Magmatic epidote in the Neoarchaean granitoids of Srinivaspura area of Eastern Dharwar Craton and its significance on emplacement mechanism of granitoids

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Magmatic epidote (mEp) in calc-alkaline, high-Mg granite is distinguished on the basis of euhedral crystals with allanite core and embayed contact, 'pistacite' components (25–32) and very low TiO_2 (<0.02%) content. Non-magmatic epidote occurs in association with biotite and chlorite, amphibole, magnetite and titanite and contains either >0.2% TiO_2 or <25% Ps. Consideration of stability of magmatic epidote under different fO_2 and dissolution characteristic against quartzo-feldspathic material suggest that these granitoids are emplaced at a faster rate to low-pressure upper crustal region under high fO_2 condition by dyking.

Keywords: High-Mg granitoids, Kolar, oxygen fugacity, pistacite.

EPIDOTE ($Ca_2Fe_xAl_{3-x}Si_3O_{12}(OH)$) is a very common accessory phase in the granitoids formed due to either primary magmatic crystallization or secondary alteration of plagioclase, biotite and amphibole. Magmatic epidote (mEp) is a useful tool in petrological studies and has been used worldwide for estimating intrusion conditions such as crystallization depth, oxygen fugacity and upward transport rate of melt[1–3]. In the present study, mEp is differentiated from non-magmatic epidote on the basis of textural and chemical criteria in the Neoarchaean granitoids of Srinivaspura area of Eastern Dharwar Craton, Kolar district, Karnataka. The significance of mEp on emplacement mechanism of granitoids is discussed.

Neoarchaean granitoids with small xenoliths of basement gneissic complex and vestiges/rafts of volcano-sedimentary litho-package are widely exposed as linear bodies in Srinivaspura area, Kolar district, Karnataka of the Eastern Dharwar craton (Figure 1). NNE–SSW to NNW–SSE trending linear bodies of calc-alkaline high-Mg (Mg# > 35, MgO > 0.5%) granitoids occur within anatectic low-Mg biotite granite[4]. These high-Mg granitoids range in composition from tonalite to granodiorite to granite and are comparable to TTG, sanukitoid derived granodiorite and Closepet-like K-feldspar-rich granites[5]. On the basis of Al-in-hornblende geobarometry and deformational microstructure (not discussed in this communication), these granitoids are inferred to be syn- to late tectonically emplaced at the middle to upper crustal levels at a pressure of ~2.5 kbar and ~800°C temperature.

Two types of epidotes are recorded in these granitoids. Secondary epidote occurs as anhedral grains within the plagioclase grains and at the margin of biotite. mEp is found as euhedral to subhedral zoned crystals with allanite-rich core. It is usually surrounded by biotite and shows embayed contacts with plagioclase and quartz (Figure 2).

Thirty-four microprobe analyses of epidote from eight samples of high-Mg granitoids were performed by Cameca SX100 EPMA at National Centre for Excellence in Geoscience Research (NCEGR) unit of Geological Survey of India, Bangalore. Representative analyses of epidotes are shown in Table 1, and distribution of its pistacite component (Ps = molar $(Fe^3/(Fe^3 + Al)) \times 100$) is shown in Figure 3. Ps components range from 25 to 37 with mean at 29.9% Ps. mEp is characterized by both high (25–32%) Ps and low (<0.2 wt%) TiO_2. Majority of mEp contain 28–32% Ps. Non-magmatic epidote occurs in association with biotite, chlorite, amphibole, magnetite, titanite and contains 7.41–36.93% Ps and 0.01–0.87% TiO_2. It contains either > 0.2% (mostly > 0.6 wt%) TiO_2 or < 25% Ps.

Distinguishing magmatic from secondary epidote is not straightforward, but can be achieved through various textural and chemical criteria[6–10]. Presence of allanite core, embayed contact, Ps content (mostly 25 to 32) and very low TiO_2 (< 0.02%) attest the magmatic origin of epidote recorded in the studied granitoids. This Ps range is in conformity with the Ps content of mEp recorded by Tulloch[6] and Liou[11]. According to epidote breakdown curves[11], pistacite content in mEp should range between

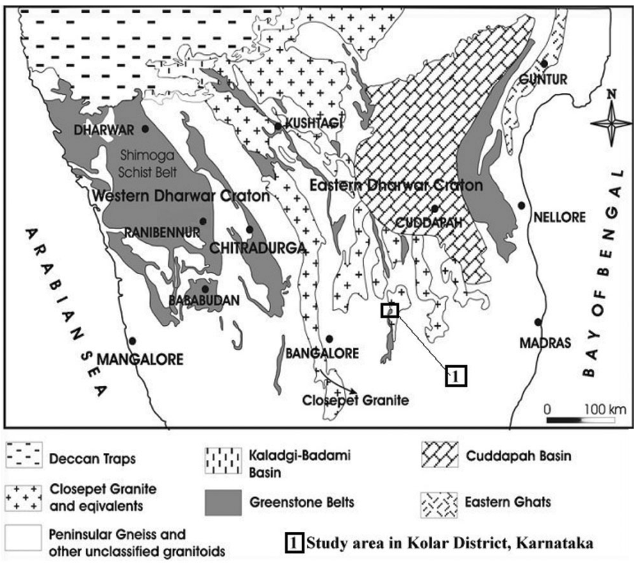

Figure 1. Geological map of the Karnataka showing the location of study area[21].

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25 and 33. According to Tulloch[6], Ps content in epidote formed from the alteration of plagioclase and biotite ranges from 0–25 and 33–38 respectively.

After identification of magmatic nature of epidote, the various characteristics of epidote are used to infer intrusion conditions such as crystallization depth, oxygen fugacity and upward transport rate of melt based on established criteria[1–3].

Temperature, fO_2 and total pressure bear important influence on mafic silicate mineral chemistry, but fO_2 is the main controlling factor[12,13]. The Ps components of epidote are indicative of pressure of emplacement and fO_2 of crystallization.

The increasing value of fO_2 of crystallization is represented by the crystallization condition of nickel–nickel oxide (NNO), quartz–fayalite–magnetite (QFM) and haematite–magnetite (HM). Granitoids generally crystallize between the NNO and HM buffer curves[11]. At these fO_2, the Ps component of mEp is 25 and 33 respectively. The mEp with 20–24 mol% Ps crystallized buffered by NNO or in the QFM to NNO range at Pf5 (pressure of 5) kbar or above and mostly occurs in epidotes from plutons emplaced at or above 5 kbar pressure[6,9]. The mEp with 27–29 mol% Ps range occurs in plutons emplaced at lower pressures (3–5 kbar) and fO_2 between the NNO and HM range.

In the studied granitoids, Ps component mostly ranges from 25 to 32. Epidotes having 25–28 Ps are likely to have crystallized at lower pressures (3–5 kbar) and fO_2 between the NNO and HM range. The relatively high (28–32) Ps components in majority of epidote, however, is indicative of still high fO_2 (crystallization between QFM and HM buffers) and lower pressure.

This inference of high fO_2 condition is supported by the presence of Mg-rich amphiboles having Fe/(Fe + Mg) value of 0.40–0.65 in hornblende[14], euhedral titanite and magnetite as early-crystallizing phases[15] and oxygen

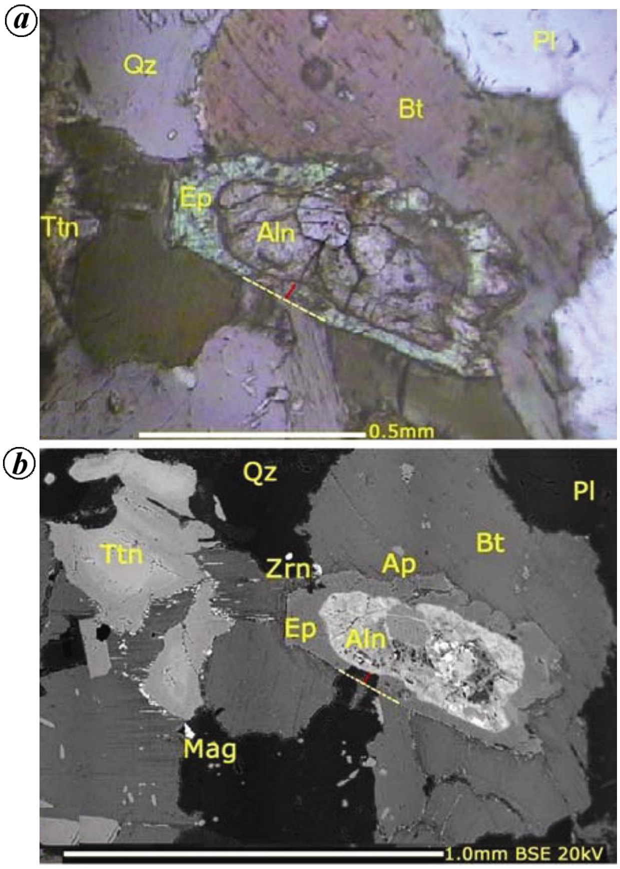

Figure 2. ***a***, Photomicrograph under PPL. ***b***, BSE image: Photos illustrating zoned magmatic epidote (Ep) with allanite (Aln) rim armoured by biotite (Bt) and dissolution of epidote rim against quartz (Qz) and plagioclase (Pl). The red and yellow lines represent width of dissolution and expected pre-dissolution boundary of epidote respectively. Also shown are zoned magmatic titanite (Ttn), zircon (Zrn), apatite (Ap) and magnetite (Mag).

Table 1. Representative EPMA analyses of epidote

Mode of occurrence	Magmatic-rim over allanite	Secondary-alteration of plagioclase	Secondary-alteration of biotite
Oxide in wt%			
SiO_2	37.10	37.09	36.45
TiO_2	0.07	0.01	0.26
Al_2O_3	22.13	23.75	19.16
FeO^T	13.95	11.12	15.81
MnO	0.22	0.24	0.01
MgO	0.02	0.01	0.02
CaO	23.19	23.07	23.22
Na_2O	0.03	0.01	0.00
K_2O	0.01	0.02	0.00
Total	96.72	95.32	94.93
Calculated cations on the basis of 12 O			
Si	2.96	2.96	2.91
Ti	0.00	0.00	0.02
Al	2.08	2.24	1.80
Fe_3	0.93	0.74	1.06
Mn	0.01	0.02	0.00
Mg	0.00	0.00	0.00
Ca	1.99	1.97	1.99
K	0.00	0.00	0.00
Na	0.00	0.00	0.00
Sigma Cat	7.99	7.94	7.78
Ps	30.90	24.95	36.93

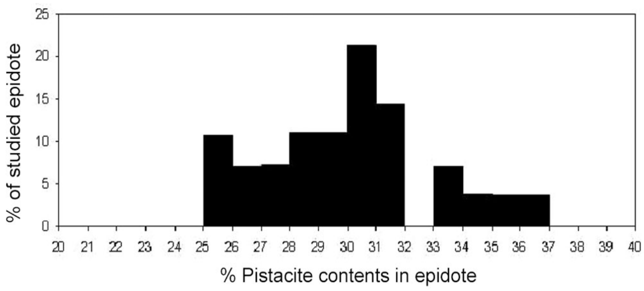

Figure 3. Mole per cent (mol%) pistacite in epidotes ($N = 34$) from high-Mg granitoids of Srinivaspura, Kolar district, Karnataka.

fugacity estimates[16] (log $fO_2 = -18.41$ to -20.73) in the studied granitoids. The presence of assemblage quartz + titanite + magnetite which requires fO_2 slightly above the QFM buffer[16] further confirms these oxygen fugacity conditions.

Occurrence of mEp has significant bearing on the emplacement mechanism of the magma. Its stability field and dissolution properties are widely used to infer the rate of upward transport of granitic magma. At water-saturated conditions and fO_2 buffered by NNO, epidote has a wide magmatic stability field in calc-alkaline tonalitic magmas[1] with a minimum pressure of about 5 kbar. Experiments performed with fO_2 buffered by HM show that epidote may be stable down to 3 kbar pressure. In general, mEp exists at a minimum pressure of 4–6 kbar[7,17,18] and dissolved in granitic melts in contact with feldspar at lower pressure at relatively fast rate[19]. mEp can survive this rapid dissolution only if granitic magma rapidly moves upwards and solidifies quickly. Qualitatively, mere presence of mEp in low-level granitoids is therefore indicative of very rapid upward transport rate for the studied granitoids. Quantitative estimation of upward migration rates of host magmas is possible for partially dissolved epidote, armoured by biotite and plagioclase[1–3].

In the high-Mg granitoids, occurrence of partially dissolved magmatic epidote almost wholly to partially rimmed by biotite and having a core of allanite is observed (Figure 2). Using the formula $t = dz^2/(5 \times 10^{-17})$, where dz = width of dissolution zone (m); t = time for partial dissolution of epidote (s)[3], the time for partial dissolution of epidote of 0.0218 mm width turns out to be ~ 0.3 year. It means that mEp granitoids were emplaced from a minimum pressure (Pm), where mEp can coexist with granitic melt (4–6 kbar, mean 5 kbar) to pressure of crystallization in kbar (Pe = 2.5 kbar), arrived on the basis of Al-in-hornblende geobarometry in ~ 0.3 year. This gives a minimum emplacement rate of 27,650 m per year using the formula[3] $Tr = Lr/t$, where Tr = transport rate (m/year), $Lr = (Pm–Pe) \times 104/3$ (m). This rate is much higher than that reported by Sial *et al.*[3], a rate of 455–1851 m per year at higher pressure. There may be two reasons for the differences between the upward migration rate recorded by Sial *et al.*[3] and the present case. Firstly, the partial dissolution rate of epidote[3] was calculated for tonalitic magma, whereas in the present case, the rock is a monzogranite. Second, there is a possibility that migration is faster at lower pressure (present case) than at higher pressure[3].

The fast upward migration rate has important bearing on the mechanism of emplacement. During slow upward migration through diapirism, most of the mEp is likely to have been resorbed completely before the final crystallization of the magma. On the other hand, if magma migrates rapidly by dyking, epidote grains may escape resorption and there is possibility of occurrence of mEp in high-level granitoids. The estimated migration rate is fast enough for dyking as emplacement mechanism. The rapid upward migration of magma emplaced in linear bodies is thus suggestive of emplacement by dyking rather than by diapirism. The presence of mEp in calc-alkaline plutons is also indicative of low CO_2 activity[20].

Presence of mEp in Neoarchaean high-Mg granitoids has been recorded based on textural and chemical criteria. Its presence has placed important constraints on the depth, mechanism of emplacement and fO_2 of crystallization of these granitoids. The high Ps content (25–32) in mEp and its characteristic dissolution suggest that these granitoids are emplaced at low-pressure and high fO_2 condition by dyking.

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ACKNOWLEDGEMENTS. We thank Shri S. C. Rath, Director General, GSI and Shri S. Balakrishnan, Dy Director General and HOD, GSI, SR for their support and permission to publish this paper. We also thank Shri J. N. Das, Director, NCEGR, GSI, Bangalore for guidance, encouragement and support.

Received 8 January 2014; accepted 21 July 2014

Observation on foreshore morphodynamics of microtidal sandy beaches

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Foreshore morphology and morphodynamics were examined to identify stability of two microtidal sandy beaches, Kundapura and Padukare, along the Karnataka shoreline on the west coast of India during three annual cycles from March 2008 to March 2011. The net observation at both sites exhibits slow rate of sediment accretion followed by non-uniform sediment erosion and accretion processes. Study revealed that the beaches are unfavourable for recreational activity because of their narrow width and steeper slope. During summer monsoon, the absence of backshore zone at Padukare makes it more vulnerable to erosion than Kundapura beach.

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Keywords: Beach profile, erosion/accretion, Kundapura, Padukare, west coast of India.

INFORMATION on beach morphodynamics is one of the primary requirements for integrated sustainable coastal zone management studies. Beach profiles provide significant insights for understanding short and long-term spatio-temporal beach morphodynamics[1,2]. Also, beach profile is an essential tool in predicting beach morphodynamics and for estimating equilibrium beach profiles[3]. Hence, understanding beach morphology and morphodynamics is crucial for planning coastal development strategies. Undoubtedly, the sandy beaches are more dynamic and the beach morphodynamics are usually associated with artificial constructions as well as natural phenomena, and exhibit dramatic variation with respect to space and time[4–7]. Kumar *et al.*[8] observed that ~75% of the Karnataka coast is covered with sandy beaches. In this study, morphodynamic observation was carried out at two sandy beaches, Kundapura and Padukare, spaced at a distance of ~40 km along Karnataka coast (Figure 1). The Kundapura beach, south of Gangoli river mouth covers a stretch of ~3 km, whereas the Padukare beach, south of Udiyavara river mouth runs for ~6.2 km along the shoreline. Both sites are well-known fishing zones along west coast of India and also popular tourist places. However, there was no field data available on the beach morphodynamics covering different annual cycles at these two locations. In this context, our study aims to observe the foreshore sediment accretion and erosion processes in

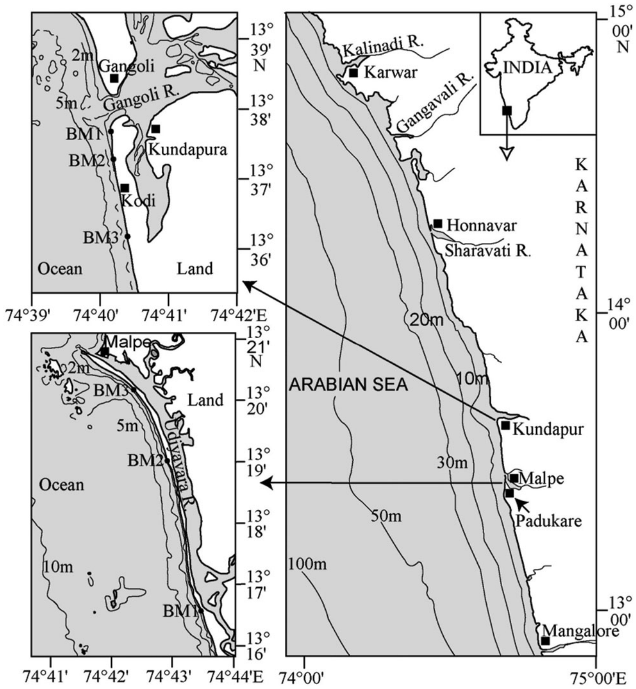

Figure 1. Study area covering two microtidal sandy beaches (Kundapura and Padukare) along Karnataka shoreline, west coast of India.