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Isotope zonation in basement crustal blocks of southeastern China: Evidence for multiple terrane amalgamation

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Nd and Sr isotopic data for Mesozoic Yanshanian granites sampled across major NNE-trending faults in eastern Guangdong Province record conspicuous compositional variations in the crustal basement. Two principal crustal domains can be distinguished: Paleoproterozoic-dominated in the northwest and Mesoproterozoic-dominated in the southeast. Within the Mesoproterozoic-dominated domains, thin tectonic slivers of isotopically homogeneous Paleoproterozoic crust are interspersed with narrow belts displaying mantle-derived characteristics. Combined with other published data, the Nd-Sr isotopic signatures from eastern Guangdong show that the Precambrian basement in southeastern China is largely heterogeneous and made up of a series of narrow, crustal slices. The major domain boundaries coincide with large-scale NNE-trending strike-slip faults in the cover sequences. We postulate that these boundaries developed in the crust during the Mesoproterozoic and largely controlled the geological development of SE China throughout the Phanerozoic.

Introduction

SE China is composed of two major tectonic crustal blocks: the Yangtze Block in the north and the Cathaysia (or Huanan) Block in the south (Figure 1). The Yangtze Block is widely recognised as a cratonic shield area whereas the Cathaysia Block is made up of several mobile belts, including a broad (400 km) NE-trending belt of Mesozoic intrusions extending through the maritime provinces of Guangdong, Fujian and Zhejiang (Figure 1). Considerable debate has centred on the age of the basement of the Cathaysia Block, its tectonic evolution (Hsü et al., 1988, 1990; Li, 1997, and references therein), and the timing of its collision with the Yangtze Block. Although strongly overprinted by Phanerozoic tectonomagmatic activity, the

Cathaysia Block is commonly assumed to be underlain by Paleo- to Mesoproterozoic continental crust (Jahn et al., 1990; Li et al., 1992; Li, 1994; Li, 1998; Chen and Jahn, 1998). Since exposures of Precambrian crystalline rocks in southeastern China are rare, the best way to study the basement structure is through isotopic studies of granitoid rocks which preserve signatures of their source areas.

Previous isotopic investigations of Mesozoic magmatic rocks in the coastal region of SE China have demonstrated the existence in some areas of isotopic inhomogeneity in the crustal basement (Huang et al., 1986; Huang and DePaolo, 1989; Pei and Hong, 1995). In one of the few documented regional Nd-Sr studies, Huang et al. (1986) distinguished three isotopic zones within Cretaceous magmatic rocks from Fujian Province: an inland zone with $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.711$ to 0.737 and $\epsilon_{\text{Nd}}(T) = -8.2$ to -12.2 , a central zone with $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.706$ to 0.713 and $\epsilon_{\text{Nd}}(T) = -2.1$ to -11 , and a coastal zone with $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7058$ to 0.7073 and $\epsilon_{\text{Nd}}(T) = -1.7$ to -3.6 . They considered that the general trend of higher ϵ_{Nd} and lower initial Sr ratio from the inland area to the coast could be explained by

Figure 1 Generalised map of southeastern China showing the main tectonic elements and location of the study area. Isotope data from Huang et al. (1986). CNF = Changle-Nan'ao Fault, HF = Heyuan Fault, LZF = Lianhuashan Fault Zone, LHF = Lishui-Haifeng Fault, SF = Shenzhen Fault.

an increasing mantle influence. This is consistent with a widely held view that late Mesozoic intrusive activity was related to westerly subduction of the paleo-Pacific plate beneath the Asian continent; a tectonic event known as the Yanshanian Orogeny (190–80 Ma, Jahn et al., 1976; Yang et al., 1986). Somewhat more controversial has been the suggestion by Huang et al. (1986) that the boundary between the inland and central zones approximates the eastern limit of Precambrian crystalline basement. This interpretation has been challenged by Gilder et al. (1995) who argued that the published mean depleted-mantle (T_{DM}) model ages from the region agree within error (1σ), thereby implying that the basement materials are isotopically homogeneous. Variations in isotopic signatures from inland areas to the coast are inferred by these authors to be controlled by late Mesozoic subduction processes.

A characteristic feature of the Cathaysia Block is the presence of several large-scale NNE-trending faults. These are represented by ductile shear zones and are commonly associated with small, fault-bounded Cretaceous-Tertiary depositional basins. Two of these major faults have been considered as surface expressions of deep-seated sutures: the Changle-Nan'ao Fault separating metamorphosed early Paleozoic volcanic arc assemblages in the east from the Mesozoic igneous province in the west (Guo et al., 1989; Gao and Huang, 1991), and the Lianhuashan Fault Zone (Chen, 1987) which parallels the continental margin from just south of Shanghai to Hong Kong (Figure 2). Recent isotopic evidence suggests that these faults may coincide with deep crustal boundaries. For example, Zhou et al. (1996) position a deep crustal boundary between the central and coastal zones of Huang et al. (1986) which is coincident with the

Changl-Nan'ao Fault, whereas Pei and Hong (1995) define a 0.708 Sr_i isoline extending from Zhejiang, through Fujian to eastern Guangdong, which coincides with the Heyuan Fault. In a Nd-Sr isotope study of granites in the Hong Kong region, Darbyshire and Sewell (1997) have suggested that the NNE-trending Lianhuashan Fault Zone (LFZ) may also mark an important deep crustal boundary. This 30 km-wide zone is bounded by two major NNE-trending faults: the Shenzhen Fault in the north and the Lishui-Haifeng Fault in the south. Granites in the northwestern part of Hong Kong are characterised by $\epsilon_{Nd}(T) < -9$, T_{DM} between 1.67 and 2.02 Ga, and $^{87}Sr/^{86}Sr_i > 0.710$, whereas in the southeast they have $\epsilon_{Nd}(T)$ between -5.5 and -6.5 , T_{DM} between 1.39 and 1.47 Ga and $^{87}Sr/^{86}Sr_i$ 0.7071–0.7109. The variation in isotopic signatures and T_{DM} model ages reflects the interaction of mantle-derived melts with two distinct crustal sources. Paleoproterozoic and Mesoproterozoic crustal signatures in the granites have been recently confirmed by zircon inheritance studies (Davis et al., 1997). The oldest precise upper intercept age of 2714 ± 4 Ma from inherited components suggests that an Archean contribution cannot be entirely excluded. New geophysical evidence (Fletcher et al., 1997) supports the presence of a NNE-trending deep crustal discontinuity through the Hong Kong region.

The available data suggest that the crustal basement in SE China is isotopically heterogeneous and that major NNE-trending faults may delineate important tectonic boundaries. We further investigate these hypotheses by presenting the results of a Nd and Sr isotope transect across major NNE-trending fault zones in eastern Guangdong.

Eastern Guangdong traverse

Mesozoic plutonic rocks in SE China belong to a broad (400 km) NE-trending belt of intrusives comprising dominantly I-type granites, although A-type granites have been reported from the coastal areas (e.g., Martin et al., 1991, 1994; Charoy and Raimbault, 1994). The granitoids are generally assigned to five main Yanshanian episodes: 195 ± 5 Ma, 170 ± 5 Ma, 155 ± 5 Ma, 137 ± 5 Ma and 100 ± 5 Ma (BGMGRP, 1988). High precision U-Pb zircon age-dating of granitic rocks in Hong Kong (Davis et al., 1997) has revealed four principal Middle Jurassic to Early Cretaceous magmatic events in southern Guangdong: 164.6 ± 0.2 Ma, 146.6 ± 0.2 Ma, 142.8 ± 0.2 Ma and 140.8 ± 0.2 Ma. These ages, together with whole-rock geochemistry (Sewell and Campbell, 1997), provide a useful framework for calibrating the data from eastern Guangdong, particularly where precise ages of middle Yanshanian granites are unknown (see below).

Twenty-one granite samples from four structural zones were collected across a 200 km transect beginning west of the Heyuan Fault and extending to east of the Chao'an-Puning Fault (Figure 2). The samples were analyzed for major and trace elements, and Nd and Sr isotopes. Isotopic data are presented in Table 1.

$\epsilon_{Nd}(T)$, $^{87}Sr/^{86}Sr_i$ values and T_{DM} have been calculated according to the method described in Darbyshire and Sewell (1997). This involves using a Sm/Nd ratio which is dependent on crustal age. Where possible,

Figure 2 Simplified basement terrane and structural map of eastern Guangdong Province showing the location of sample sites, distribution of Paleoproterozoic- and Mesoproterozoic-dominated crustal domains, distribution of Cretaceous-Tertiary sedimentary basins, zones of mantle-influenced crust, and location of major deep fault systems. Circled numbers refer to the four main structural zones for which averaged values of T_{DM} and $\epsilon_{Nd}(T)$ are given. Data for Hong Kong from Darbyshire and Sewell (1997). Reference numbers for sample sites as for Table 1. CPF=Chao'an-Puning Fault, SHF=Shantou-Heilei Fault.

Table 1 Rb-Sr and Sm-Nd data

Zone	Description	Ref. No.	Sample No.	Lat. °N	Long. °E	Age ¹ (Ma)	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	Sm (ppm)	Nd (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	ε _{Nd} (T)	⁸⁷ Sr/ ⁸⁶ Sr _i	T _{DM} (Ga)
I	Biotite Granite	18	X167	23°52'	114°47'	164	378	83	13.15	0.74011	7.50	40.54	0.1119	0.51212	-8.3	0.70945	1.61
I	Biotite Granite	19	X168	23°55'	114°49'	157 ^b	556	70	23.13	0.76072	7.92	35.14	0.1363	0.51217	-7.9	0.70909	1.58
I	Biotite Granite	20	X169	24°08'	115°02'	164	425	65	18.86	0.75053	9.13	37.85	0.1458	0.51214	-8.7	0.70656	1.64
I	Biotite Granite	21	X170	24°06'	115°12'	164	263	579	1.317	0.71901	13.2	81.11	0.0985	0.51198	-10.8	0.71594	1.78
II	Microgranite	16	X165	23°41'	115°01'	148 ^a	326	112	8.42	0.72607	3.82	14.72	0.1569	0.51237	-4.5	0.70837	1.33
II	Biotite Granite	17	X166	23°42'	115°00'	148 ^a	295	193	4.43	0.71768	3.61	15.55	0.1405	0.51233	-4.9	0.70835	1.36
II	Biotite Granite	12	X161	23°38'	115°25'	120 ^a	257	79	13.06	0.72942	14.2	81.89	0.1046	0.51244	-2.5	0.70714	1.15
II	Biotite Granite	13	X162	23°41'	115°41'	120 ^a	518	22	67.65	0.82161	4.28	23.02	0.1125	0.51253	-0.8	0.70623	1.02
II	Granodiorite	14	X163	23°38'	115°12'	164 ^b	201	228	2.55	0.71500	5.01	24.74	0.1226	0.51219	-7.2	0.70905	1.54
III	Biotite Granite	15	X164	23°40'	115°10'	148 ^a	383	35	31.98	0.77373	5.30	19.68	0.1628	0.51222	-7.5	0.70646	1.55
III	Microdiorite	5	X152	23°35'	115°42'	142	42	593	0.203	0.70660	7.09	37.02	0.1158	0.51244	-2.4	0.70619	1.16
IV	Qtz Monzonite	6	X155	23°36'	115°41'	142 ^b	162	301	1.555	0.70887	11.2	61.23	0.1107	0.51237	-3.7	0.70573	1.26
IV	Biotite Granite	3	X150	23°23'	115°55'	142	241	194	3.60	0.71218	6.11	36.36	0.1015	0.51239	-3.1	0.70490	1.22
IV	Biotite Granite	4	X151	23°23'	115°55'	142	259	184	4.07	0.71308	6.56	35.52	0.1116	0.51243	-2.5	0.70487	1.17
IV	Biotite Granite	7	X156	23°26'	115°51'	142	243	210	3.35	0.71316	7.56	40.08	0.1140	0.51234	-4.3	0.70640	1.31
IV	Biotite Granite	8	X157	23°34'	116°03'	164	179	118	4.38	0.71689	6.99	38.67	0.1093	0.51218	-7.1	0.70668	1.53
IV	Biotite Granite	10	X159	22°48'	115°21'	164	339	58	16.93	0.74421	7.22	33.38	0.1307	0.51210	-9.1	0.70474	1.67
IV	Quartz Porphyry	1	X148	23°16'	116°33'	142	278	47	17.12	0.74312	5.72	15.73	0.2197	0.51244	-4.3	0.70857	1.31
IV	Biotite Granite	2	X149	23°16'	116°33'	164	264	191	4.00	0.71671	8.58	42.76	0.1213	0.51220	-7.0	0.70739	1.52
IV	Biotite Granite	9	X158	23°24'	116°15'	142	289	115	7.27	0.71847	7.66	29.90	0.1548	0.51240	-3.9	0.70379	1.28
IV	Biotite Granite	11	X160	23°25'	116°37'	130 ^a	203	124	4.74	0.71200	3.79	19.85	0.1155	0.51245	-2.3	0.70324	1.14

Notes: 1 ¹ – Ages estimated according to geochemical comparison with Hong Kong data unless otherwise indicated.

2 ε_{Nd} calculated relative to a chondritic reservoir with ¹⁴³Nd/¹⁴⁴Nd of 0.512638 and ¹⁴⁷Sm/¹⁴⁴Nd of 0.1967.

3 T_{DM} Nd model ages calculated according to a 2-stage model (after Borg, et al., 1990; DePaolo, et al., 1991).

4 Sample ratios adjusted to Nd and Sr standards run with each batch of measurements (La Jolla Nd=0.511858, NBS987 Sr=0.710251).

5 ^a – BGMRGP data (1988).

6 ^b – HKU Unpublished data.

crustal ages for the granites have been assigned according to published radiometric ages in the Chinese literature. However, where these data are not available, intrusive ages are based on correlation with the Hong Kong data.

On a TiO₂ versus Zr diagram (Figure 3), the analyzed middle Yanshanian samples from eastern Guangdong generally fall into two age categories defined by the Hong Kong data: c.164 Ma and c.142 Ma. The TiO₂ versus Zr diagram has been found to be an extremely useful plot for discriminating the major episodes of Middle Jurassic to Early Cretaceous magmatism in Hong Kong (Campbell & Sewell, 1997). Concentrations of Zr and Ti are abundant in the analyzed samples and both elements have low susceptibility to mobility during alteration. Each group of volcanic and plutonic rocks has a characteristic Zr/TiO₂ ratio, and the general pattern of magmatic evolution is for the least-evolved compositions of each group to become more Zr-enriched and TiO₂-depleted with time. The variation in the initial Zr/TiO₂ ratios of each group is considered to reflect heterogeneities in the source region. Separate batches of magma generated in the Hong Kong region at 164–159 Ma, 146 Ma, 142 Ma and 140 Ma are thought to have been derived from variable degrees of partial melting of crustal material involving a mantle-derived component (Sewell & Campbell, 1997).

As an independent check on the reliability of using the TiO₂ versus Zr plot to infer the intrusive ages of granites in eastern Guangdong Province, three samples from separate structural zones were dated by U–Pb single zircon techniques (HKU, unpublished data). These revealed ages of 164.2 ± 0.4 Ma, 156.9 ± 0.4 Ma and 141.8 ± 0.4 Ma in general accord with the Hong Kong groupings, although there is evidence for slight regional variation in the timing of magmatic activity. As with the Hong Kong data (Davis et al., 1997), Pre-

cambrian inheritance was also found to affect the ages of granitoids in eastern Guangdong, indicating the presence of late Archean and Proterozoic components in the source regions of these magmas.

Isotope results

Averaged values for ε_{Nd}, T_{DM} and ⁸⁷Sr/⁸⁶Sr_i from each of the four zones are shown on Figure 2. Granites from Zone I west of the Heyuan Fault are all of middle Yanshanian age. On a TiO₂ versus Zr diagram, they plot in the field for Hong Kong granites dated at 164 Ma (Figure 3). ε_{Nd}(T) values vary between –7.9 and –10.8, whereas ⁸⁷Sr/⁸⁶Sr_i lie between 0.70656 and 0.71594 and T_{DM} are in the range 1.58 to 1.78 Ga. Six granite samples from Zone II vary from Late Jurassic (148 Ma) to Early Cretaceous (120 Ma) age and show markedly higher ε_{Nd} values (–7.5 to –0.8) than Zone I, along with lower overall initial Sr ratios (0.70905 to 0.70623), and lower depleted–mantle model ages (1.55 to 1.02 Ga). Two granite samples from Zone III between the Shenzhen and Lishui–Haifeng faults have distinctly lower ε_{Nd}(T) (–3.7 to –2.4) and T_{DM} (1.26 to 1.16 Ga). On a TiO₂ versus Zr diagram, these granites plot with Hong Kong granites dated at 142 Ma (Figure 3). Zone III corresponds to the Lianhuashan Fault Zone from which highly variable isotope values are known (Darbyshire and Sewell, 1997). Granites in Zone IV between the Lishui–Haifeng and Shantou–Heilei faults have ε_{Nd}(T) values in the range –9.1 to –2.3, initial Sr ratios between 0.70857 and 0.70324, and T_{DM} between 1.67 and 1.14. On a TiO₂ versus Zr diagram, these granites plot with Hong Kong granites which have been dated at 164 Ma and 142 Ma.

Figure 3 TiO_2 versus Zr diagram for analyzed samples showing the field boundaries for Middle Jurassic and Lower Cretaceous granites from Hong Kong. Open square=Jurassic granites, Open triangles=Cretaceous granites.

Discussion

The NE-trending isotopic zonation of the crustal basement of SE China suggests that at least four predominantly Paleoproterozoic and Mesoproterozoic crustal domains occur beneath the Neoproterozoic and Phanerozoic cover sequences. The boundaries to these isotopic zones are coincident with major faults that can be traced throughout the coastal provinces. The isotopic signatures and T_{DM} model ages of Zone I to the northwest of the Heyuan Fault, are compatible with a model of crustal anatexis involving a predominantly Paleoproterozoic protolith but with significant input of Mesoproterozoic crust to these melts. This crustal basement probably forms part of the Paleoproterozoic core to the Cathaysia Block. To the southeast, Zone II lies between the Heyuan and Shenzhen faults. This zone is between 60 and 90 km wide and is underlain by predominantly Mesoproterozoic crust although a Paleoproterozoic component cannot be ruled out. However, along its southeastern boundary the Mesozoic granites have strongly mantle-influenced signatures. Zone III is coincident with the Lianhuashan Fault Zone which is up to 30 km wide and bounded by the Shenzhen and Haifeng faults. The isotopic zonation within the Lianhuashan Fault Zone is well-documented in Hong Kong (Darbyshire and Sewell, 1997), with predominantly Paleoproterozoic signatures to the northwest and more mafic Mesoproterozoic components towards the southeast. In addition, mantle-derived magmas define a narrow SE-trending belt in the central part of the fault zone (Figure 3). Similar mantle-influenced isotopic values have been found in the central part of the Lianhuashan Fault Zone along the Guangdong traverse. Zone IV displays an average Mesoproterozoic signature with minimal mantle influence. However, isolated samples from Zone IV have produced both Paleoproterozoic and mantle isotopic values.

No general trend of increasing mantle component towards the southeast, as suggested by Gilder et al. (1995), has been identified, either in the detailed survey of Hong Kong or in the Guangdong traverse. Rather, the mantle-influenced samples occur in narrow belts, some of which lie close to the main zonal boundaries. The lateral continuity of mantle-derived magmas within the Lianhuashan Fault

Zone would strongly suggest the presence of a deep, SE-trending, crustal discontinuity. But it is still too early to identify the regional significance of other mantle-derived samples.

Conclusions

The isotopic signatures of the Mesozoic granites of southeastern China would strongly indicate that the Precambrian basement is heterogeneous and made up of a series of Paleoproterozoic- and Mesoproterozoic-dominated crustal domains interspersed with a few narrow belts displaying mantle-derived characteristics. However, detailed sampling in Hong Kong has shown that within these domains the truly isotopically homogeneous subzones may be as narrow as 20 km. Thus, it is probable that the Paleoproterozoic signatures yielded by some samples in Zones II and IV, which are characterised by Mesoproterozoic-derived magmas, relate to narrow tectonic slivers of Paleoproterozoic crust. Although it would be tempting to designate the four isotopic zones as tectonic terranes, the current data would indicate that the composition of the crust is much more complicated, and isotopically homogeneous segments may be extremely narrow.

The nature of the zonal boundaries is still uncertain, but they are coincident with major fault zones in the cover sequences. It is postulated that the boundaries developed in the crust during the Mesoproterozoic and could represent subduction zones, major strike slip faults, or the margins of greenstone belts. However, once formed, they largely controlled the geological development of SE China throughout the Phanerozoic.

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