

Significance of allanite-(Ce) in granitic gneisses from the ultrahigh-pressure metamorphic terrane, Dabie Shan, central China

XIAOCHUN LIU¹, SHUWEN DONG¹, HUAIMIN XUE² AND JIANXIONG ZHOU³

¹ Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081,

² Nanjing Institute of Geology and Mineral Resources, Chinese Academy of Geological Sciences, Nanjing 210016

³ Institute of Mineral Deposits, Chinese Academy of Geological Sciences, Beijing 100037, China

ABSTRACT

A recent study of granitic gneisses in the ultrahigh-pressure (UHP) metamorphic terrane from Dabie Shan, central China reveals that allanite-(Ce) is a widespread *REE*-bearing accessory phase. The microprobe analyses show that allanites-(Ce) have nearly uniform chemical compositions, with total *REE* contents ranging from 23 to 28 wt.% and a La/Ce ratio of 0.57–0.73. All allanites-(Ce) are replaced or rimmed by epidotes and commonly form a relatively *REE*-poor rim near the interfaces. The textural relations and mineral chemistry suggest that allanite-(Ce) crystallized prior to metamorphism and therefore was of igneous origin, whereas the surrounding epidote was the product of metamorphism. Granitic gneiss, composed chiefly of sodic plagioclase, microcline and quartz with minor amounts of Mn-rich garnet, biotite, low Si phengitic mica, epidote, chlorite and sometimes amphibole, was formed at 495°C and ~5 kbar, corresponding to the retrograde metamorphism of UHP rocks. Accordingly, it is believed that granitic gneisses have not experienced UHP metamorphism. This implies that a large scale tectonic juxtaposition developed before the epidote-amphibolite facies retrograde metamorphism of UHP rocks during the late continental collision in Dabie Shan.

KEYWORDS: allanite-(Ce), granitic gneisses, UHP rocks, tectonic juxtaposition, Dabie Shan.

Introduction

ALLANITE, $(Ca,Mn,REE,Y,Th)_2(Fe^{2+},Fe^{3+},Al)_3Si_3O_{12}OH$, a *REE*-rich member of the epidote group, occurs as a common accessory mineral in many granitic rocks and pegmatites, but also in some volcanic rocks, metamorphic rocks and calcareous skarns even though it is uncommon (Deer *et al.*, 1986). The formation of allanite is generally considered to be related to the late-stage magmatic fluid (or hydrothermal fluid) and zoned allanite reflects the variation of the chemical environment during magmatic fractional crystallization or hydrothermal metasomatism (Exley, 1980; Gromet and Silver, 1983; Sawka *et al.*, 1988; Sorensen, 1991).

Recently, allanite-(Ce) has also been recognized in granitic gneisses, controversially associated with UHP rocks from Dabie Shan, central

China. Until recently, it has been unclear, because of the lack of index minerals, whether these granitic gneisses have ever undergone UHP metamorphism (Liou *et al.*, 1996). The discovery of allanite-(Ce) and the confirmation of its igneous origin support the fact that granitic gneisses are only of low metamorphic grade, and have never been subjected to UHP metamorphism.

Field relations and petrology of granitic gneisses

The geological setting of Dabie Shan in central China has been described by many geologists (Okay *et al.*, 1993; Xu *et al.*, 1994; Liou *et al.*, 1995; Cong *et al.*, 1996; You *et al.*, 1996). Liou *et al.* (1995) divided Dabie Shan into four metamorphic belts (Fig. 1B). They are, from

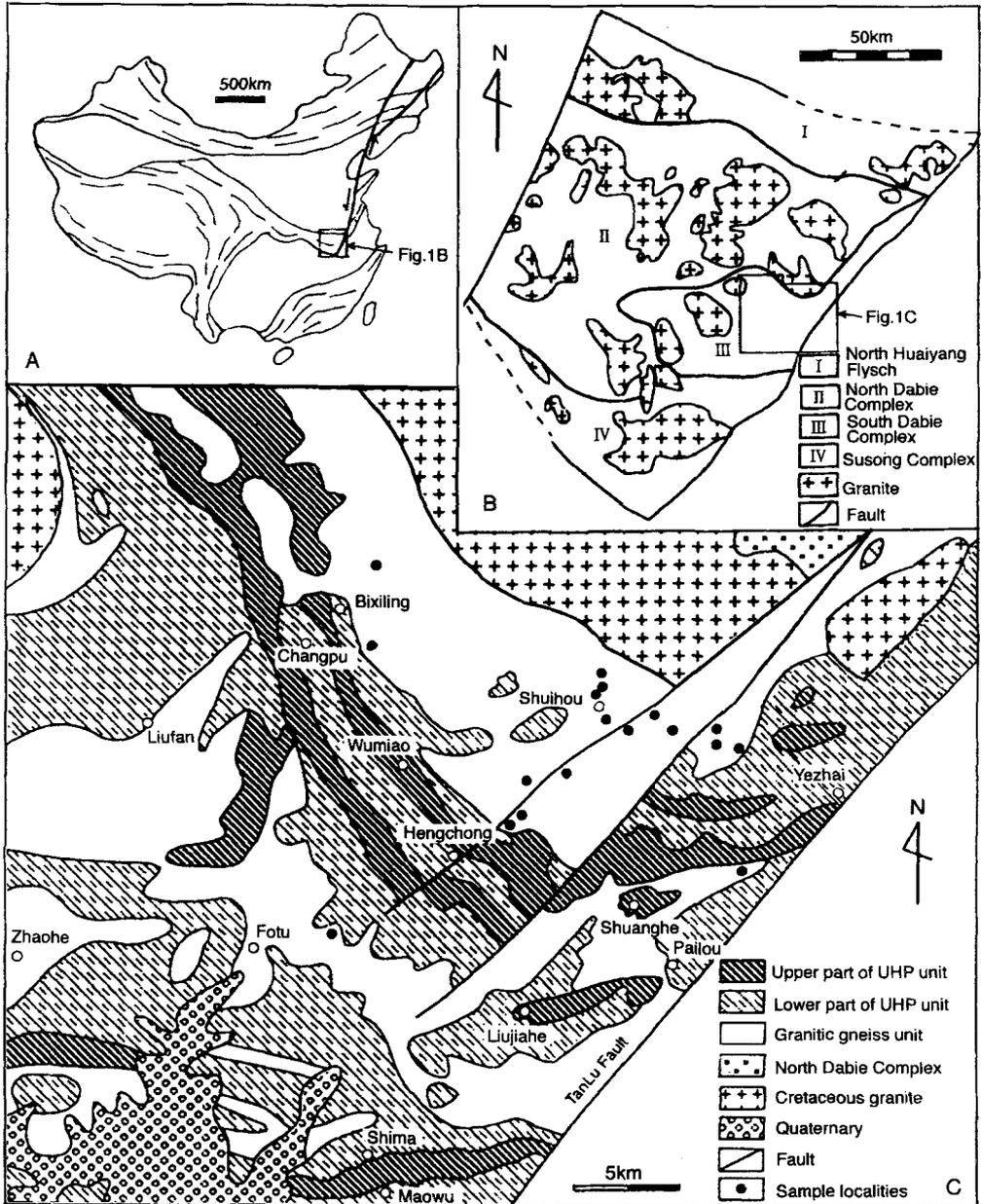


FIG. 1. Simplified geological map of the UHP terrane in the southern Dabie Shan (C) and its location in Dabie Shan (B) and in the tectonic framework of China (A).

north to south, the North Huaiyang Flysch, the North Dabie Complex, the South Dabie Complex, and the Susong complex. According to textural, mineralogical and structural features, the UHP

terrane defined in southern Dabie Shan can be divided into two units: the UHP unit and the granitic gneiss unit (Fig. 1C). The UHP unit, commonly occurring as supracrustal rocks,

consists of two parts: the upper part is predominantly composed of calc-silicate gneiss, marble, two-mica schist, and quartzite with many eclogite pods or lenses; the lower is composed of fine-grained garnet-biotite gneiss with some eclogite lenses or blocks. The main component of the granitic gneiss unit is a two-feldspar granitic gneiss with certain amounts of granodioritic gneiss and trondhjemitic gneiss, characterized by coarse-grained texture. Generally, there are mylonites in the contacts between the UHP and granitic gneiss units, but there are fewer deformational episodes developed in granitic gneisses than in UHP rocks. Regionally, the UHP terrane seems to be a thin-skin thrust sheet as suggested by Dong *et al.* (1996).

Granitic gneiss is largely composed of sodic plagioclase, microcline and quartz with minor amounts of garnet, biotite, white mica, epidote, chlorite and sometimes amphibole. The main accessory minerals are allanite-(Ce), titanite, zircon, apatite and magnetite. Garnet, which occurs in very limited amounts, is euhedral and mostly very small with an average grain size of <0.1 mm, but sometimes as large as 1.0 mm. Garnet is very variable in composition, but most of the crystals are rich in Mn and extremely poor in Mg, with a maximum spessartine content of 49 mol.%. All garnets exhibit pronounced zoning, with increasing spessartine and decreasing almandine from core to rim, but some larger grains display reverse zonation. Biotite, often replaced by chlorite, is Fe²⁺-rich, with a Mg/Fe²⁺+Mg ratio of 0.11–0.37. White mica is phengitic, with a Si value of 3.24–3.40 p.f.u., different from the high Si phengite encountered in UHP rocks. Epidote is rich in Fe³⁺, with a Ps parameter (i.e. Fe³⁺/Al+Fe³⁺ ratio) ranging from 0.26 to 0.31. Some epidotes display compositional zoning, with Fe³⁺ increasing from core to rim and a minimum Ps of 0.18. The metamorphic temperature calculated by garnet-amphibole geothermometer (Graham and Powell, 1984) from two amphibole-bearing samples, ranges from 439–557°C, with an average of 495°C, and the pressure is ~5 kbar based on an Al-in-hornblende geobarometer (Schmidt, 1992), in accordance with epidote-amphibolite facies conditions.

Occurrence of allanite-(Ce)

Allanite-(Ce) is widespread as an accessory phase in the granitic gneisses. The well-preserved allanite-(Ce) occurs as euhedral crystals with

pleochroism from dark brown to pale yellowish brown and simple twinning (Fig. 2a). The mineral is invariably replaced or rimmed by epidote, and some crystals display embayed outline and relict texture (Fig. 2b). A narrow, pale brown rim often formed near the surrounding epidote. Allanite-(Ce) sometimes contains zircon, titanite, prismatic apatite, ilmenite and quartz inclusions and is often in contact with titanite, but never encloses garnet, biotite or white mica.

Allanite-(Ce) occurs here in the form of large crystals, with a typical grain size ranging from 0.1 to 1.0 mm, and a maximum size of 2.5 mm, discordant with fine-grained metamorphic minerals. They are generally oriented parallel to the foliation plane of the granitic gneiss, but many grains are markedly oblique to the foliation. Moreover, the surrounding epidote with a relict core of allanite-(Ce) is sometimes elongated parallel to the foliation (Fig. 2c), and some allanite-(Ce) grains are also found to be flexured and deformed (Fig. 2d), implying that allanite-(Ce) was formed before the peak deformation while the surrounding epidote crystallized during the deformation.

Mineral chemistry

The analyses of allanite-(Ce) and the surrounding epidote were performed by a JEOL JXA-8800R wavelength-dispersive electron microprobe at Institute of Mineral Deposits, Chinese Academy of Geological Sciences. The operating conditions were 20 kV accelerating voltage, 2 × 10 A beam current and 1 µm beam size. The counting time at each peak was >20 s. The standards used for REE and Y were synthetic ReP₅O₁₄ series, but for Th pure synthetic oxide was used. The allanite and epidote analyses have been recalculated by using the charge balance criterion of 8 cations per 25 negative charges to enable the estimation of the Fe²⁺/Fe³⁺ ratio.

The analyses of representative allanite-(Ce) and the surrounding epidote are given in Table 1. Allanites-(Ce) from different locations display nearly uniform chemical compositions, with total REE contents ranging from ~23–28 wt.%. The increase in REE is accompanied by an increase in Fe²⁺ and a decrease in Ca and Al (Fig. 3), which corresponds to the charge-balanced coupled replacement Ca²⁺(Al,Fe)³⁺ = REE³⁺Fe²⁺ (Deer *et al.*, 1986). The REE in allanite-(Ce) comprise Ce, La, Nd and some Pr, with a La/Ce ratio ranging from 0.57–0.73. The distribution of REE

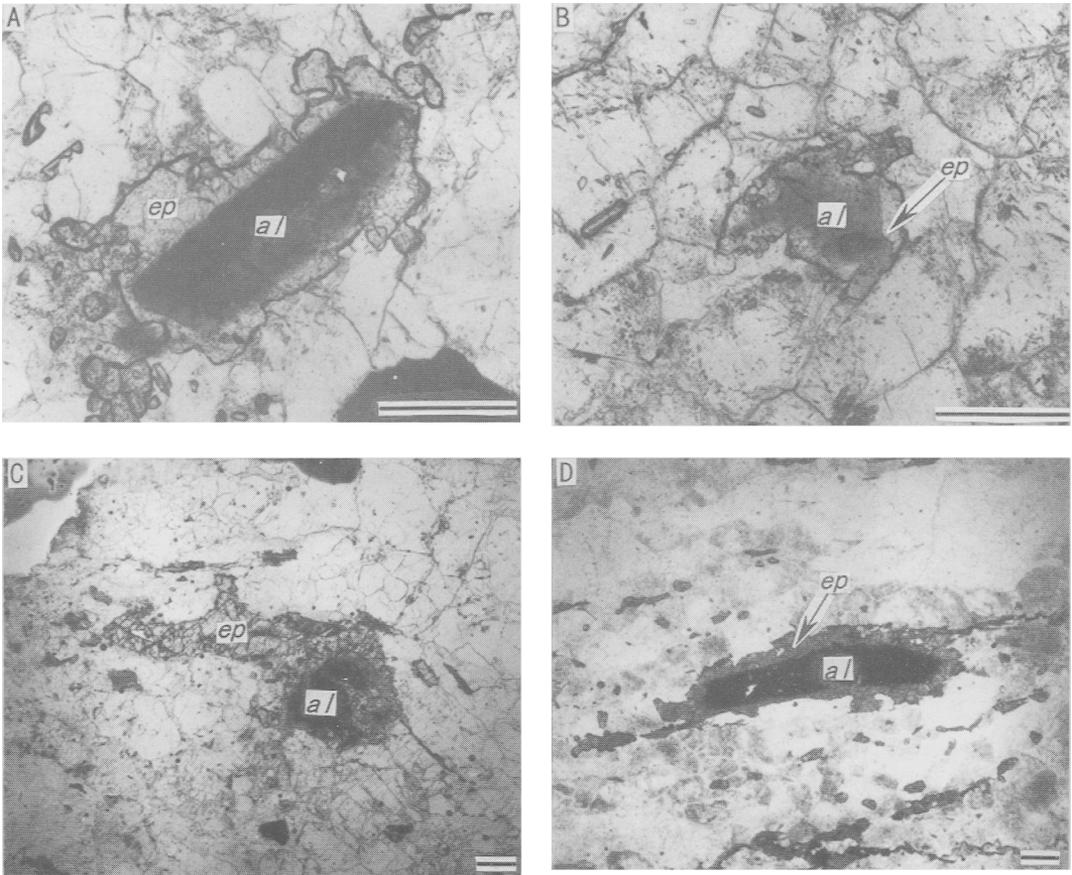


FIG. 2. Photomicrographs of allanite-(Ce) and the surrounding epidote in granitic gneisses from Dabie Shan, central China. (A) Euhedral crystal of allanite-(Ce) (al) with the simple twinning. (B) Relict allanite-(Ce) replaced by epidote (ep). (C) Elongation of the surrounding epidote with a relict core of allanite-(Ce). (D) Flexural deformation of allanite-(Ce). Scalebar = 1.0 mm.

contents in allanite-(Ce) is better illustrated in Fig. 4, which shows normal, right-leaning, chondrite-normalized *REE* patterns, very similar to those of the host rock. The La/Ce ratio obtained from the granitic gneisses ranges from 0.54–0.66.

The main part of the allanite-(Ce) grains is homogeneous, but most have a narrow *REE*-poor rim near the interfaces with epidote, similar to the detrital allanite from the Sanbagawa pelitic schists in Japan (Sakai *et al.*, 1984). The compositional variation, decreasing *REE* and Fe^{2+} and increasing Ca and Al in the rim, suggests a normal zonation, which is generally interpreted to reflect the environmental variation of crystallization during formation of allanite (Sorensen,

1991). However, the textural relations confirm that the formation of zoned allanite-(Ce) from Dabie Shan is related to the replacement of epidote.

The surrounding epidotes on allanite-(Ce) display similar compositions when compared with individual epidote grains in the granitic gneisses. Zonation of the surrounding epidote has been detected in some samples with increasing Fe^{3+} and decreasing Al towards the outer part. The minimum Ps value of the inner part is only 0.16, i.e. identical to that of the cores of individual grains and therefore indicating a similar origin. Allanite-(Ce) can form a complete solid solution with end-member epidote through

ALLANITE-(Ce) IN GRANITIC GNEISSES

TABLE 1. Microprobe analyses and structural formulae of representative allanite-(Ce) and the surrounding epidote

Sample no. Mineral	SH07-1			SH07-3			GS02-1			XT01-2		
	al(c)	al(r)	ep	al(c)	al(r)	ep	al(c)	al(r)	ep	al(c)	ep(i.p.)	ep(o.p.)
SiO ₂	29.26	32.93	36.57	29.59	33.94	37.78	30.20	32.35	38.04	30.64	38.02	37.53
TiO ₂	0.87	0.24	0.13	2.33	1.76	0.09	2.43	3.20	0.13	0.33	0.08	0.02
Al ₂ O ₃	13.13	17.25	22.43	10.96	16.37	22.10	11.36	13.48	22.26	16.33	26.60	25.67
Fe ₂ O ₃	5.57	7.48	15.86	4.56	2.44	14.59	4.35	—	11.01	2.92	8.03	10.00
FeO	10.99	7.29	—	12.61	12.67	1.30	12.82	14.46	2.93	9.65	0.05	0.47
MnO	1.31	1.04	0.39	1.01	0.69	0.10	0.51	0.41	0.22	2.19	0.25	0.30
MgO	0.38	0.29	—	0.51	0.44	0.05	1.09	0.46	—	0.45	—	0.14
CaO	8.51	13.82	22.41	8.69	11.77	22.48	8.76	10.43	21.59	9.30	23.05	22.41
La ₂ O ₃	7.96	5.00	0.04	8.07	5.16	0.08	8.21	5.39	0.29	7.01	—	0.84
Ce ₂ O ₃	13.35	8.35	0.01	13.02	8.30	0.11	12.72	10.91	0.58	11.85	0.08	1.21
Pr ₂ O ₃	1.10	0.83	—	1.06	0.75	0.01	0.98	0.91	0.04	1.01	0.16	0.12
Nd ₂ O ₃	4.81	3.25	—	4.83	3.22	0.06	3.73	3.56	0.37	4.67	0.28	0.47
Sm ₂ O ₃	0.48	0.29	0.10	0.39	0.23	—	0.13	0.25	0.03	0.46	0.04	0.02
Y ₂ O ₃	0.35	0.37	0.02	0.29	0.08	0.14	0.11	0.23	0.16	1.24	1.69	0.08
ThO ₂	0.21	0.30	0.06	0.46	0.42	—	1.05	2.49	0.02	0.05	—	0.04
Total	98.28	98.73	98.02	98.38	98.24	98.89	98.45	98.53	97.67	98.10	99.78	99.32

Numbers of ions on the basis of 8 cations												
Si	2.930	2.994	2.941	2.980	3.106	3.011	2.999	3.107	3.074	2.965	2.984	2.966
Ti	0.066	0.016	0.008	0.176	0.121	0.005	0.181	0.231	0.008	0.024	0.005	0.001
Al	1.550	1.849	2.127	1.301	1.767	2.077	1.329	1.526	2.120	1.863	2.462	2.391
Fe ³⁺	0.420	0.512	0.960	0.346	0.168	0.875	0.325	—	0.670	0.212	0.474	0.595
Fe ²⁺	0.920	0.554	—	1.063	0.970	0.087	1.064	1.162	0.198	0.781	0.033	0.031
Mn	0.111	0.080	0.026	0.086	0.054	0.007	0.043	0.034	0.051	0.180	0.017	0.020
Mg	0.056	0.039	—	0.077	0.059	0.006	0.161	0.066	—	0.065	—	0.017
Ca	0.914	1.346	1.932	0.938	1.154	1.920	0.932	1.073	1.869	0.964	1.939	1.897
La	0.294	0.168	0.001	0.300	0.174	0.002	0.301	0.191	0.009	0.250	—	0.024
Ce	0.489	0.278	—	0.480	0.278	0.003	0.463	0.384	0.017	0.420	0.002	0.035
Pr	0.040	0.028	—	0.039	0.025	—	0.035	0.032	0.001	0.036	0.005	0.003
Nd	0.172	0.106	—	0.174	0.105	0.002	0.132	0.122	0.011	0.162	0.008	0.013
Sm	0.017	0.009	0.003	0.013	0.007	—	0.004	0.008	0.001	0.015	0.001	0.001
Y	0.019	0.018	0.001	0.016	0.004	0.006	0.006	0.012	0.007	0.064	0.071	0.003
Th	0.005	0.006	0.001	0.010	0.009	—	0.024	0.054	0.001	0.001	—	0.001

— = not detectable; al = allanite-(Ce); ep = epidote; c = core; r = rim; i.p. = inner part; o.p. = outer part

coupled substitution, as many have demonstrated (Sakai *et al.*, 1984; Gieré, 1986; Pan and Fleet, 1990; Carcangiu *et al.*, 1997). However, the compositional variation suggests that there was a break in the growth between allanite-(Ce) and epidote in the granitic gneisses from Dabie Shan (Fig. 3), implying a two-stage crystallization.

Discussion

Origin of allanite-(Ce)

It is very important to determine the origin of allanites because of their diverse modes of occurrence, especially those from metamorphic

rocks. The porphyritic texture, non-aligned structure, mineral inclusion type and compositional variation indicate that allanite-(Ce) in granitic gneisses from Dabie Shan crystallized prior to metamorphism and deformation, whereas the surrounding epidote was the product of metamorphism. Moreover, a narrow compositional range of REE suggests that the formation of allanite-(Ce) is not due to metasomatism (Exley, 1980). In fact, no evidence of hydrothermal metasomatism has been found in these granitic gneisses. Accordingly, the allanite-(Ce) from Dabie Shan is believed to be of igneous origin. The concordance of the chondrite-normal-

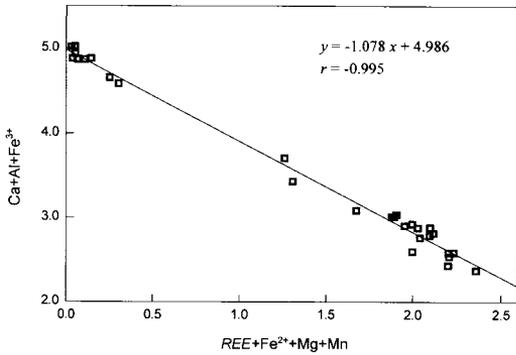


FIG. 3. $REE + Fe^{2+} + Mg + Mn$ vs $Ca + Al + Fe^{3+}$ diagram for allanites-(Ce) and the surrounding epidotes.

ized *REE* patterns between allanite-(Ce) and the primary granitic rock indicates that they formed at the same time, but the many accessory phases occurring as inclusions in allanite may imply that the allanite was the late-crystallized product of residual magma.

Metamorphic allanite has been reported from migmatitic rocks (Čech *et al.*, 1972; Pavelescu and Pavelescu, 1972; Campbell and Ethier, 1984; Sorensen, 1991), low-grade pelitic schists (Sakai *et al.*, 1984; Cappelli *et al.*, 1993; Inger and Cliff, 1993) and blueschists (Banno, 1993). The most

important example comes from the Sanbagawa pelitic schists, Japan, where the strong preferred orientation and the increase in both average grain size and volume with metamorphic grade suggest a metamorphic origin of the *REE*-bearing epidote (contains $\Sigma REE < 15$ wt.%); whereas the irregular, anhedral shape and the constant grain size with increasing metamorphic grade suggest a detrital origin of allanite (contains ΣREE up to 26 wt.%) (Sakai *et al.*, 1984). Actually, the textural relations of allanite-(Ce) in granitic gneisses from Dabie Shan are very similar to those of detrital allanite from Sanbagawa pelitic schists. Thus, it seems that the primary magmatic or detrital allanite could be preserved well during low-grade metamorphism.

Relations between UHP rocks and granitic gneisses

There has been much debate on the relationships between UHP rocks and associated rocks since coesite was discovered in eclogite from Dabie Shan, central China (Xu, 1987; Okay *et al.*, 1989; Wang *et al.*, 1989). It is now accepted that a suite of fine-grained garnet-biotite gneiss, calc-silicate gneiss, marble and quartzite associated closely with eclogite have all experienced UHP metamorphism. However, because of the lack of significant mineralogical evidence, there is still controversy over whether or not the coarse-

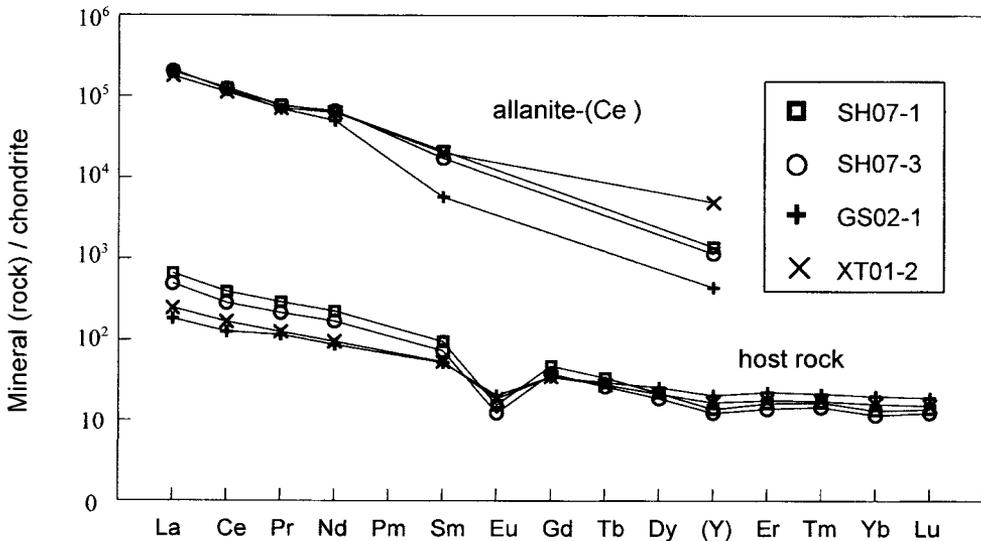


FIG. 4. Chondrite-normalized *REE* patterns of allanites-(Ce) and the host rocks.

grained granitic gneisses have undergone UHP metamorphism. Some geologists have considered them to be UHP rocks re-equilibrated at low-pressure conditions (Wang and Liou, 1991; Okay, 1993; Liou *et al.*, 1996), but others have argued that they had never been equilibrated at pressures above the plagioclase stability field (Carswell *et al.*, 1993; Cong *et al.*, 1995). In fact, significant differences in fabric, deformation and metamorphism between UHP rocks and granitic gneisses suggest that granitic gneiss is a unit that is not related to UHP metamorphism. The appearance of magmatic allanite-(Ce) also provides additional support for the non-UHP metamorphic origin of granitic gneisses. If so, the protolith age of 772.5 Ma and metamorphic age of 218.5 Ma obtained from granitic gneiss by Rowley *et al.* (1997), which agrees well with those from UHP rocks (Ames *et al.*, 1996), can not be simply regarded as the evidence of *in situ* UHP metamorphism.

In contrast, the mineral assemblage, chemistry and *P-T* conditions of granitic gneisses correspond systematically to those of fine-grained garnet-biotite gneiss within the UHP unit. The metamorphic conditions for such gneiss, estimated to be 460–570°C and 4–6 kbar, are also in accord with the retrograde metamorphic conditions of UHP rocks (Liou *et al.*, 1996). This implies that the granitic gneisses were mixed together with the UHP rocks before the epidote-amphibolite facies retrograde metamorphism of UHP rocks. How can we explain this mixing process? Cong *et al.* (1995) proposed a tectonic juxtaposition of UHP rocks and associated granitic gneisses at a high crustal level. The widespread development of a tectonic boundary between UHP rocks and granitic gneisses supports this interpretation, although in some places the boundary is unclear because of the late metamorphism and deformation. The protolith age of the granitic gneisses (Rowley *et al.*, 1997) has also precluded them from being synorogenic granitic intrusions. More recently, some low-grade metamorphic volcanic rock sheets with well-preserved blasto-pyroclastic texture (Dong *et al.*, 1997) and a Susong pelitic schist sheet characterized by the typical assemblage of kyanite + Fe-chloritoid + Fe-staurolite + muscovite + paragonite (Susong complex, situated in the south of the UHP terrane, Fig. 1B) have been found in the UHP unit, suggesting that a large scale tectonic juxtaposition developed during the late continental collision in Dabie Shan.

Acknowledgements

This research was carried out with the support of the National Natural Science Foundation of China (No. 49502027), the Sino-Germany project (major project no. 9501102-4) supported by MGMR of China and the Foundation of Young Geologists, MGMR of China (No. 9608). We are grateful to Prof. R. Gieré and Dr D.A. Carswell for their critical reviews and valuable comments, which helped to improve the paper. We also thank Prof. Zhendong You of China University of Geosciences for his constructive comments and suggestions on the manuscript.

References

- Ames, L., Zhou, G. and Xiong, B. (1996) Geochronology and isotopic character of ultrahigh-pressure metamorphism with implications for collision of the Sino-Korean and Yangtze Cratons, central China. *Tectonics*, **15**, 472–89.
- Banno, Y. (1993) Chromian sodic pyroxene, phengite and allanite from the Sanbagawa blueschists in the eastern Kii Peninsula, central Japan. *Mineral. J.*, **16**, 306–17.
- Campbell, F.A. and Ethier, V.G. (1984) Composition of allanite in the footwall of the Sullivan orebody, British Columbia. *Canad. Mineral.*, **22**, 507–11.
- Cappelli, B., Franceschelli, M. and Memmi, I. (1993) *LREE* zoning in allanite (Ce) from low temperature metamorphics, Alpi Apuane, Italy. *Terra*, **5**, 414–5.
- Carcangiu, G., Palomba, M. and Tamanini, M. (1977) *REE*-bearing minerals in the albitites of central Sardinia, Italy. *Mineral. Mag.*, **61**, 271–83.
- Carswell, D.A., Wilson, R.H., Cong, B., Zhai, M. and Zhao, Z. (1993) Areal extent of the ultra-high-pressure metamorphism of eclogites and gneisses in Dabieshan, central China. *Terra*, **5**, 5.
- Čech, F., Vrana, S. and Povondra, P. (1972) A non-metamict allanite from Zambia. *Neues Jahrb. Mineral. Abh.*, **116**, 208–23.
- Cong, B. (1996) *Ultrahigh-pressure Metamorphic Rocks in the Dabieshan-Sulu Region of China*. Science Press, Beijing, China, and Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Cong, B., Zhai, M., Carswell, D.A., Wilson, R.N., Wang, Q., Zhao, Z. and Windley, B.F. (1995) Petrogenesis of the Ultrahigh-pressure rocks and their country rocks at Shuanghe in Dabieshan, central China. *Eur. J. Mineral.*, **7**, 135–50.
- Deer, W.A., Howie, R.A. and Zussman, J. (1986) *Rock-forming Minerals*, 2nd ed., Vol. **1A**, Longmans, London.
- Dong, S., Wu, X., Gao, R., Lu, D., Li, Y., He, Y., Tang,

- J., Gao, F., Hou, M. and Huang, D. (1996) Preliminary study on deep geology of Dabie Orogenic belt. *Continental Dynamics*, **1**, 103–8.
- Dong, S., Wang, X. and Huang, D. (1997) Discovery of low grade metamorphic volcanic rock sheets within UHP in Dabie Mts, and its implications. *Chinese Sci. Bull.*, **42**, 1199–203.
- Exley, R.A. (1980) Microprobe studies of REE-rich accessory minerals: Implications for Skye granite petrogenesis and REE mobility in hydrothermal systems. *Earth Planet. Sci. Lett.*, **48**, 97–110.
- Gieré, R. (1986) Zirconolite, allanite and hoegbomite in a marble skarn from the Bergell contact aureole: Implications for mobility of Ti, Zr and REE. *Contrib. Mineral. Petrol.*, **93**, 459–70.
- Graham, C.M. and Powell, R. (1984) A garnet-hornblende geothermometer: Calibration, testing and application to the Pelona Schist, Southern California. *J. metam. Geol.*, **2**, 13–31.
- Gromet, L.P. and Silver, L.T. (1983) Rare earth element distributions among minerals in a granodiorite and their petrogenetic implication. *Geochim. Cosmochim. Acta*, **47**, 925–39.
- Inger, S. and Cliff, R.A. (1993) More precise dating of tectonometamorphic evolution in the Eastern Alps: Rb-Sr white mica and U-Pb sphene & allanite ages from the Tauern Window. *Terra*, **5**, 388.
- Liou, J.G., Wang, Q., Zhang, R.Y., Zhai, M. and Cong, B. (1995) Ultrahigh-P metamorphic rocks and their associated lithologies from the Dabie Mountain. *Chinese Sci. Bull.*, Supplement, 1–17.
- Liou, J.G., Zhang, R.Y., Wang, X., Eide, E.A., Ernst, W.G. and Maruyama, S. (1996) Metamorphism and tectonics of high-pressure and ultra-high-pressure belts in the Dabie-Sulu region, China. In: *The Tectonic Evolution of Asia* (A. Yin and M.T. Harrison, eds), Cambridge University Press, 300–44.
- Okay, A.I., Xu, S. and Sengor, A.M.C. (1989) Coesite from the Dabie Shan eclogites, central China. *Eur. J. Mineral.*, **1**, 595–8.
- Okay, A.I. (1993) Petrology of a diamond and coesite-bearing metamorphic terrain: Dabie Shan, China. *Eur. J. Mineral.*, **5**, 659–73.
- Okay, A.I., Sengor, A.M.C. and Satn, M. (1993) Tectonics of an ultrahigh-pressure metamorphic terrane: The Dabie Shan/Tongbai Shan orogen, China. *Tectonics*, **12**, 1320–34.
- Pan, Y. and Fleet, M.E. (1990) Halogen-bearing allanite from the White River gold occurrence, Hemlo area, Ontario. *Canad. Mineral.*, **28**, 67–75.
- Pavelescu, L. and Pavelescu, M. (1972) Study of some allanites and monazites from the south Carpathian (Romania). *Tschermaks. Mineral. Petrol. Mitt., Ser. 3*, **17**, 208–14.
- Rowley, D.B., Xue, F., Tucker, R.D., Peng, Z.X., Baker, J. and Davis, A. (1997) Ages of ultrahigh pressure metamorphism and protolith orthogneisses from the eastern Dabie Shan: U/Pb zircon geochronology. *Earth Planet. Sci. Lett.*, **151**, 191–203.
- Sakai, C., Higashino, T. and Enami, M. (1984) REE-bearing epidote from Sanbagawa pelitic schists, central Shikoku, Japan. *Geochem. J.*, **18**, 45–53.
- Sawka, W.N. (1988) REE and trace element variations in accessory minerals and hornblende from the strongly zoned McMurry Meadows pluton, California. *Trans. Royal Soc. Edinb.: Earth Sci.*, **79**, 157–68.
- Schmidt, M.W. (1992) Amphibole composition in tonalite as a function of pressure: An experimental calibration of the Al-in-hornblende barometer. *Contrib. Mineral. Petrol.*, **110**, 304–10.
- Sorensen, S.S. (1991) Petrogenetic significance of zoned allanite in garnet amphibolites from a paleo-subduction zone: Catalina schist, southern California. *Amer. Mineral.*, **76**, 589–601.
- Wang, X. and Liou, J.G. (1991) Regional ultrahigh-pressure coesite-bearing eclogitic terrane in central China: Evidence from country rocks, gneiss, marble, and metapelite. *Geology*, **19**, 933–6.
- Wang, X., Liou, J.G. and Mao, H.K. (1989) Coesite-bearing eclogites from the Dabie Mountains in central China. *Geology*, **17**, 1085–8.
- Xu, S., Liu, Y., Jiang, L., Su, W. and Ji, S. (1994) *Tectonic Regime and Evolution of Dabie Mountains*. Science Press, Beijing (in Chinese).
- Xu, Z. (1987) Etude tectonique et microtectonique de la chaîne paléozoïque et triasique des Qinlings (Chine). These de doctorat, Univ. Sci. Tech. Languedoc, Montpellier, France.
- You, Z., Han, Y., Yang, W., Zhang, Z., Wei, B. and Liu, R. (1996) *The High-pressure and Ultra-high-pressure Metamorphic Belt in the East Qinling and Dabie Mountains, China*. China University of Geosciences Press, Wuhan.

[Manuscript received 1 June 1998;
revised 27 October 1998]