Early Archean inheritance in zircon from Mesozoic Dalongshan granitoids in the Yangtze Foldbelt of Southeast China

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Zircon U-Pb isotopic data on the early Cretaceous Dalongshan granitoids in the Yangtze Foldbelt of Southeast China provides evidence for the incorporation of old Archean crustal material. The age of inherited radiogenic lead is determined by the three-dimensional U-Pb discordia plane method to be about 3330 ± 180 Ma, indicating that the early Archean basement probably exists underneath the northwest part of the Yangtze Foldbelt. The nature of the source region of initial lead in the zircon demands that the Archean basement is responsible for a lower crust or a depleted mantle.

INTRODUCTION

U-Pb zircon geochronology on young granitoids has often revealed the contribution of an old crustal component to the origin of the granitoids. There are many examples of intrusive granitoids containing old inherited radiogenic Pb in zircons which show an incomplete resetting of the U-Pb systems during melting event. These include the Vire-Carolles granite from Normandy (Pastells, 1970), the Bergell granite from the southern Alps (Gulson and Krogh, 1973), the Idaho batholith (Grauert and Hofmann, 1973), the Labrador adamellites (Krogh and Davis, 1973), a number of Caledonian granites from Scotland and England (Pidgeon and Johnson, 1974; Pankhurst and Pidgeon, 1976; Pidgeon and Aftalion, 1978), the western Calicia granites from NW Spain (Kuijper *et al.*, 1982), the Palung granite from Himalaya (Schärer and Allégre, 1983), the Tera and Finister granodiorites from the Berridale

Batholith (Williams *et al.*, 1983), the Coast granitoids from Peninsular Malaysia (Liew and McCulloch, 1985), the Berkshire granite from the Connecticut (Zartman *et al.*, 1986), the Narragansett Pier granite from New England (Zartman and Hermes, 1987), and the Tertiary granite from the Himalaya (Copeland *et al.*, 1988). Even zircons from volcanics were detected to contain the inherited radiogenic Pb signature (e.g., Peucat *et al.*, 1986).

The presence of the inherited radiogenic Pb in zircons is evidence that old crustal components have been incorporated into young granitoid magmas. In cases where the source zircons have not suffered extensive pre- and post-emplacement Pb loss, inheritance ages allow to estimate the ages of the zircon-bearing protoliths of the young granitoids. In this context, the determination of inheritance ages can shed light on the growth and evolution of continental crust. There is substantial evidence for the episodic growth of continental crust. The ques-

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tions are when the crustal addition was made in a given region and how much new crust was formed during each episode. The present study presents U-Pb isotopic data for zircons from the early Cretaceous Dalongshan granitoid massif in the Yangtze Foldbelt of Southeast China. An old Archean crustal material is indicated by zircon U-Pb inheritance age, implying that the early Archean basement probably exists in this region.

GEOLOGICAL SETTING

East China is divided into two large cratons: the Sino-Korean craton in the north and the Yangtze craton in the south (Zhang *et al.*, 1984). Archean basements have been documented to occur in the Sino-Korean craton (Jahn and Zhang, 1984; Liu *et al.*, 1985; Huang *et al.*, 1986; Jahn *et al.*, 1987; Liu *et al.*, 1989). The Yangtze craton has been dated to contain Proterozoic to late Archean basements (Zhu *et al.*, 1979; Chen *et al.*, 1985; Li *et al.* 1989).

Fig. 1. Sketch map showing locality of the Anqing City by the Yangtze River in Southeast China.

The Yangtze Foldbelt is between the Sino-Korean craton and the Yangtze craton and strikes northeast along the Yangtze River (Figs. 1 and 2). The Dalongshan granitoid massif of

Fig. 2. Schematic geological map of the Yangtze Foldbelt in southern Anhui Province showing the distributions of intermediate to acidic intrusions and Precambrian rocks (modified after Geochemical Institute of Academia Sinica, 1979). The stippled patterns indicate granitoid intrusions. The dashed lines indicate major faults: 1—the Tancheng-Lujiang Fault, 2—the Yangtze Fault, 3—the Guangde-Dexing Fault. The dotted line from the southwest (coincident with the Tancheng-Lujiang Fault) to the southeast represents the known limits of Archean and Proterozoic basements, respectively.

Fig. 3. Sketch map of the Dalongshan granitoid massif. 1—early stage quartz syenite, 2—late stage alkali-feldspar granite, 3—Jurassic feldspar-quartz sandstone, 4—Quaternary cover, 5—sampling site.

concern in the present study is located in the north of the Yangtze River. Tectonically it is located between the Tancheng-Lujiang Fault and the Yangtze Fault. The age of basements beneath the Yangtze Foldbelt is uncertain as the Archean occurs to the northwest and the Proterozoic to late Archean to the southeast. Mesozoic sedimentary and volcanic units are widespread in this Foldbelt.

The Dalongshan granitoid massif is located near Anqing City, Anhui Province (Fig. 2). It is a composite intrusion exposed over approximately 90 km² (Fig. 3). The magmas were emplaced into the Jurassic feldspar-quartz sandstones. The early stage intrusion was quartz syenites; these rocks were in turn intruded by a late stage alkali-feldspar granite. The detailed petrographic and geochemical characteristics of the granitoids have been described by Zhai (1985). Rb-Sr whole-rock dating shows that the quartz syenites have an isochron age of 136 ± 5 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7071 ± 0.0008 , and that the alkali-feldspar granite has an isochron age of 117 ± 4 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7082 ± 0.0011 (Zhang, 1988).

Inasmuch as the Dalongshan massif is associated with striking-slip faulting (anorogenic) and has alkaline geochemical features ($\text{Na}_2\text{O} + \text{K}_2\text{O} > 9\%$), Zhai (1985) identified the Dalongshan granitoids as the A-type granites as defined by Loiselle and Wones (1979). In the light of feldspar Pb isotope investigation Zhang (1988) suggested that a lower crustal material was involved in the genesis of the granitoids.

ANALYTICAL METHODS

The rock samples were collected from the late stage intrusion of the Dalongshan granitoids (Fig. 3). After crushing and grinding the samples, heavy minerals were separated using a Wilfley table, heavy liquid and magnetic methods. The recovered zircons were sieved into size fractions and split further according to their magnetic susceptibility. Seven zircon fractions were separated for the sample D103-2, in which fraction 7 has the same size and magnetic susceptibility as fraction 3. After hand picking under a binocular microscope to 99% purity, all separates were cleaned by repeated rinsing with

warm HNO₃, but fractions 1 to 6 of the sample D103-2 in an ultrasonic bath. The size fractions were then dissolved, and Pb and U were extracted following the methods described by Krogh (1973).

Pb isotopic ratios were measured on a MAT261 thermion mass spectrometer in Beijing Institute of Uranium Geology. All the Pb isotopic ratios have been normalized to the NBS SRM981 standard composition using a discrimination factor of 0.12% per mass unit. Correction for the laboratory Pb background effect differentiation were determined by the method reported by Li and Xu (1987). Uncertainties of $\pm 1.0\%$ and $\pm 0.1\%$ (1σ) are estimated for Pb/U and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios, respectively.

RESULTS

The results of ten zircon U–Pb isotopic analysis are given in Table 1. Uranium concentration is lower in the fraction of low magnetic susceptibility than that of high susceptibility. Additionally uranium concentration increases generally with decreasing grain size.

Minimum $^{206}\text{Pb}/^{204}\text{Pb}$ ratio for the investigated samples is as low as 46.262, indicating

that common (initial) lead component is appreciable and that errors due to uncertainty in correcting for it are significant. In general, for those samples with low $^{206}\text{Pb}/^{204}\text{Pb}$ ratio (e.g., < 100), knowledge of the common lead isotopic composition is critical, especially for $^{207}\text{Pb}/^{204}\text{Pb}$. The detection of inherited radiogenic lead in the U–Pb system of zircons is usually carried out with the aid of a Wetherill's (1956) concordia diagram. In this respect, the correction for the proper initial Pb isotope composition responsible for a previous event at time t_1 is of crucial importance in using the two-stage U–Pb episodic model for probing early events (Zheng, 1990). The U–Pb isotopic data for a suite of cogenetic samples may be corrected for any initial Pb isotopic composition other than that at time t_2 (later event). And the data may or may not form a linear array in the conventional concordia diagram. In most cases, the lower (younger) intersection age (t_2) is close to the true age of the last stage U–Pb episodic event. But whether the upper (older) intersection age (t_1) is realistic or not is subject to uncertainties of the correction for initial lead. To eliminate the effect of the unknown common lead correction, a three-dimensional U–Pb discordia plane method

Table 1. Zircon U–Pb isotopic data on the later stage intrusion of the Dalongshan granitoids in the Yangtze Foldbelt of South China

No.	Sample number	Fraction (mesh)	Concentration		Isotopic ratios				Model ages (Ma)*		
			U (ppm)	Pb (ppm)	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$	$\frac{^{235}\text{U}}{^{207}\text{Pb}}$	$\frac{^{204}\text{Pb}}{^{207}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$
1	D103-2	+140, low susceptib.	501.74	13.84	318.175	10.272	3.7716	0.032285	119	126	265
2	D103-2	+140, high	634.49	17.58	226.061	8.433	3.1885	0.037304	113	123	332
3	D103-2	–140, +180	520.21	13.32	725.775	12.381	4.6788	0.017060	119	148	637
4	D103-2	low –140, +180 high	708.95	19.80	241.943	8.419	3.1928	0.034797	113	137	571
5	D103-2	–180, +220 low	535.66	13.37	700.022	13.311	5.1194	0.019015	117	131	387
6	D103-2	–180, +220 high	704.37	20.14	229.358	8.498	3.1162	0.037053	116	130	386
7	D103-2	No. 3 but no ultrasonic bathing	608.69	31.94	62.062	3.264	0.8869	0.052600	120	191	1195
8	D029	+250	333	18.41	68.051	3.696	0.8769	0.054307	142	169	554
9	D041	+250	308	26.07	46.262	2.667	0.4879	0.057652	152	198	789
10	D014	+250	463	25.28	88.177	4.602	1.0934	0.052185	154	163	293

*calculated using the average isotope ratio of lead from feldspars in the Dalongshan granitoids for the correction of common lead: $^{206}\text{Pb}/^{204}\text{Pb} = 18.37$ and $^{207}\text{Pb}/^{204}\text{Pb} = 15.52$ (Zhang, 1988)

Fig. 4. Three-dimensional $^{206}\text{Pb}/^{207}\text{Pb}$ versus $^{235}\text{U}/^{207}\text{Pb}$ and $^{204}\text{Pb}/^{207}\text{Pb}$ plot for zircons from the late stage intrusion of the Dalongshan granitoids in the Yangtze Foldbelt of Southeast China.

described by Zheng (1990) is applied in this study. This method uses only the directly measured isotopic ratios $^{235}\text{U}/^{207}\text{Pb}$, $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{204}\text{Pb}/^{207}\text{Pb}$ to yield two ages t_1 and t_2 responsible for two episodic events. It does not require any knowledge of the isotopic ratios of initial lead for correction, provided that only one type of initial Pb isotope composition is justified for the investigated samples.

A least-squares fit to the data given in Table 1 yields the following parameters:

$$a = 1.9906 \pm 0.1094$$

$$b = 3.5660 \pm 0.2053$$

$$c = -32.20 \pm 3.28$$

$$t_1 = 3330 \pm 180 \text{ Ma}$$

$$t_2 = 112 \pm 6 \text{ Ma.}$$

The calculated coefficient of polycorrelation is 0.9971, indicating that the data points all fall on the fitted discordia plane within the estimated analytical errors. A modified discordia line is drawn by taking the $(^{206}\text{Pb}/^{207}\text{Pb}) - c(^{204}\text{Pb}/^{207}\text{Pb})$ for ordinate and the $^{235}\text{U}/^{207}\text{Pb}$ for abscissa respectively, as depicted in the right of Fig. 4; a lead-line is drawn in the left of Fig. 4, using the isotopic data uncorrected.

DISCUSSION

The good linear distribution of discordia data points in the right of Fig. 4 allows us to derive age information which has geological significance. The fractions 1, 3 and 5 with low magnetic susceptibility are closer to the upper (younger) intersection than the fractions 2, 4 and 6 with high susceptibility; the smaller the fraction with the low susceptibility, the closer to the younger intersection their U-Pb discordia data points. This can be attributed to the loss of inherited lead component caused by the ultrasonic bathing. The principal benefit of the ultrasonic bathing is that it induces a good linear distribution of discordia data points in the concordia diagram and therefore it enables us to derive age information of geochronological significance.

The obtained t_2 age is $112 \pm 6 \text{ Ma}$, which can be reasonably interpreted as the closure age of U-Pb isotopic system during crystallization of the late stage granitoid magma. This age is well comparable with the Rb-Sr isochron age of $117 \pm 4 \text{ Ma}$ for the late stage alkali-feldspar granite.

The t_1 age of $3330 \pm 180 \text{ Ma}$ may represent

the age of inherited radiogenic lead component in the zircons that has incorporated into the granitoid magma. This assumes that the discordia is an undisturbed mix of the inherited component with a young magmatic component at time ~ 112 Ma. In fact, model age pattern of $t(^{206}\text{Pb}/^{238}\text{U}) < t(^{207}\text{Pb}/^{235}\text{U}) < t(^{207}\text{Pb}/^{206}\text{Pb})$ in Table 1 and the lead-line with an intercept out of concordance in the left of Fig. 4 indicate the existence of inherited radiogenic lead in the zircons. The presence of inherited radiogenic lead component indicates that early Archean crustal material has been incorporated into the Mesozoic granitoids. Although the old component may have suffered Pb loss (or U gain) before it was incorporated into the magma, the good discordia plane is suggestive of that the t_1 age can provide a reliable age of the old lead component.

The basement of *ca.* 3330 Ma has been reported to exist in the Sino-Korean craton. Using the single zircon stepwise evaporation technique, Liu *et al.* (1989) acquired an U-Pb age of 3.3 Ga for a zircon sample from Archean gneiss in the craton. This age is the oldest zircon age so far found in China. The consistent Sm-Nd isochron ages of 3.5 Ga were obtained by Huang *et al.* (1986) and Jahn *et al.* (1987) for the Archean amphibolites from eastern Hebei Province within the craton. The present result indicates that the early Archean basement could be extended southwards to the northern part of the Yangtze Foldbelt adjacent to the Sino-Korean craton. Because the younger intersection age of the modified discordia from the present zircon U-Pb data is in good agreement with the whole-rock Rb-Sr isochron age of the same intrusion, we can consider the older intersection age of *ca.* 3330 Ma as the age of basement which could exist beneath the Yangtze Foldbelt.

The question of the origin of the inherited lead in the zircons is intimately related to the origin of the granitoids themselves. The old component could be derived from wallrocks stopped off during magma emplacement or they could have survived from the original source material of the granitoid magma. The proportion of the

old inherited lead in the zircons must be quite high to account for the spread of the discordia data points on the concordia plot. A high degree of assimilation can explain the observed zircon U-Pb systematics. However, the Dalongshan granitoids intrude into Mesozoic volcano-sedimentary rocks at shallow levels. This geological environment may not be favorable for the wall-rock assimilation at shallow depths, but partial melting or assimilation of deep Precambrian basement rocks can be considered as the source of the inherited radiogenic lead. The old lead could also be contained in old zircons which were abundantly present in the source region of the granitoid magma and were incorporated without complete dissolution during partial melting. In either case, the t_1 age of *ca.* 3330 Ma represents a real isotopic event and the old lead could have been derived from such a *ca.* 3.3 Ga old Archean basement.

The position of the zircon U-Pb data points on the discordia cannot be simply used to provide quantitative estimates of the proportion of old-inherited to newly-formed radiogenic lead component without taking into account: (1) the complexity of the inherited radiogenic lead, (2) the nature and degree of isotopic discordance sustained by the inherited lead before and during crystallization of the granitoid magma, and (3) the magnetic susceptibility of inherited zircon relative to newly-formed zircon to post granitoid isotopic disturbance.

Within the framework of a restricted U-Pb three-stage model (Ulrych, 1969), it is calculated that the investigated zircons have identical initial Pb isotope ratios $^{206}\text{Pb}/^{204}\text{Pb}=10.63$ and $^{207}\text{Pb}/^{204}\text{Pb}=12.01$ at time $t_1=3330$ Ma, and that original system had a $^{238}\text{U}/^{204}\text{Pb}$ ratio (μ_1 value) of 3.73 for time interval from t_0 to t_1 , given that we take the meteoritic parameters determined by Tatsumoto *et al.* (1973) for starting conditions (i.e., $\alpha_0=9.307$, $\beta_0=10.294$ and $t_0=4.57$ Ga). This calculation has to require that the early Archean basement originated from a primitive mantle with a μ value of about 3–4. Such a low μ value conflicts with the current knowledge of the primitive mantle μ values.

Alternatively, in view of the complex history experienced by the mantle before 4 Ga ago, an extended three-stage episodic model for U-Pb isotopic evolution may be more appropriate, in which case the starting parameters assigned by Zartman and Haines (1988) for Version IV of plumbotectonic model can be utilized (i.e., $\alpha_0=10.06$, $\beta_0=11.40$ and $t_0=4.2$ Ga). Then it is obtained that the initial Pb isotope ratios at time $t_1=3330$ Ma are $\alpha_1=10.62$ and $\beta_1=12.01$ and that the μ_1 value is 2.33.

In either case, the calculated initial Pb isotope ratios are identical and the μ_1 values are considerably low. The low μ_1 values require a U/Pb-depleted reservoir for the source region of the initial lead incorporated into the zircons at the time *ca.* 3.3 Ga. Lower crust (or depleted mantle) is a probable candidate for the reservoir because only it has μ values lower than both primitive mantle and upper crust (O'Nions *et al.*, 1979; Allgre *et al.*, 1988; Zartman and Haines, 1988). In term of a U-Pb budget for various terrestrial reservoirs Zindler and Hart (1986) have estimated a mean $\mu=3.8$ (range from 1 to 9) for the lower crust. The depletion of U in the lower crust relative to Pb and its concentration into the upper crust are well exemplified by the high-grade Archean metamorphic terranes (e.g., Moorbath *et al.*, 1969; Black *et al.*, 1971). Such internal differentiation of the continental crust has left the lower crust with U/Pb ratios lower than the upper crust and the primitive mantle. In addition, the lowest μ values measured on MORB glasses are about 5 (Cohen *et al.*, 1980). Neither seawater alteration nor partial melting can make μ values decrease (Allgre *et al.*, 1988). Therefore, the lower crust (or depleted mantle) could have μ values lower than 5 due to the U/Pb differentiation. Accordingly the lower crust (or depleted mantle) can be reasonably responsible for the U/Pb-depleted reservoir required by the isotopic composition of initial lead in the zircons. This argument is well comparable not only with the results from the feldspar Pb isotope data on the Dalongshan granitoids by Zhang (1988), but also with the positive $\epsilon_{Nd}(T)$ values of +2.7 to +3.3 for the Archean am-

phibolites from the eastern Hebei Province by Huang *et al.* (1986) and Jahn *et al.* (1987). Recent works on anorogenic granites suggest that they may form from primary magmas produced by partial melting of relatively anhydrous lower crustal source rocks (e.g., Barker *et al.*, 1975; Collins *et al.*, 1982; Anderson, 1983; Jackson *et al.*, 1984). Furthermore, if the formation of lower crust was related to the extraction of sialic upper crustal material from the primitive mantle, the U-Pb isotope data of the Dalongshan granitoids lend support to the assumption by Jahn *et al.* (1987) based on the Sm-Nd isotope data of the Archean amphibolites that the existence of the sialic crust can be looked back before 4 Ga ago.

The μ_2 values for time interval from t_1 and t_2 can be further calculated and U/Pb differentiation factor is then given by $f_1=\mu_1/\mu_2$ at t_1 and $f_2=\mu_2/\mu_3$ at t_2 (where μ_2 and μ_3 are responsible for the $^{238}\text{U}/^{204}\text{Pb}$ ratios at time t_2 and the present day, respectively). The obtained μ_2 values are 15–84, f_1 values are 0.03–0.25 and $f_2=0.0013$ –0.02 for the zircons from the Dalongshan granitoids, indicating an enrichment of uranium relative to lead at the two episodic events. The μ_2 values are so scattered that a Pb-Pb secondary isochron would not be yielded even if the lead isotope ratios are corrected back to those at time $t_2=112$ Ma.

CONCLUSIONS

Involvement of early Archean crustal material in the formation of the Mesozoic Dalongshan granitoids is indicated by the inherited radiogenic lead in zircons. The t_1 age of 3330 Ma defines the formation age of an old crust from which the inherited radiogenic lead was incorporated. This points to the presence of early Archean rocks at the depth at which the granitoid magma was derived or assimilated. The northern part of the Yangtze Foldbelt is probably underlain by the Archean basement, and Proterozoic basements occur in the southern part of this Foldbelt. The nature of the initial U-Pb isotope system in the zircons indicates that

the early Archean basement is responsible for the lower crust in this region.

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