrigendum to Verma and Armstrong-Altrin (2016)

quartzites. Therefore, these studies indicate that a stable continental crust had existed in the Dharwar Craton by ∼3.3 Ga which supplied detritus for the Sargur basin. The subsequent Sargur and Dharwar orogeny predominantly affected the volcano-sedimentary lithounits of Sargur Group which resulted in the release of metal-rich fluids that gave rise to various mineral deposits in the Dharwar Craton.

## 6 Conclusions

In the Ghattihosahalli belt, the fuchsite quartzites are associated with the ultramafic rocks and consist of Cr-rich muscovite i.e., fuchsite, quartz, feldspars along with accessory minerals such as kyanite, rutile and zircon. They are enriched in Cr, Ba, Sr, Zn and depleted in Nb and Ta indicating moderate to intense paleo-weathering conditions and the matured nature of sediments. They are characterized by depleted LREE with conspicuous positive Eu-anomalies suggesting hydrothermal signatures which is evidenced by the associated barytes. Low $TiO_2$ and Zr, depleted La/Sc and Th/Co ratios attest to the influence of ultramafic rocks. The geochemical characteristics indicate a passive continental margin environment for the deposition of quartzites which are later infiltrated by Cr-bearing fluids released from the associated ultramafic rocks during the orogenic events that led to the formation of fuchsite quartzite. These studies throw light on the existence of a stable continental crust before the formation of the Sargur Group and that the orogenic events played a key role in the development of various mineral deposits in the Dharwar Craton.

**Acknowledgements** The authors thank Dr. Prakash Kumar, Director, CSIR-NGRI for permitting to publish this work. CS acknowledges the funds MLP 6406-28 (MRM) of CSIR-NGRI. GH acknowledges DST-INSPIRE for PhD Fellowship (No. DST/INSPIRE/03/2021/001295). CM acknowledges the CSIR Emeritus Project funds. The authors thank Dr. Binbin Wang for his efficient editorial handling. The authors also thank three anonymous reviewers for their constructive comments, which have enhanced the scientific content of the earlier version of the manuscript. We thank Drs D. S. Sarma, A. Keshav Krishna and M. Satyanarayanan for extending the SEM lab facility and providing major, trace element data.

**Declarations**

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

## References


Argast S (1995) Detrital origin of fuchsite-bearing quartzites in the western Dharwar craton, Karnataka, India. J Geol Soc Ind 45:559–575

Arora M, Naqvi SM (1993) Geochemistry of archaean arenites formed by anoxic exogenic processes—an example from Bababudan schist belt India. J Geol Soc India 42:247–268

Austrheim H, Corfu F, Renggli CJ (2021) From peridotite to fuchsite bearing quartzite via carbonation and weathering: with implications for the Pb budget of continental crust. Contrib Min Petrol 176:94

Bindeman IN, Zakharov DO, Palandri J, Greber ND, Dauphas N, Retellack GJ, Hofmann A, Lackey S, Bekker A (2018) Rapid emergence of subaerial landmasses and onset of a modern hydrologic cycle 2.5 billion years ago. Nature 557:545–548

Boskabadi A, Pitcairn IK, Leybourne MI, Teagle DAH, Cooper MJ, Hadizadeh H, Bezenjani RN, Bagherzadeh RM (2020) Carbonation of ophiolitic ultramafic rocks: Listvenite formation in the Late Cretaceous ophiolites of eastern Iran. Lithos 352–353:105307

Brigatti MF, Kile DE, Poppi M (2001) Crystal structure and crystal chemistry of lithium-bearing muscovite. Can Mineral 34:1171–1180

Chadwick B, Vasudev VN, Hegde GV (2000) The Dharwar Craton, Southern India, interpreted as the result of Late Archaean oblique convergence. Precambrian Res 99:91–111

Challis A, Grapes R, Palmer K (1995) Chromian muscovite, uvarovite, and zincian chromite: products of regional metasomatism in northwest Nelson, New Zealand. Can Mineral 33:1263–1284

Cho T, Ohta T (2022) A robust chemical weathering index for sediments containing authigenic and biogenic materials. Palaeogeogr Palaeoclimatol Palaeoecol 608:111288

Chowdhury P, Mulder JA, Cawood PA, Bhattacharjee S, Roy S, Wainwright AN, Nebel O, Mukherjee S (2021) Magmatic thickening of crust in non-plate tectonic settings initiated the subaerial rise of Earth's first continents 3.3 to 3.2 billion years ago. Proc Nat Acad Sci 118:e2105746118

Condie KC (1993) Chemical composition and evolution of the upper continental crust: contrasting results from surface samples and shales. Chem Geol 104:1–37

Condie KC, Wronkiewicz DJ (1990) A new look at the archean-proterozoic boundary: sediments and the tectonic setting constraint. Dev Precambrian Geol 8:61–83

Cox R, Low DR, Cullers RL (1995) The influence of sediment recycling and basement composition on evolution of mudrock chemistry in the southwestern United States. Geochim Cosmochim Acta 59:2919–2940

Cui XH, Zhai MG, Guo JH, Zhao L, Zhu XY, Wang HZ, Huang GY, Ge SS (2018) Field occurrences and Nd isotopic characteristics of the meta-mafic-ultramafic rocks from the Caozhuang complex, eastern Hebei: implications for the Early Archean crustal evolution of the North China craton. Precambrian Res 310:425–442

Cullers RL (2000) The geochemistry of shales, siltstones and sandstones of pennsylvanian-permian age, Colorado USA: implications for provenance and metamorphic studies. Lithos 51:181–203

Das AK, Khaoash S, Mishra P, Mohapatra BK, Mohanty J (2021) Chromite-bearing quartzite in the southern fringe of Singhbhum Craton around Ghutrigaon, Eastern India: petrogenetic implication. Geol J 56:3472–3496

De Wit MJ, Hart R, Martin A, Abbot P (1982) Archaean abiogenic and probable biogenic structures associated with mineralised hydrothermal vent systems and regional metasomatism with implications for greenstone belt studies. Econ Geol 77:1783–1802

Deb M, Hoefs J, Baumann A (1990) Isotopic composition of Precambrian stratiform barite deposits from the Indian shield. Geochim Cosmochim Acta 55:303–308

Devaraju TC, Murthy A (1978) Mineralogy of the fuchsites from Ghattihosahalli, Chitradurga district. Proc Indian Acad Sci 807:255–261

Devaraju TC, Raith MM, Spiering B (1999) Mineralogy of the Archean barite deposit of Ghattihosahalli. Karnataka, India. Can Mineral 37:603–617

Dhiume B, Hawkesworth CJ, Cawood PA, Storey CD (2012) A change in the geodynamics of continental growth 3 billion years ago. Science 335:1334–1336

Emam A, Zoheir B (2013) Au and Cr mobilization through metasomatism: microchemical evidence from ore-bearing listvenite, South Eastern Desert of Egypt. J Geochem Explor 125:34–45

Ferenc S, Uher P, Spišiak J, Šimonová V (2016) Cr- and Ni-rich micas and associated minerals in listvenite from the Muránska Zdychava, Slovakia: products of hydrothermal metasomatic transformation of ultrabasic rock. J Geosciences 61:239–254

Floyd PA, Winchester JA, Park RG (1989) Geochemistry and tectonic setting of Lewisian clastic metasediments from the Early Proterozoic Loch Maree Group of Gairloch, N.W. Scotland. Precambrian Res 45:203–214

Friend CRL, Nutman AP (1992) Response of U-Pb isotopes, and whole rock geochemistry to $CO_2$ induced granulite metamorphism, Kabbaldurga, Karnataka, south India. Contrib Mineral Petrol 111:299–310

Gao S, Wedepohl KH (1995) The negative Eu anomaly in Archean sedimentary rocks: implications for decomposition, age and importance of their granitic sources. Earth Planet Sci Lett 133:81–94

Ghosh S, De S, Mukhopadhyay J (2016) Provenance of >2.8 Ga Keonjhar Quartzite, Singhbhum Craton, Eastern India: implications for the nature of Mesoarchean Upper crust and geodynamics. J Geol 124:331–351

Hall C, Zhao R (1995) Listvenite and related rock-perspectives on terminology and mineralogy with reference to an occurrence at Cregganbaun. Miner Depos 30:303–313

Harnois L (1988) The CIW index: a new chemical index of weathering. Sed Geol 55:319–322

Haugaard R, Justina FD, Roots E, Chareaghi S, Vayavur R, Hill G, Snyder D, Ayer J, Naghizadeh M, Smith R (2021) Crustal-scale geology and fault geometry along the gold-endowed matheson transect of the abitibi greenstone belt. Economic Geol 116:1053–1072

Hayashi KI, Fujisawa H, Holland HD, Ohmoto H (1997) Geochemistry of approximately 1.9 Ga sedimentary rocks from northeastern Labrador, Canada. Geochim Cosmochim Acta 61:4115–4137

Huang J, Hao J, Huang F, Sverjensky DA (2019) Mobility of chromium in high temperature crustal and upper mantle fluids. Geochem Perspect Lett 12:1–6

Jayananda M, Kano T, Peucat J-J, Channabasappa S (2008) 3.35 Ga komatiite volcanism in the western Dharwar craton: constraints from Nd isotopes and whole rock geochemistry. Precambrian Res 162:160–179

Johan Z, Martin RF, Ettler V (2017) Fluids are bound to be involved in the formation of ophiolitic chromite deposits. Eur J Mineral 29:543–555

Khanna TC, Sai VVS (2018) Petrology, mineral chemistry and geochemistry of the chromian muscovite bearing quartzite in the Neoarchean Veligallu schist belt, eastern Dharwar Craton, India. J Ind Geophys Union 22:325–332

Krishna AK, Murthy NN, Govil PK (2007) Multielement analysis of soils by wavelength-dispersive X-ray fluorescence spectrometry. Atom Spectr 28:202

Maibam B, Lenaz D, Foley S, Berndt J, Belousova E, Wangjam M, Goswami JN, Kapsiotis A (2021) U-Pb and Hf isotope study of detrital zircon and Cr-spinel in the Banavara quartzite and implications for the evolution of the Dharwar Craton, south India. Geol Mag 158:1671–1682

Manikyamba C, Ganguly S (2020) Annals of Precambrian lithospheric evolution and metallogeny in the Dharwar Craton. Recent paradigms and perspectives, India. Proc Indian Nat Sci Acad 86:35–54

Martyn JE, Johnson GI (1986) Corrigendum: Geological setting and origin of fuchsite-bearing rocks near Menzies, Western Australia. Aust J Earth Sci 33:1–18

McCollom T, Bach W (2009) Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks. Geochim Cosmochim Acta 73:856–875

McLennan SM (1989) Rare earth elements in sedimentary rocks: influence of provenance and sedimentary process. Rev Miner 21:169–200

McLennan SM (1993) Weathering and global denudation. J Geol 101:295–303

McLennan SM, Hemming S, McDaniel DK Hanson GN (1993) Geochemical approaches to sedimentation, provenance and tectonics. In Johnsson MJ, Basu A (Eds) Processes controlling the composition of clastic sediments, vol 285. Geology Society for America Special Papers pp 21–40

Morata D, Higueras PL, Bella SD, Parra J, Roldan FV, Aparacio P (2001) Fuchsite and other Cr-rich phyllosilicates in ultramafic enclaves from Almadén mercury mining district, Spain. Clay Min 36:345–354

Moussa HE, Azer MK, Matty MAA, Maurice AE, Yanni NN, Akarish AIM, Elnazer AA, Elsagheer MA (2021) Carbonation of Neoproterozoic mantle section and formation of gold-bearing listvenite in the Northern Nubian Shield. Lithos 406–405:106525

Muller E, Philippot P, Rollion-Bard C, Cartigny P, Assayag N, Marin-Carbonne J, Sarma MRM, DS, (2017) Primary sulfur isotope signatures preserved in high-grade Archean barite deposits of the Sargur Group, Dharwar Craton, India. Precambrian Res 295:38–47

McLeod MC (2001) The role of hydrothermal fluids in identifying base and precious metal sources on the property of flag resources in Rathbun and Mackelcan Townships, Ontario. Exploration Report, Ontario, Canada

Naqvi SM, Govil PK, Rogers JJW (1981) Chemical sedimentation in Archaean-Early Proterozoic greenschist belts of the Dharwar Craton, India. In: Glover JE, Groves DI (ed) Archaean Geology 2nd Int Symp Perth Spec Pubs 7 Geology Society of Australia pp 245–254

Naqvi SM, Condie KC, Allen P (1983) Geochemistry of some unusual Early Archaean sediments from Dharwar Craton, India. Precambrian Res 22:125–147

Nesbitt HW, Young GM (1982) Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. Nature 299:715–717

Nutman AP, Friend CRL, Paxton S (2009) Detrital zircon sedimentary provenance ages for the Eoarchaean Isua supracrustal belt southern West Greenland: Juxtaposition of an imbricated ca. 3700 Ma juvenile arc against an older complex with 3920–3760 Ma components. Precambrian Res 172:212–233

Paranthaman S (2005) Geology and geochemistry of Archaean ghattihosahalli mafic-ultramafic complex, Chitradurga, Karnataka. J Geol Soc India 66:653–657

Pearce JA (1996) Sources and settings of granitic rocks. Episodes 19:120–125

Pearton JN (1981) Gold and antimony mineralisation in altered komatiites of the Murchison Greenstone Belt, South Africa. In: Arndt NJ, Nisbet EG (eds) Komatiites. George Allen and Unwin, London, pp 459–476

Peucat JJ, Jayananda M, Chardon D, Capdevila R, Fanning CM, Paquette JL (2013) The lower crust of the Dharwar Craton, Southern India: patchwork of Archean granulitic domains. Precambrian Res 227:4–28

Raase P, Raith M, Ackermand D, Viswanatha MN, Lal RK (1983) Mineralogy of chromiferous quartzites from south India. J Geol Soc India 24:502–521

Radhakrishna BP, Srinivasaiah C (1974) Bedded barites from Precambrian of Karnataka. J Geol Soc India 15:314–315

Raith MM, Devaraju TC, Spiering B (2014) Paragenesis and chemical characteristics of the celsian "hyalophane" K-feldspar series and associated Ba–Cr micas in barite-bearing strata of the Mesoarchean Ghattihosahalli belt, Western Dharwar Craton, South India. Miner Petrol 108:153–176

Randive KR, Korakappa MM, Muley SV, Varade AM, Khandare HW, Lanjewae SG, Tiwari RR, Aradhi KK (2015) Paragenesis of Cr-rich muscovite and chlorite in green-mica quartzites of Saigaon-Palasgaon area, Western Bastar Craton, India. J Earth Sys Sci 124:213–225

Rao NK, Dora ML, Baswani SR, Malpe DB, Deshmukh MS (2018) Petrography and geochemistry of the proterozoic sandstones of Somanpalli Group from Pomburna area, Eastern Belt of Pranhita-Godavari Valley, central India: implications for provenance, weathering and tectonic setting. J Earth Sys Sci 127:90

Ravindran A, Mezger S, Balakrishnan S, Berndt J, Ranjan S, Upadhyay D (2023) Formation of paleo- to Meso-Archean continental crust in the western Dharwar Craton, India: constraints from U Pb zircon ages and Hf–Pb–Sr isotopes of granitoids and sedimentary rocks. Chem Geol 615:121196

Raza M, Bhardwaj V, Ahmad AHM, Mondal MEA (2010) Provenance and weathering history of Archaean Naharmagra quartzite of Aravalli craton, NW Indian shield: petrographic and geochemical evidence. Geochem J 44:331–345

Rogers JJW (1986) The Dharwar Craton and the assembly of peninsular India. J Geol 94:129–144

Sadashivaiah MS, Karisiddaiah SM (1976) Fuchsite from Nemakallu (A.P.) near Bellary, Karnataka State, India. Karnatak Univ J Sci 21:55–73

Schreyer WB (1982) Fuchsite-aluminium silicate rocks in Archaean greenstone belts: are they metamorphosed alunite deposits? Geol Rundsch 71:347–360

Sengupta S, Ramachandra HM, Roy A (2020) Ductile shear zones along the margins of Neoarchaean Chitradurga Schist Belt with particular reference to tectonic status of Ghattihosahalli Belt of Dharwar Craton, India. Indian J Geosci 74:295–306

Sleep NH, Bird DK, Pope EC (2011) Serpentinite and the dawn of life. Philos Trans Royal Soc 366:2857–2869

Srinivasaiah C, Vasudev VN, Rao NVC (2015) Tungsten, barium and base metal mineralization in a layer of Amphibolite in Mesoarchaean Ghattihosahalli belt, western Dharwar Craton, Karnataka, India. J Geol Soc India 86:648–656

Staddon LG, Parkinson IJ, Cavosie AJ, Elliott T, Valley JW, Fournelle J, Kemp AIS, Shirey SB (2021) Detrital chromite from Jack Hills, Western Australia: signatures of metamorphism and constraints on provenance. J Petrol 62:1–30

Swami Nath J, Ramakrishnan M (1981) The Early Precambrian Supracrustals of Southern Karnataka. Mem Geol Survey India 112:350

Taylor SR, McLennan SM (1985) The continental crust: its composition and evolution. Blackwell, Oxford, p 312

Treloar PJ (1987) The Cr-minerals of Outokumpu—their chemistry and significance. J Petrol 28:867–886

Verma SP, Armstrong-Altrin JS (2016) Geochemical discrimination of siliciclastic sediments from active and passive margin settings. Sed Geol 332:1–12

Whitmore DRE, Berry LG, Hawley JE (1946) Chrome micas. Am Mineral 31:1–21