RESEARCH COMMUNICATIONS


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Occurrence of monazite in the auriferous zones of Gadag gold field, Karnataka

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Monazite (Ce, La, Nd)PO4 occurs as an accessory mineral in the auriferous zones of Gadag gold field, Karnataka. It is characterized by uniform LREE (Ce + La + Nd) content and Ce/La ratio, and higher concentration of P2O5 (av. 36.06 wt%). Occurrence of monazite in the auriferous zones could be attributed to the mobilization and concentration of LREE during hydrothermal alteration, related with gold mineralization in the area. Near-consistent association of monazite with auriferous zones suggests a possible genetic link between monazite and gold mineralization.

Keywords: Auriferous zones, Gadag gold field, gold mineralization, monazite.

A large amount of data that have accumulated in recent years on the rare earth element (REE) abundance of whole rocks and ores, have provided considerable insight into the genesis of ore deposits. As a result, REE geo-

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chemistry has been widely utilized to model ore genesis and exploration for a variety of mineral deposits. However, there is a dearth of discussion on rare earth minerals associated with ore deposits and their implication to ore genesis. Monazite, a light rare earth phosphate, has been reported from the Hemlo gold deposit of Canada, Cleo gold deposit of Western Australia and the Canadian Thompson nickel sulphide deposits containing platinum and gold. Monazite has also been assuming importance in determining the pressure–temperature–time–metamorphism/deformation–fluid (P–T–t–d–f) histories of metamorphic terrains, and the enclosed mineral deposits. In the light of such interesting studies, we have chosen to discuss here the mineral chemistry and paragenesis of monazite in the auriferous zones of Gadag gold field, Karnataka. Its occurrence is recorded here for the first time in the auriferous zones of not only Gadag, but also from elsewhere in India.

The Gadag gold field, covering an area of about 120 sq. km (long. 73°34′–75°43′E, lat. 15°20′–15°27′N), has three almost parallel, tabular auriferous zones designated as western, central and eastern (Figure 1). The western zone is hosted by pillowed metavolcanics, the central zone is in both metavolcanics and metasediments, while the eastern zone is hosted exclusively in metasediments. The gold mineralization is structure-controlled and is characterized by different degrees of chloritization, sericitization, carbonatization and silicification, with sulphide disseminations and bands. The characteristics of gold mineralization in the area are consistent with a structurally controlled metamorphic/hydrothermal epigenetic model. Monazite occurs in association with quartz, carbonates, chlorite, sericite, muscovite, sulphides + carbonaceous matter as an accessory mineral disseminated in the form of irregular to euhedral, tiny specks of 10–50 μm in the wall-rock alterations of auriferous zones (Figure 2). At places, it occurs as tiny inclusions in arsenopyrite and pyrite of auriferous quartz veins and wall rocks. Besides, it also occurs as inclusions in the silicates of wall rocks.

Samples for mineral analysis were collected from drilled cores of the western and central auriferous zones. Mineral analysis has been carried out at the Institute of Electron Optics, University of Oulu, Linnanmaa, Finland employing JEOL-SEM equipped with an Energy Dispersive Spectrometer and LINK AN 10,000 X-ray analyser, mainly following the method described by Alapieti and Sivonen. Standard analytical conditions included an acceleration voltage of 15 kV and sample current of 1.5 nA. The standards used were wollastonite for Si and Ca, apatite for P and pure metals for the remaining elements. The practical detection limits varied from 0.05 to 0.5 wt%, depending upon the element analysed. ZAF-4 program has been adopted to make necessary corrections for overlapping peaks of different elements. The analytical facilities in the laboratories proved to be adequate for obtaining acceptable analyses of grains measuring more than 1.5 μm.

The chemical analyses of monazite from Gadag auriferous zone along with the average chemical composition of monazite from auriferous zones of Hemlo, Ontario are given in Table 1 for comparison. Monazite from the auriferous zones of Gadag mainly contains LREE, viz.

![Figure 1](image1.png)

**Figure 1.** Geological map of Gadag gold field showing the western, central and eastern auriferous zones (modified after Ugarkar).

![Figure 2](image2.png)

**Figure 2.** Backscattered electron image of monazite (white) associated with quartz and other silicate minerals in the auriferous zone of Gadag. Scale bar = 10 μm.
Table 1. Chemical composition of monazite from Gadag auriferous zones

<table>
<thead>
<tr>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>Average</th>
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<tbody>
<tr>
<td>La₂O₃</td>
<td>09.59</td>
<td>12.99</td>
<td>11.56</td>
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<td>10.68</td>
<td>12.31</td>
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<td>07.63</td>
<td>11.90</td>
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<td>Ce₂O₃</td>
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<td>31.51</td>
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<td>32.02</td>
<td>31.59</td>
<td>33.28</td>
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<td>29.30</td>
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<tr>
<td>Pr₂O₃</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>03.47</td>
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<td>3.87</td>
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<tr>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>—</td>
<td>—</td>
<td>—</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>06.67</td>
<td>05.39</td>
<td>—</td>
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<td>01.34</td>
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<td>ThO₂</td>
<td>—</td>
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<td>—</td>
<td>—</td>
<td>01.96</td>
<td>01.68</td>
<td>03.18</td>
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<td>CaO</td>
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<td>00.36</td>
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<td>00.90</td>
<td>00.69</td>
<td>00.68</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>00.36</td>
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<tr>
<td>P₂O₅</td>
<td>37.97</td>
<td>37.58</td>
<td>38.42</td>
<td>38.24</td>
<td>34.00</td>
<td>32.68</td>
<td>35.50</td>
<td>35.19</td>
<td>34.90</td>
<td>36.04</td>
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<td>Total</td>
<td>99.80</td>
<td>99.99</td>
<td>99.97</td>
<td>100.13</td>
<td>99.99</td>
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<tr>
<td>ΣREE</td>
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<td>60.58</td>
<td>60.09</td>
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<td>57.61</td>
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<tr>
<td>Ce/La</td>
<td>02.46</td>
<td>02.31</td>
<td>02.58</td>
<td>02.19</td>
<td>02.86</td>
<td>02.35</td>
<td>02.26</td>
<td>02.20</td>
<td>03.66</td>
<td>02.48</td>
<td>1.94</td>
</tr>
</tbody>
</table>

1–4, Western auriferous zone (metavolcanics); 5–9, Central auriferous zone (metasedimentary); H, Monazite from Hemlo auriferous zones.

La₂O₃ (av. 11.90%), Ce₂O₃ (av. 31.75%), Nd₂O₃ (av. 16.20%), and P₂O₅ (av. 36.06%). The mineral is inhomogeneous in respect of distribution of some of its important elements which range from nil up to the following values: ThO₂ (3.18%), Pr₂O₃ (3.87%), Y₂O₃ (6.67%) and CaO (0.90%). While Sm₂O₃, Gd₂O₃, UO₂ and SiO₂ are absent, only one grain of monazite analyses Sm₂O₃ (4.80%). In general, monazite contains 4–12% ThO₂, but cheralitic variation analyses much higher ThO₂ (up to 30%)5. It is evident from the analyses that monazite of Gadag is not significantly enriched in ThO₂ (av. 1.10%). The relative proportions of Ce₂O₃, Nd₂O₃, La₂O₃, P₂O₅, ΣREE and Ce/La of the mineral are similar. However, monazite from the central auriferous zone hosted in metasediments analyses higher amount of ThO₂, P₂O₅ and Y₂O₃, while they are absent in the western auriferous zone hosted in metavolcanics (Table 1). The relative proportions of La₂O₃, and ΣREE of Gadag monazite are lower, while ThO₂, P₂O₅, Y₂O₃ and Ce/La are higher compared to that of monazite from the auriferous zones of Hemlo, Ontario. As the data generated in the present study are limited, definite reasons for these differences cannot be mentioned. However, the observed differences could be correlated with those in the whole rock geochemistry of the host rocks.

Reports of monazite from gold deposits, particularly in gold-quartz vein-types are few and far between, which generally are localized in greenschist facies domain of metamorphosed rocks17. However, this generalization needs to be verified as there is paucity of information pertaining to the accessory minerals of the auriferous zones. Monazite appears to be extremely rare in greenschist facies and other lower-grade metamorphic rocks, because of its chemical instability at lower temperature conditions, although its phase relations are not well known18. It is a widespread accessory mineral in schists and gneisses of upper amphibolite and granulite metamorphic grade19.

Schandl et al.5 have opined that monazite is a common accessory mineral in chlorite-rich rocks at Kidd Creek and other volcanogenic massive sulphide deposits of the Superior Province. Brown and Fletcher8 have suggested that monazite is deposited during ore formation at the world-class Cleo gold deposit, Eastern Gold Fields Province of Western Australia. Rare earth minerals (mainly monazite and allanite) have recently been found to be responsible for the local concentration and remobilization of the REE in the precious metal deposits, as in the Hemlo gold deposits, Ontario6,7 and in the Thompson Nickel sulphide deposits of Manitoba containing platinum group minerals and gold6. Formation of monazite appears to be related to mobilization of LREE and their concentration during hydrothermal alteration5. According to Campbell et al.20, HREE are relatively stable, whereas LREE are more mobile during hydrothermal alteration processes. They have argued thatREE mobility increases with the degree of alteration and can therefore be used as a potential exploration guide. This could also be true of monazite.

Giritharan and Rajamani8 have studied the rare earth element geochemistry of the host metabasalts, alteration zones, auriferous quartz veins (ore veins) and bulk sulphides separated from the ore veins and the alteration zones of Kolar, Huttu and Ramagiri gold fields of the Dharwar craton. They have suggested that: (i) the REE chemistry of the alteration zones tends to be modified by fluids which added LREE; (ii) auriferous quartz veins have abundance of LREE, and (iii) sulphides formed during mineralization have pronounced LREE concentrations, suggesting enrichment of LREE in the ore fluids involved in gold mineralization. The hydrothermal activity is attributed to ore-forming fluid, charged with various cationic radicals and might have carried rare metals and REE in the form of soluble complexes or compounds, and precipitated them under favourable geochemical conditions21.
evidenced from the study of Ugarkar et al.\(^{22}\) (and D. N. Nerlikar, unpublished), the fluid was rich in volatiles like CO\(_2\) and S, and was probably capable of forming complexes or soluble compounds with LREE and other incompatible elements. Three types of inclusions, i.e. H\(_2\)O (with 2–6% NaCl), CO\(_2\) and mixed H\(_2\)O–CO\(_2\) inclusions are recorded in the ores of study area (D. N. Nerlikar, unpublished)\(^{22}\). In the auriferous zones of Gadag, considering the fact that monazite is distributed in the ore veins as well as in the wall-rock alteration zones, it could be surmised that gold precipitation and monazite formation have resulted from a combination of decreasing temperature and fluid–wall rock interaction within suitable structural sites (shear zones), largely below amphibolite–greenschist transition\(^{14,23}\). Progressive carbonatization of wall rocks with decreasing temperature and pressure might have led to fluid immiscibility and separation of H\(_2\)O-rich (2–6% NaCl) and CO\(_2\)-rich phases, thereby significantly changing the solubility of gold and LREE, causing deposition of gold and also monazite. The available evidences from gold deposits suggest that a high water/rock ratio prevailed during hydrothermal alteration in the mineralized zones, and elevated contents of volatiles, including CO\(_2\) were present in the hydrothermal fluid, at least for a period of time during alteration\(^{7,24}\). Such a fluid could promote the mobility of the LREE and result in their local concentration, especially during intensive alteration processes such as carbonatization\(^{25,26}\).

Association of monazite with quartz, carbonates, chlorite, sercite, muscovite, sulphides ± carbonaceous matter in the auriferous zones of Gadag gold field suggests that events like hydrothermal alterations, including carbonatization and sulphidation, formation of monazite, gold mineralization and hydrothermal activity were broadly contemporaneous. The hydrothermal alteration of minerals, the last event to cause recrystallization and stability of these minerals, was more significant in defining the present mineralogy of auriferous zones. Thus, monazite appears to have formed during the hydrothermal alteration reactions utilizing the light REE, especially Ce, La and Nd present in the hydrothermal system. Therefore, it is emphasized that the scale of REE mobility apparently was restricted to the auriferous zones and the hydrothermal system. All these features suggest a probable genetic relationship between the occurrence of monazite and gold mineralization in the area.

Magnetovariational study over Lakshadweep Islands, southwestern continental margin of India

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The Chagos–Laccadive Ridge (CLR) is a prominent aseismic topographic feature in the northern Indian Ocean. The evolution and origin of the CLR continues to be a subject of great debate. Geomagnetic depth sounding studies have been carried out in five different Lakshadweep Islands. Transfer functions, summing relationship between anomalous and normal components of transient geomagnetic variations, by virtue of their sensitivity to sub-surface electrical conductivity distribution facilitate to constrain the deep structure and thermal state of the CLR.

The induction arrows over a wide range of periods indicates dominance of island effect. The residual induction arrows (obtained after accounting for the Island effect) suggest the concentration of anomalous induced currents in an elongated structure corresponding with track of the Reunion hotspot. Further, the thin sheet modelling of the residual induction arrows brings out a narrow belt of high-conductivity zone close to the eastern margin of the CLR. This is interpreted in terms of partial melt associated with the northward drifting of Indian plate over the Reunion mantle plume (65 Ma). The increase in the longitudinal conductance from north to south can be attributed to the degree of partial melting with younging of the age of volcanic intrusion to the south.

Keywords: Chagos–Laccadive Ridge, induction arrows, Lakshadweep Islands, Reunion hotspot.

The southwestern continental margin of India comprises several tectonic features, including the Chagos–Laccadive Ridge (CLR), Pratap Ridge and a chain of grabens filled with sediments bordering the west coast of India. The CLR is a prominent aseismic topographic feature over which the Laccadive (Lakshadweep), Maldives and Chagos group of islands have formed. The Lakshadweep group of islands forms the northern part of the CLR and is parallel to the western continental margin of India.

Various theories have been proposed regarding the evolution of the CLR.

(a) Fisher et al.1 and McKenzie and Sclater2 associated the Chagos–Laccadive ridge with an old transform fault formed during the Cretaceous to Eocene period while India moved northward.

(b) Francis and Shor3 have considered a hotspot origin for the ridge. This ridge was formed from the interaction of transiting Indian plate with the Reunion hotspot.

(c) Ben Avraham and Bunce4 proposed diverse segmental origin for the CLR. The north and south segments have a volcanic origin, whereas the central part (Maldives) is a continental fragment drifted away from India.

(d) From the joint interpretation of seismic reflection and magnetic profiles, Naini and Talwani5 and Harbison and Bassinger6 suggested that the northern part of the CLR was a fragment of the Indian continent.

(e) Based on free-air anomaly and seismic profiles, Radha Krishna et al.7 inferred that the northern part of the ridge formed a transition between continental crust and oceanic crust to the east and west respectively.

To constrain the nature of the crust beneath the northern part of the CLR, by conductivity imaging, we have carried out long-period magnetotelluric and geomagnetic depth sounding (GDS) experiments during April–May 2004 at five different Lakshadweep Islands (Figure 1). In this communication, we present the results obtained from the GDS experiment.

In GDS, deduction of the lateral conductivity distribution is based on the three components of the time-varying geomagnetic field, generally the geographic north (X), east (Y) and vertical (Z) components. The time-varying magnetic fields, which have their origin in the current systems in the ionosphere and distant magnetosphere, act as a natural source and induce secondary currents in the conductive layers of the earth. Transformation of the time-varying magnetic fields into frequency-dependent response functions is suitable for drawing qualitative and