Fertility of Late Archaean basement granite in the vicinity of U-mineralized Neoproterozoic Bhima basin, peninsular India

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Late Archaean granitoids constituting the basement for the Neoproterozoic Bhima Group are exposed along the southern margin of the Bhima basin in southern India. These are rich in accessory minerals such as sphene, allanite, apatite and zircon, which are the main carriers of uranium and thorium. *In situ* gamma-ray spectrometric analysis reveals that these granitoids have higher abundances of Th, U and K (Th range 10–43 ppm, mean 26 ppm; U range 3–21 ppm, mean 8 ppm; K range 1.2–5.2%, mean 4.0%) relative to granitoids occurring farther away from the basin. Thus, they belong to the class of fertile granitoids from the point of view of uranium mineralization. The granitoids have been mylonitized and hydrothermally altered in the Gugi–Ukkinal fault zone, which constitutes the zone of uranium mineralization discovered recently along the southern margin of the Bhima basin. Uranium apparently derived from hydrothermal leaching of basement granitoid rocks may have got deposited in the fault zone at the contact of carbonate rocks, which provided favourable geochemical environment (Eh–pH conditions) for uranium precipitation.

LATE Archaean granitoid rocks consisting of radioelement-rich accessory minerals – the fertile granitoids – have contributed to uranium mineralization at the interface

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*For correspondence. (e-mail: senthilngri@rediffmail.com) of the Archaean and Proterozoic formations. Where fertile Archaean granitoids were affected by erosion under anoxic conditions (prior to 2.1 Ga), they have given rise to detrital uraninite deposits, especially in the quartz pebble conglomerates at the base of Proterozoic sequences[1]. Elsewhere, where the granitoids have been affected by oxidizing waters, they have given rise to hydrothermal deposits at or close to the Archaean–Proterozoic unconformity[2]. In either case, fertile late Archaean granitoids have served as an important source for the U-deposits at the base of Proterozoic sequences. These deposits are both stratigraphically and structurally controlled. The most recent discovery of such a deposit in India is at the base of the Neoproterozoic Bhima Group which overlies the granitoids correlatable with the 2.5 Ga old K-rich Closepet Granite of the Dharwar craton[3,4]. The objective of the present communication is to examine the fertility of the granitoids exposed in the vicinity of the Bhima basin along its southern border, where U-mineralization has been discovered. The communication gives the geological setting, U, Th and K distribution in the basement granitoids, nature of accessory minerals which are present in the granitoids, alteration of granitoids in the fault zones which have controlled the mineralization and briefly discusses the possible origin of U-mineralization at this locality in the southern Indian Precambrian terrain.

The epicratonic Mesoproterozoic Kaladgi Supergroup and Neoproterozoic Bhima Group overlie the Archaean granite-greenstone basement in Karnataka, of southern India (Figure 1). The Archaean granite-greenstone terrain consists of Dharwar greenstone belts distributed in a sea of TTG gneisses designated as the 'Peninsular gneiss'. Cratonization of the Archaean tectonic province occurred ~ 2.5 Ga ago accompanied by emplacement of K-rich granitoids referred to as the 'Closepet Granite' (ages after Friend and Nutman[5]; Jayananda *et al.*[6]). Sedimentary rocks of the Kaladgi Supergroup and the Bhima Group were deposited on the eroded edges of this cratonized terrain.

Uranium mineralization has been documented close to the southern border of the Bhima Group of rocks where they are in juxtaposition over a large part with the K-rich granitoid rocks of the Closepet Granite suite. The Closepet Granite is an interesting granitoid pluton that transects the metamorphic facies boundaries in southern India. Close to the Bhima basin it is in greenschist facies crustal level (less than 8 km palaeodepth calculated from P–T data (after Harris and Jayaram[7]), whereas farther south it is in amphibolite and granulite facies crustal levels. Granitoids occurring along the southern margin of the Kaladgi and Bhima basins are commonly coarse-grained, sometimes porphyritic, pink and grey coloured, and are in weakly foliated variety. Mafic microgranular enclaves in them are common. Both pegmatite and aplite veins invade these rocks. A study of textures and mineralogical composition of the Closepet Granite has shown that the usually porphyritic monzogranite of intermediate and deeper levels gives way to more homogeneous granitoids in greenschist facies crustal level[8]. It has been observed that accessory mineral phases such as sphene, allanite, apatite and zircon become abundant in the greenschist facies crustal level relative to granitoids of deeper levels, in accordance with the behaviour of accessory minerals in I-type granitoids as observed by Bea[9]. Such an accessory mineral-rich granitoid phase is observed close to the southern boundary of the Bhima basin.

At the base, the Bhima Group consists of oligomictic conglomerate and sandstone which are overlain by shales and limestones in the upper part. It is the carbonate rocks that are dominant in the Bhima Group. Stratigraphy of the Group has been discussed by Misra *et al.*[10] and Kale *et al.*[11]. Rocks of the Bhima Group and the basement granitoids, have been affected by faulting close to the interface between the two along the southern border of the basin.

A major fault can be traced along east-west strike from Kuralagere in the west to the east of Gugi (Figure 1) along the southern border of the Bhima basin. This fault zone designated as the 'Gugi fault' is about 500 m wide and has affected both the carbonate and the granitoid rocks. Within the fault zone, the generally horizontal sedimentary beds of the Bhima Group have acquired steep dips. The carbonate rocks show strong lamination, local brecciation and asymmetric folds in the fault zone.

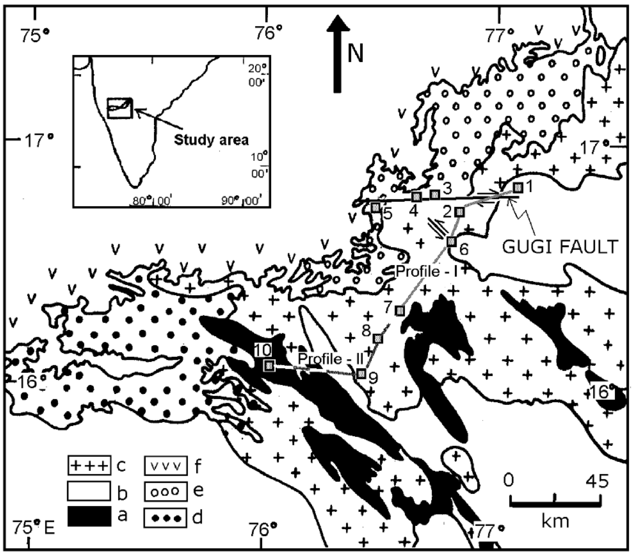

Figure 1. Geological sketch map of the Proterozoic Bhima and Kaladgi basins and adjacent cratonic terrane. a, Archaean supracrustal belts; b, Peninsular gneiss; c, Closepet Granite; d, Kaladgi Supergroup; e, Bhima Group; f, Deccan basalts. 1, Yadgir; 2, Shahpur; 3, Gugi; 4, Ukkinal; 5, Kuralagere; 6, Bijaspur; 7, Tinthini; 8, Lingsugur; 9, Mudgal, and 10, Hungund. Uranium mineralization is reported from near Gugi and Ukkinal in the Gugi fault zone. Profiles I and II along which the radioelemental measurements have been carried out are also shown.

Shear planes in the fault zone dip steeply towards north. Axes of asymmetric folds in the fault zone suggest oblique slip faulting. Northern block has moved up relative to southern block and the horizontal component of movement is dextral. The granitoid rocks show mylonitization and intense saussuritization. Investigations by Pandit *et al.*[3] and Dhana Raju *et al.*[4] have shown that U-mineralization is confined to this fault zone at the interface of the Archaean granitoids and Neoproterozoic Bhima Group of rocks. Uranium is hosted mainly in sheared phosphatic limestone, non-phosphatic limestone, shale and basement granitoid. The radioactive minerals are pitchblende and coffinite. These are associated with sulphide minerals, pyrite, chalcopyrite as well as carbonaceous matter[3]. There are other NW-SE striking faults, which have affected the granitic basement. One such fault close to the southern margin of the Bhima basin is observed near Bijaspur. In this fault zone, shear planes are steeply dipping and slickenlines are subhorizontal. Stretching lineations marked by feldspar and mafic mineral streaks plunge at 10° towards 135°.

The petrographic study reveals that granitoid rocks occurring in the vicinity of the Bhima basin (profile-I, Figure 1) consist of quartz, K-feldspar (microcline), plagioclase, biotite and minor hornblende. They are enriched in accessory minerals, sphene, allanite, apatite, zircon and epidote (Figure 2). Magnetite is the principal opaque accessory. Granitoid rocks along profile-II (Figure 1), away from the Bhima basin, are richer in plagioclase and poorer in accessory minerals relative to those in the rocks along profile-I.

In the Gugi and Bijaspur fault zones, plagioclase is intensely saussuritized and K-feldspar shows development of flame perthites (Figure 3). It must be mentioned that flame perthites are restricted to mylonitized and saussuritized granitoids in the fault zones and are absent outside such zones. It has also been observed that accessory minerals, which are generally fresh outside the fault zones are altered within them. For example, in the fault zones sphene is fractured, and the fractures are filled by secondary allanite and bastnaesite. Secondary leucoxene has been noted. Primary allanite is more altered in the fault zones than outside (Figure 4).

Petrographic evidences indicate occurrence of more K-feldspar and accessory minerals such as allanite, sphene, apatite and zircon in greater abundance in the granitoids close to the Bhima basin. Therefore a measure of fertility of granitoid rocks here was undertaken by conducting *in situ* gamma-ray spectrometric surveys along profiles, Yadgir–Shahpur–Tinthini (profile-I) close to the southern margin of the Bhima Group of rocks, and Tinthini–Lingsugur–Mudgal–Hungund (profile-II) farther away from the Bhima Group of rocks. The experimental procedure is given in Box 1. The K, U and Th concentrations of granitoids along these profiles are given in Table 1 and

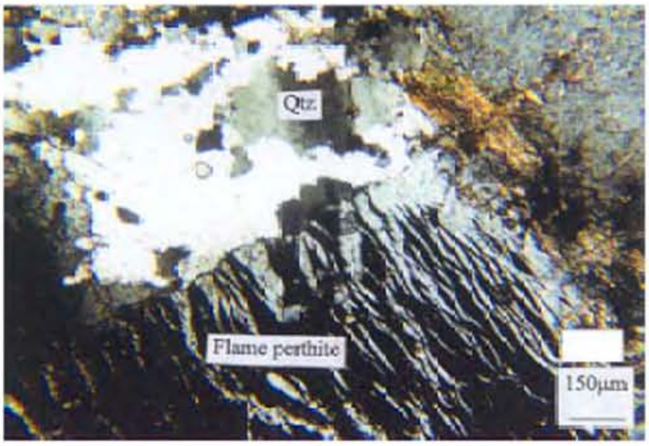

Figure 3. Occurrence of flame perthite in the fault zone of basement granite near Bijaspur. Note the coexistence of flame perthite with muscovite (sericite) replacing plagioclase. Strained quartz (Qtz) can also be seen.

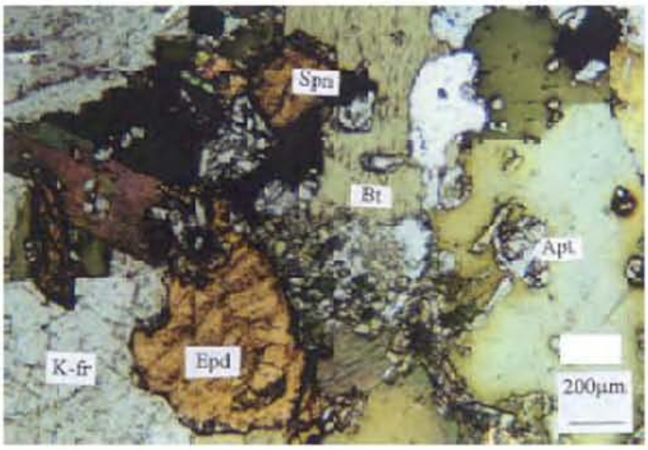

Figure 2. Photomicrograph of accessory mineral-enriched part of granite showing sphene (Spn), apatite (Apt), epidote (Epd). Opaques are magnetite. Location–Shahpur.

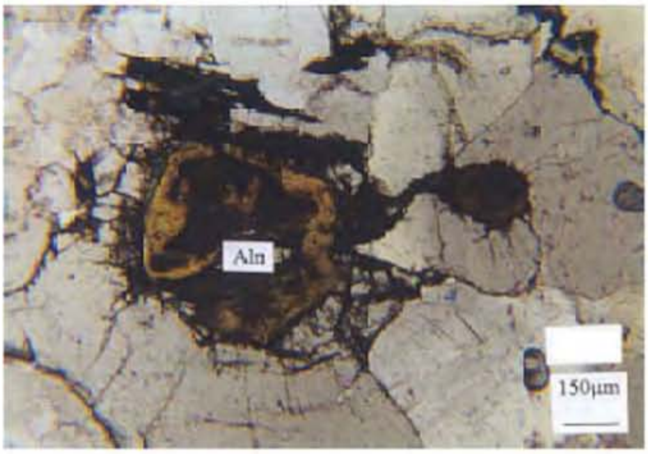

Figure 4. Photomicrograph of allanite (Aln) showing formation of secondary alteration products along its margin. Metamictic nature of core and radiation damage around allanite can be seen.

plotted in K–Th, K–U and U–Th scatter diagrams (Figure 5 *a*–*c*).

It is observed that basement rocks along profile-I are enriched with K, U and Th and have a wide range of concentration of U (range 3.08–20.76 ppm, mean 8.18 ppm), Th (range 9.77–42.53 ppm, mean 25.67) and K (range 1.17–5.15%, mean 4.03%). By contrast, granitoids along profile-II show lower abundances of K, U and Th, and comparatively narrow range of concentration of U (range 0.53–5.65 ppm, mean 1.78 ppm), Th (range 3.04–19 ppm, mean 7.05 ppm), and K (range 0.68–3.02%, mean 1.89%) (Table 1). The available data therefore suggest that the granitoids in the vicinity of the Bhima Group of rocks are characterized by nearly four times enrichment in U and Th, and two times enrichment in K relative to the granites farther away (Table 1, Figure 5 *a*–*c*).

Box 1. Experimental procedure

A four-channel, spectrum-stabilized gamma-ray spectrometer, with a large NaI (Tl-activated) crystal (5 inch diameter and 6 inch height) as detector was used. Background measurements were carried out over the Hussain Sagar Lake in Hyderabad located in a granitic area similar to those observed in the study area. Gamma-ray spectrometric measurements were made by placing the detector directly over fresh outcrops. *In situ* analyses carried out provide estimates representative of larger mass of the order of 40 kg of the rock in contrast to the laboratory analysis on much smaller samples of 1 kg or less. Care was taken to avoid outcrops close to hill slopes and other features which could distort 2π geometry. Counting time was set to at least 300 s. Observed count rates in three energy windows centred on the 2.62, 1.76 and 1.46 MeV peaks (characteristic of Tl^{208}, Bi^{214} and K^{40}) were corrected for background, Compton scattering effects (using stripping constants), and well-determined sensitivity factors were applied to the net count rates. Precision is estimated at 0.1 ppm for U, 0.5 ppm for Th and 0.1% for K.

Table 1. Th, U and K concentrations of granitoids in the vicinity and farther away from the Proterozoic Bhima basin

*n**	Th ppm	U ppm	K%
Profile-I: Yadgir–Shahpur–Tintini (close to the Bhima basin)			
28	25.67 (8.57)	8.18 (5.21)	4.03 (0.85)
Profile-II: Tintini–Lingsugur–Mudgal–Hungund (away from the Bhima basin)			
32	6.87 (4.67)	1.79 (1.34)	1.89 (0.62)

*Number of sites at which U, Th and K were measured. Standard deviations are given within brackets.

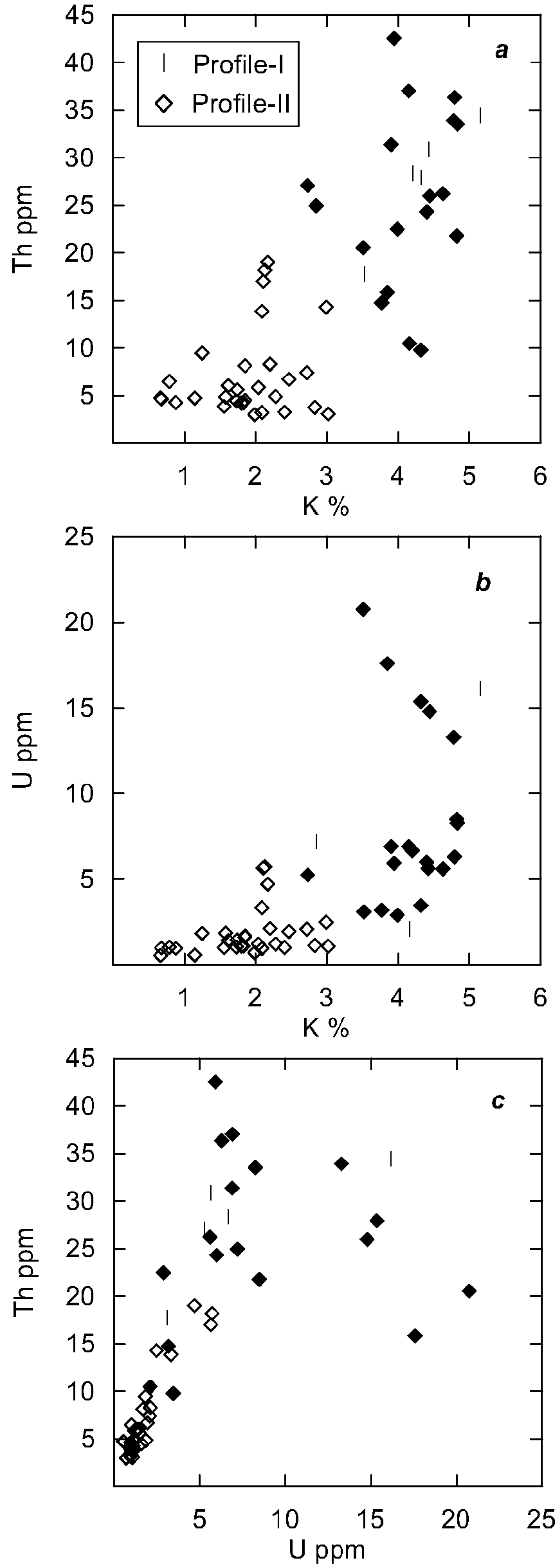

Figure 5. *a*, K–Th; *b*, K–U and *c*, U–Th scatter diagrams for the granitoid basement rocks near and farther away from the Bhima basin. ◆, Granitoid rocks along the profile Yadgir–Shahpur–Tinthini (profile-I); ◊, Granitoid rocks along the profile Tinthini–Lingsugur–Mudgal–Hungund (profile-II). The profiles are shown in Figure 1. Note that the profile-I rocks are enriched in all three elements relative to those along profile-II.

Highest concentrations of U, Th and K are found in mylonitized basement granitoids of the fault zones. Two analyses of mylonitized granitoids show U content 26.13 and 36.28 ppm, Th 23.72 and 42.60 ppm and K 5.03 and 5.36%.

The present study has shown the following features:

(1) Granitoids close to the southern border of the Bhima basin (profile-I) are enriched in U and Th, nearly four times higher than in those occurring farther away along profile-II.
(2) Granitoids have been strongly hydrothermally altered in the fault zones along the southern margin of the Bhima basin.
(3) Mineralization has been observed in the fault zone at the interface of the basement granitoids with the overlying carbonate sedimentary rocks of the Bhima Group.

It has been observed that the granitoids along profile-I are characterized by higher contents of K-feldspar and biotite, which account for the observed higher abundance of K in these rocks. Gromet and Silver[12] and Bea[9] have observed that U and Th contents in rocks are largely determined by the abundance of accessory minerals which carry these elements. Nearly four times higher concentration of U and Th observed in the granitoids occurring close to the Bhima basin can be attributed to higher abundance of accessory minerals such as sphene, allanite, apatite, zircon, etc. in them.

The above-mentioned granitoids have been mylonitized in fault zones along the southern border of the Bhima basin. In the fault zone, plagioclase feldspar shows intense saussuritization and K-feldspar development as flame perthites. Flame perthites in granites could be formed by deuteric activity in the late stages of granite magmatism or due to deformation and fluid migration in fault zones[13,14]. Flame perthites in the study area are restricted to the fault zone rocks. This evidence suggests that flame perthites here are not a product of deuteric activity formed during the late stages of granite magmatism, but are related to deformation and fluid migration in fault zones as envisaged by Pryer and Robin[14], and Smithson[15]. In fault zone rocks at the southern margin of the Bhima basin, a close relationship has been observed between the intensity of saussuritization of plagioclase and development of flame perthites in K-feldspar. This is explained by the process which involves release of Na from plagioclase during the formation of albite and epidote, and its migration to form flame perthite in K-feldspar. Potassium released during exchange reaction from K-feldspar, replaces Na in plagioclase to give rise to muscovite (sericitic mica). These exchange reactions indicate mobilization of K and Na during mylonitization in the fault zone. Formation of muscovite/sericite/epidote points to the activity of H_2O-rich fluids. It has been observed that these H_2O-rich fluids could also have affected the accessory minerals as indicated by alteration of allanite (Figure 4).

Higher concentration of uranium has been observed in the fault zones. This feature can be attributed to the precipitation of uranium from hydrothermal solution in the fault zones. Occurrence of bastnaesite and allanite, in the fractures and along the margins of sphene, points to such a secondary precipitation of uranium. In a worldwide study of the morphology of sphene in granites, Pan *et al.*[16] have observed such a feature in the Closepet Granite. It is well known that uranium and thorium are mobile under hydrothermal conditions[17–21]. Fertile granitoid rocks constituting the basement for the Bhima Group may have been affected by hydrothermal fluids, which leached out uranium from the accessory mineral phases and transported them along fault zones. According to Wood[20], Keppler and Wyllie[22], and Lee and Byrne[23], ligands such as CO_3^{2-}, HCO_3^-, F^-, Cl^-, HS^- and HPO_4^{2-} in hydrothermal fluids, which can form complexes with REEs and actinides play an important role in not only bringing about leaching of U and Th from accessory minerals, but also help in transporting the leached uranium to the site of mineralization. Brittle deformed fault zone rocks have served as pathways for migration of fluids. Precipitation of uranium in the fault zones has been observed wherever uranium-rich fluids came into contact with the carbonate rocks/carbonaceous or phosphatic limestones/pyritic layers in carbonate rocks[3,4] due to change in Eh-pH conditions. Similar observations have been made elsewhere for the origin of uranium deposits[2,24,25]. The ultimate source of hydrothermal solutions that leached uranium from the fertile granitoids and precipitated it in the fault zones is yet to be established by isotope geochemical studies.

1. Backstrom, J. W. V., in Proceedings of a Workshop, 13–15 October, Golden, Colorado. U.S. Geol. Surv. Prof. Pap. 1161-D, 1975, pp. D1-D8.
2. Hecht, L. and Cuney, M., *Miner. Deposita*, 2000, **35**, 791–795.
3. Pandit, S. A., Ali, M. A., Swarnkar, B. M. and Banerjee, D. C., in *Field Workshop on Integrated Evolution of the Kaladgi and Bhima Basins*, Geological Society of India, 1999, pp. 53–56.
4. Dhana Raju, R., Kumar, M. K., Babu, E. V. S. S. and Pandit, S. A., *ibid*, pp. 47–53.
5. Friend, C. R. L. and Nutman, A. P., *J. Geol. Soc. India*, 1991, **38**, 357–368.
6. Jayananda, M., Martin, H., Peucat, J. J. and Mahabaleswar, B., *Contrib. Mineral. Petrol.*, 1995, **119**, 314–329.
7. Harris, N. B. W. and Jayaram, S., *Lithos*, 1982, **15**, 89–98.
8. Senthil Kumar, P., Unpublished Ph D thesis, submitted to Osmania University, 2001, p. 218.
9. Bea, F., *J. Petrol.*, 1996, **37**, 521–552.
10. Misra, R. N., Jayaprakash, A. V., Hans, S. K. and Sundaram, V., *Mem. Geol. Soc. India*, 1987, **6**, 227–237.
11. Kale, V. S., Mudholkar, A. V., Phansalkar, V. G. and Peshwa, V. V., *J. Palaeontol. Soc. India*, 1991, **35**, 91–103.
12. Gromet, L. P. and Silver, L. T., *Geochim. Cosmochim. Acta*, 1983, **47**, 925–939.

13. Smith, J. V. and Brown, W. L., *Feldspar Minerals 1*, Springer-Verlag, Berlin, 1988, p. 828.
14. Pryer, L. L. and Robin, P. Y. F., *J. Metamorph. Geol.*, 1995, **13**, 645–658.
15. Smithson, S. B., *Norsk. Geol. Underskr.*, 1963, 219.
16. Pan, Y., Fleet, M. E. and MacRae, N. D., *Geochim. Cosmochim. Acta*, 1993, **57**, 355–367.
17. Exley, S. A., *Earth Planet. Sci. Lett.*, 1980, **48**, 97–110.
18. Humpheris, S. E., in *Rare Earth Element Geochemistry* (ed. Henderson, P.), Elsevier, 1984, pp. 317–342.
19. Brookins, D. G., *Rev. Mineral.*, 1989, **21**, 201–225.
20. Wood, S. A., *Chem. Geol.*, 1990, **88**, 97–110.
21. Pan, Y. and Fleet, M. E., *Can. Mineral.*, 1990, **28**, 67–75.
22. Keppler, H. and Wyllie, P. J., *Contrib. Mineral. Petrol.*, 1991, **109**, 139–150.
23. Lee, H. G. and Byrne, R. H., *Geochim. Cosmochim. Acta*, 1992, **56**, 1127–1137.
24. Negga, H. S., Sheppard, S. M. F., Rosenbaun, J. and Cuney, M., *Contrib. Mineral. Petrol.*, 1986, **93**, 179–186.
25. Tupin, L., Leroy, J. L. and Sheppard, S. M. F., *Chem. Geol.*, 1990, **88**, 85–98.

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