PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Isotope Geochemistry of the 1985 Tibet Geotraverse, Lhasa to Golmud

N. B. W. Harris, Xu Ronghua, C. L. Lewis, C. J. Hawkesworth and Zhang Yuquan

Phil. Trans. R. Soc. Lond. A 1988 **327**, 263-285
doi: 10.1098/rsta.1988.0129

Phil. Trans. R. Soc. Lond. A **327**, 263–285 (1988) [263]
Printed in Great Britain

Isotope geochemistry of the 1985 Tibet Geotraverse, Lhasa to Golmud

By N. B. W. Harris[1], Xu Ronghua[2], C. L. Lewis[1], C. J. Hawkesworth[1] and Zhang Yuquan[3]

[1] *Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, U.K.*
[2] *Institute of Geology, Academia Sinica, P.O. Box 634, Beijing, People's Republic of China*
[3] *Institute of Geochemistry, Academia Sinica, Guizang, Guizhou, People's Republic of China*

Geochronological data from the Golmud–Lhasa section across the Tibetan Plateau indicate progressively younger periods of magmatism from north to south associated with successively younger ocean closures.

Pre-collision Eocene magmatism (50–40 Ma) exposed along the southern margin of the Lhasa Terrane in the Gangdise Belt resulted from anatexis of mid-Proterozoic crust (~ 1000 Ma) at depths greater than 10 km, but at higher crustal levels subduction-related intrusions were predominantly mantle-derived with ~ 30% crustal assimilation.

Intrusions from the northern Lhasa Terrane are early Cretaceous in age (130–110 Ma). These form a bimodal suite comprised of two-mica granites derived from anatexis of Mid-Proterozoic crust and of biotite-hornblende granodiorites from about 60% crustal assimilation by mantle magmas above a post-collision subduction zone. They place a minimum constraint on collision between the Lhasa and Qiangtang Terranes of 130 Ma.

Granite magmatism from the Kunlun Mountains is late Permian–early Jurassic in age (260–190 Ma). The Kunlun batholith represents reworked mid-Proterozoic crust (1400–1000 Ma) at an active continental margin from 260–240 Ma. Post-tectonic granites were emplaced in a post-collision setting (200–190 Ma). Collision between the Qiangtang and Kunlun Terranes is dated as end-Triassic.

Nd model ages of sediments from across the plateau record uplift and erosion of young source regions throughout the Phanerozoic confirming that the Tibetan Plateau is the site of multiple continental collision through time. Phanerozoic magmagenesis throughout the plateau requires considerable crustal reworking and limited crustal growth which suggests thickened continental crust in the region may predate the most recent Eocene collision.

1. Introduction

The Sino–British Geotraverse of Tibet identified at least three continental fragments which now comprise the Tibetan Plateau; the Lhasa, Qiangtang and Kunlun Terranes (Chang *et al.* 1986). The distribution of plutonic rocks throughout these terranes is described in detail in Harris, Xu, Lewis & Jin (this volume). They are concentrated in a Palaeogene belt from the southern Lhasa Terrane, a Cretaceous belt from the northern Lhasa Terrane and a late Permian–early Jurassic belt from the Kunlun Terrane. Isotopic studies from the geotraverse have concentrated firstly on the geochronology and petrogenesis of granitoids in these three belts, and secondly on the Nd isotope compositions of sediments from across the plateau in order to constrain periods of new crust formation and of crustal accretion (collision) from the Tibetan Plateau. This paper describes the geochronology and isotopic constraints on source characteristics of the three granitoid belts, in order of increasing age (from south to north).

Reconnaissance oxygen isotope data from the intrusions are also described. Nd isotopic data from clastic sediments are presented and integrated into a synthesis of the isotopic evolution of the Tibetan Plateau.

2. Paleogene magmatism of the southern Lhasa Terrane

(a) *Introduction*

The calc-alkaline magmatic province exposed along the southern margin of the Lhasa Terrane is part of the 3000 km Gangdise Belt within which four regions have been the subject of isotopic studies (figure 1): Kohistan, Ladakh, Kailas and the Lhasa–Zangbo traverse (see table 1 for references). The major and trace element geochemistry of granitic rocks from the belt support magmagenesis at an active continental margin above a northward-dipping subduction zone now represented by the Zangbo Suture. Published isotopic data (table 1) indicate that calc-alkaline magmatism occurred throughout the belt during the Paleogene (61–39 Ma), continuing at least with minor intrusions until 29 Ma. An earlier Cretaceous pulse (111–94 Ma) has been recorded in Kohistan, Ladakh and Dazhuka (150 km WSW of Lhasa). There is no indication that magmatism was diachronous along strike of the belt. Isotopic studies on the main Paleogene period of magmatism indicate a predominantly low Rb/Sr source (initial $^{87}Sr/^{86}Sr < 0.707$) in contrast to the initial $^{87}Sr/^{86}Sr$ of the crustally derived High Himalayan granites (> 0.74). Inherited lead from zircon studies of the Gangdise Belt (Scharer *et al.* 1984; Xu *et al.* 1985) indicates that a Precambrian crustal component was present in magmagenesis for intrusions from the Lhasa–Zangbo traverse. A crustal component is also indicated by both Pb–Pb systematics (Gariepy *et al.* 1985) and stable isotope studies of the belt (Blattner *et al.* 1983).

An important problem posed by the Lhasa–Yangbajain section sampled on the geotraverse is the present northern limit of Paleogene magmatism. Xu *et al.* (1985) noted the similarity of lead isotope characteristics between zircons from the Linzizong Formation, the Yangbajain granite and Nyainqentanglha orthogneisses, all of which indicate formation at 60–50 Ma with a much older (> 1000 Ma) inherited component. The geochemical similarities between the Quxu–Lhasa, Yangbajain and Nyainqentanglha intrusions have also been noted (Harris, Xu & Jin, this volume) and they are therefore considered together in this chapter.

A period of Neogene vulcanism (16–10 Ma) has been recorded from a $^{39}Ar/^{40}Ar$ study of ignimbrites west of Yangbajain (Coulon *et al.* 1986). This coincides with a period of aplites and subalkaline granites (15–9 Ma) recorded in the Karakoram (Debon *et al.* 1987). The Yangbajain pyroclastics are high K calc-alkaline in composition and are geochemically quite distinct from the Paleogene intrusives. Whereas Cretaceous and Eocene magmatism is interpreted as related to subduction processes, the Neogene phase is post-collisional and extensional in nature (Coulon *et al.* 1986).

(b) Sr–Nd *systematics*

For granite rocks the initial $^{87}Sr/^{86}Sr$ of a whole rock isochron is that of the emplaced magmas, which may in turn be used to infer the age or the Rb/Sr ratio of the source from which the granites were derived. Similarly the initial $^{143}Nd/^{144}Nd$ values are the Nd-isotope ratios of the granites at the time of emplacement, and they may be used to estimate the age or Sm/Nd ratios of their source regions. Crustal-derived granites and sediments appear to have Sm/Nd

Table 1. Published isotope data from the Gangdise Belt

	U–Pb zircon (Ma)	Rb–Sr (Ma)	Isochron	$^{39}Ar/^{40}Ar$ (Ma)	Ref
Karakorum					
Granite	—	111±6	0.7044±1		Debon *et al.* 1987
		59±2	0.7042±3		—
		43±3	0.7056±3		—
Granodiorite	95±6	97±17	0.7097±1		—
Granite	—	54±4	0.7041±1		Petterson & Windley 1985
Granodiorite	—	40±6	0.7044±1		
Tonalite	—	102±12	0.7039±1		—
Aplite	—	34±16	0.7045±1		—
		29±8	0.7052±1		—
Granite	—	—	—	19–56	Casnedi *et al.* 1978
Ladakh					
Granite	60.7±0.4	—	—		Scharer *et al.* 1983
Granodiorite	101±2	—	—		—
Granite	—	60±10	0.7048±5		Honnegar *et al.* 1982
Granodiorite	—	~ 51	~ 0.7050		Allègre & Ben Othman 1980
Kailas					
Granite	—	39±1	0.7061±2		Honnegar *et al.* 1982
Dazhuka					
Diorite	93.4±1.0	—	—		Scharer *et al.* 1984
	94.2±1.0	—	—		—
	—	—	—	90–110	Maluski *et al.* 1982
Quxu					
Granite	41.4±0.4	—	—		Scharer *et al.* 1984
	41.7±0.4	—	—		—
	—	44±14	0.7067±4		Debon *et al.* 1982
	—	46±8	0.7065±2		—
Lhasa					
Granite	~ 53	—	—		Scharer *et al.* 1984
		56±10	~ 0.7057		Xu & Jin 1984
Linzizong					
Ignimbrite	56±1	—	—		Xu *et al.* 1985
—				60	Maluski *et al.* 1982
Andesite	—	—	—	49–51	Coulon *et al.* 1986
Yangbajain					
Granite	—	47±3	0.7071±1		Debon *et al.* 1982
Migmatite	~ 50	—	—		Xu *et al.* 1985
Maquiang					
Ignimbrites	—	—	—	10–16	Coulon *et al.* 1986
Nyainqentanglha					
Gneiss	~ 50	—	—		Xu *et al.* 1985

ratios broadly similar to those of their crustal source regions, so that Sm–Nd isotope data can be used to estimate the age of crustal source rocks, which in turn allows the Rb/Sr ratio of the source to be calculated. It must be emphasized, however, that both granites and sediments are often mixtures of material from more than one source, whereupon the inferred source ages and trace element ratios will be just weighted averages of those different sources.

Initial Sr- and Nd-isotope results may be plotted together on an $\varepsilon_{Nd}(T)$–$\varepsilon_{Sr}(T)$ diagram, in which those data are expressed relative to the isotope ratios of the bulk earth at the same time. In general igneous rocks derived directly from the upper mantle, or from very young crust, tend

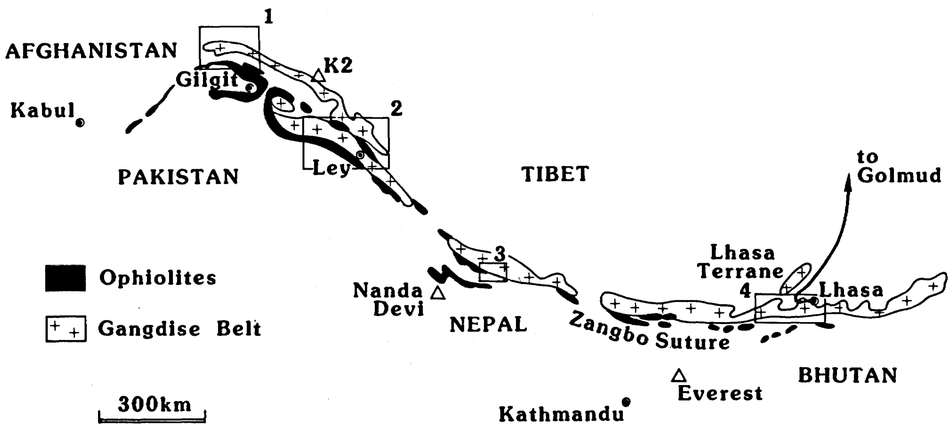

FIGURE 1. Sketch map of distribution of granitoids from the Gangdise Belt intruded north of the Zangbo Suture. Localities of published isotopic data (see table 1); 1 Karakoram and northern Kohistan, 2 Ladakh, 3 Kailas, 4 Lhasa-Zangbo traverse.

to plot in the upper quadrants (positive ε_{Nd}), sometimes slightly to the right of the so-called mantle array as seen in the field for Pan-African granites from Arabia (figure 2). Older crust plots in the lower (negative ε_{Nd}) quadrants, and so granites derived from, or simply containing more older crustal material will be displaced to lower ε_{Nd}. Moreover, since the upper crust is characterized by relatively high Rb/Sr, with time it also has relatively high $^{87}Sr/^{86}Sr$, so that S-type granites, for example, have low ε_{Nd} and relatively high ε_{Sr} (figure 2). Thus, a Himalayan leucogranite with $\varepsilon_{Sr} = +480$ and $\varepsilon_{Nd} = -16$ (Allègre & Ben Othman 1980), was probably

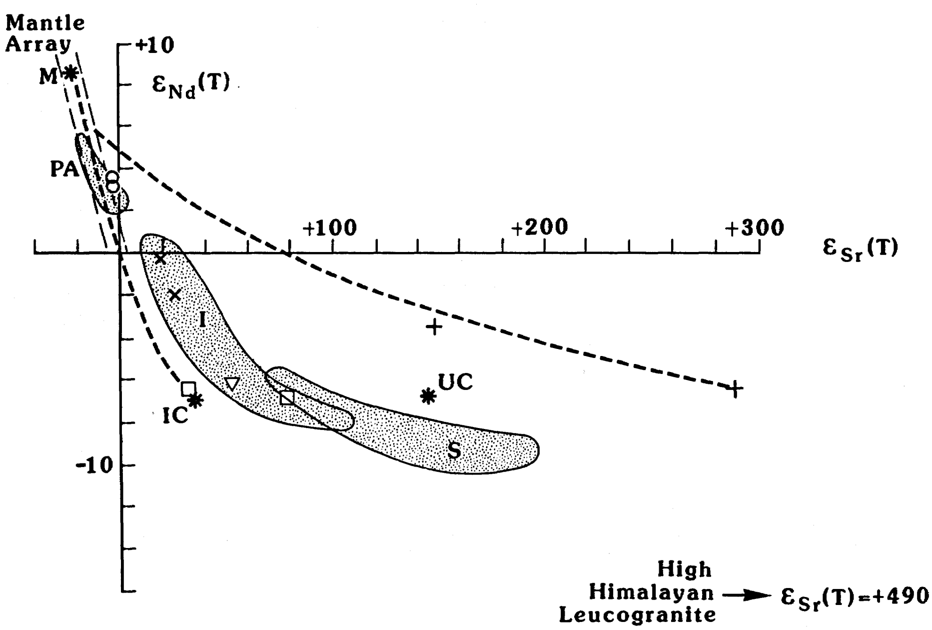

FIGURE 2. $\varepsilon_{Sr}(T)$–$\varepsilon_{Nd}(T)$ plot for samples from Lhasa Terrane; Gangdise Belt (○), Nyainqentanglha (□), Baingoin (▽), Mo Tian Ling (×) and Amdo Basement (+). PA = Pan-African Arabian granites (Duyverman *et al.* 1982), I = I-type Palaeozoic granites, S = S-type Palaeozoic granites (McCulloch & Chappell 1982). Dashed line indicates mixing curve between sample and depleted mantle. UC, IC, M indicate upper crust, intermediate crust, depleted mantle at 50 Ma, crustal extraction at 1040 Ma. Crustal parameters from Weaver & Tarney 1980. ε values calculated assuming $(^{143}Nd/^{144}Nd)_{CHUR}$(present day) 0.512 64; $(^{147}Sm/^{144}Nd)_{CHUR} = 0.1967$; $(^{87}Sr/^{86}Sr)_{UR}$(present day) = 0.7047; $(^{87}Rb/^{86}Sr)_{UR} = 0.0847$.

derived from an upper crustal Precambrian source. Granites falling in the I-type field of figure 2 can be interpreted either as melts from mixed mantle and crustal sources, or as crustal melts from low Rb/Sr source regions as in basic to intermediate igneous rocks.

For Nd, because Sm/Nd in a granite or sediment is believed to be similar to that in their source, the age of the source may also be inferred from the present day $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$. Such ages are called model Nd ages and they represent the time when material (be it granite, sediment or their source regions) with the measured present day $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ was extracted from the upper mantle. There is some choice as to the preferred isotope characteristics of the upper mantle, but the model Nd ages discussed here are calculated relative to the depleted mantle of De Paolo (1981). Finally, these model ages must be treated with some caution, because they are sensitive both to the assumption that Sm/Nd in the granite or sediment *is* the same as that in its source region, and to the problem that several source regions may be involved, whereupon the significance of the calculated (average) model Nd age may be difficult to evaluate. In the simplest case granite derived by fractional crystallization from a mantle-derived melt will have a model Nd age equal to its emplacement age.

Two samples of Gangdise Belt intrusives from near Lhasa (sample G10 is a 41.4 ± 0.4 Ma biotite granite from Quxu and sample G15A is a 56 ± 10 Ma tonalite from Dagze, see figure 3 and table 1), provide $\varepsilon_{Sr}(T)$ close to depleted mantle. Both give positive $\varepsilon_{Nd}(T)$ (+3.1, +3.5)

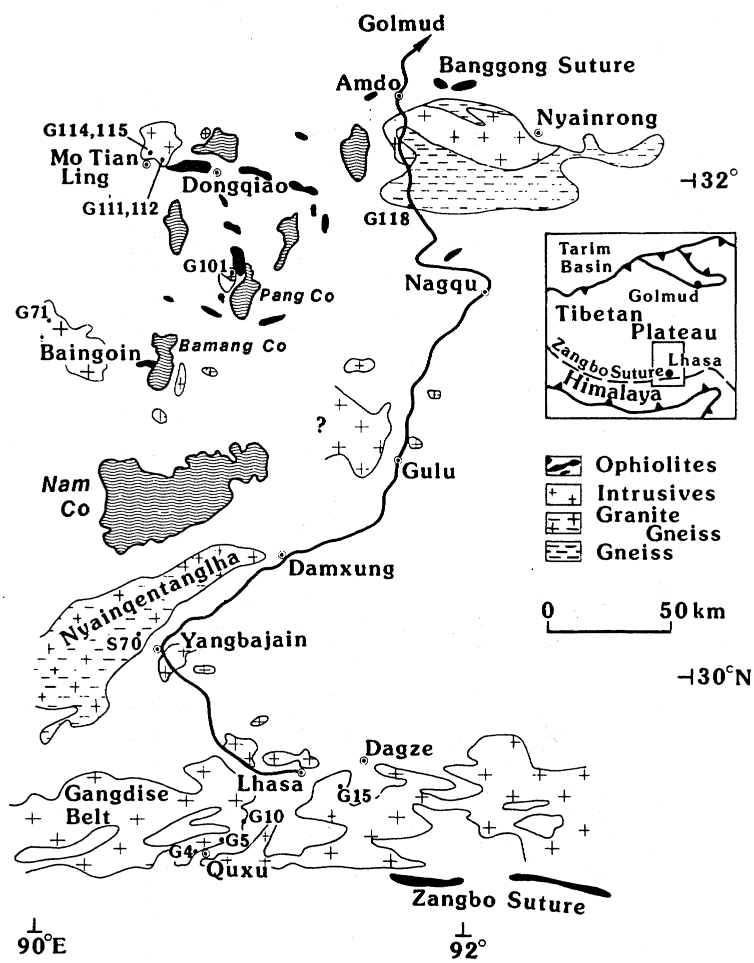

FIGURE 3. Sample location map for igneous samples selected for isotopic analysis from the Lhasa Terrane.

TABLE 2. SR–ND DATA FROM INTRUSIVES, LHASA TERRANE

Locality	Sample	Age (Ma)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	$\varepsilon_{Sr}(T)$	$^{143}Nd/^{144}Nd$	Sm	Nd	$^{147}Sm/^{144}Nd$	$\varepsilon_{Nd}(T)$	T_{DM}
Gangdese											
Granite (Quxu)	G10	41.4 ± 0.4[1]	0.70536	1.64	−3.5	0.51279 ± 1	1.68	13.8	0.073	+3.5	305
Tonalite (Dagze)	G15A	56 ± 10[2]	0.70464	0.35	−3.8	0.51278 ± 1	4.16	20.2	0.124	+3.1	481
Nyainqentanglha											
Granite gneiss	S70C	50[3]	0.71581	7.73	+81	0.51226 ± 1	8.11	38.5	0.127	−6.9	(1382)
Fol. granite	S70D	50[3]	0.70915	3.24	+31	0.51229 ± 1	6.29	37.1	0.103	−6.2	1040
Baingoin											
Granite	G71	121 ± 2[3]	0.72571	10.12	+53	0.51228 ± 1	5.18	24.0	0.130	−6.0	(1402)
Mo Tian Ling											
Diorite	G112A	129 ± 26[4]	0.70765	0.96	+19	0.51258 ± 2	4.08	19.8	0.125	0.0	815
Granodiorite	G115B	129 ± 26[4]	0.71011	2.03	+26	0.51247 ± 1	5.22	28.5	0.111	−1.9	858
Amdo											
Orthogneiss	G118A	531 ± 14[3]	0.73263	2.41	+147	0.51214 ± 2	5.68	33.7	0.102	−3.4	1242
	G118D	531 ± 14[3]	0.74505	2.73	+289	0.51206 ± 1	4.48	22.2	0.122	−6.3	1646

[1] Scharer *et al.* 1984 [2] Xu and Jin 1984 [3] Xu *et al.* 1985 [4] Table 3.

$\varepsilon_{Nd}(T)$ is the deviation from the value expected in chondritic reservoir (CHUR) at time T where $^{143}Nd/^{144}Nd_{CHUR}(T) = 0.51264–0.1967 ((\exp \lambda_{Sm} T)–1)$.
T_{DM} calculated from De Paolo 1981 (values in parentheses indicates possible Sm/Nd fractionation in sample). Analyst Xu Ronghua.

and model Nd ages of 300–500 Ma (table 2, figure 4). Although the youngest model Nd ages obtained in this study, these are significantly older than the age of intrusion and so suggest that some crustal material is present in the granites. On the isotope data alone they could represent crustal melts of a 300–500 Ma source or, and perhaps more likely, some mixture of mantle with older crustal material. It is not possible to constrain the proportion of mantle/crust in the source without defining the composition and age of the crustal end-member.

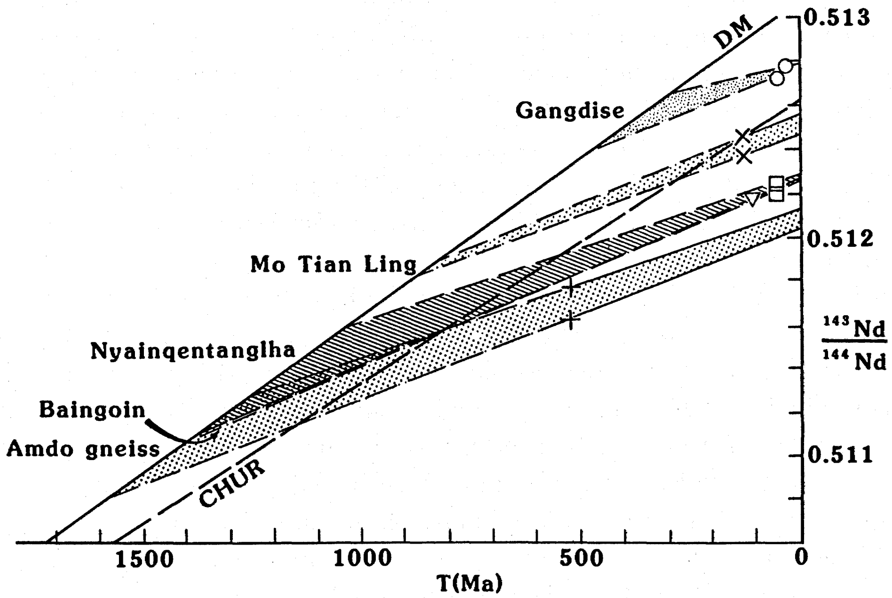

FIGURE 4. Nd evolution diagram of samples from the Lhasa Terrane. Symbols as for figure 2. DM = Depleted mantle, calculated from De Paolo (1981). Data from table 2.

Two granites from the Nyainqentanglha (S70C, S70D, figure 2) are isotopically quite distinct from the Gangdise samples; they have high positive $\varepsilon_{Sr}(T)$, negative $\varepsilon_{Nd}(T)$ and mid-Proterozoic model Nd ages (1040–1382 Ma), all indicating a greater crustal component and/or assimilation of older crust compared with the petrogenesis of the southern Gangdise Belt. Trace elements indicate elevated Rb/Zr ratios relative to the Gangdise Belt which, taken with the high SiO_2 and Rb contents of the granites are indicative of an origin by crustal anatexis. Mineral equilibria from pelitic xenoliths place a minimum depth for emplacement of 10 km (Harris, Holland & Tindle, this volume). The two Nyainqentanglha granites have very similar initial ε_{Nd} but different model Nd ages which suggests that at least one of the model Nd ages reflects Sm/Nd fractionation during magmagenesis. Of the two model Nd ages, the older value (1382 Ma) has a higher Sm/Nd and represents a highly siliceous gneiss ($SiO_2 > 76$ wt %). Small volume crustal melts appear to be characterized by higher Sm/Nd than their inferred source rocks (Hawkesworth *et al.* 1981) and such fractionation, due to residual LREE-rich accessory phases, will result in anomalously high model Nd ages. Thus the lower age of 1040 Ma provides a closer estimate of the age of the crustal progenitor.

ε values of a 1040 Ma crust at 50 Ma are plotted on figure 2 for both average upper crust (UC) and intermediate crust (IC). The Nyainqentanglha gneiss (S70C) lies close to the intermediate crust value indicating a source Rb/Sr somewhat lower than that of average upper crust. Samples from the southern Gangdise Belt lie close to a mixing line between such a crustal source and upper mantle, and can be modelled as mantle melts with ~ 30% assimilation of a mid-Proterozoic crust.

3. Cretaceous magmatism of the northern Lhasa Terrane

(a) *Introduction*

North of Nam Co to the Banggong Suture, which marks the northern limit of the Lhasa Terrane, numerous discrete granitic plutons intrude both sedimentary cover and gneissic basement. Published data on these intrusives are restricted to a monazite age of 121±2 and 130±10 Ma from two-mica granites at Baingoin and Amdo respectively (Xu *et al.* 1985). The orthogneiss basement intruded by the Amdo granite gives an upper intercept zircon age of 531±14 Ma and a sphene lower intercept age of 171±6 Ma (Xu *et al.* 1985). $^{39}Ar/^{40}Ar$ ages from volcanics in the northern Lhasa Terrane also indicate Cretaceous magmatism (74–112 Ma, Coulon *et al.* 1986).

Radiometric constraints on the closure and ophiolite obduction between the Qiangtang and Lhasa Terranes are unclear. The sphene age from the crystalline basement at Amdo (171±6 Ma) dates a low grade metamorphic event which could indicate a mid-Jurassic age for collision or ophiolite obduction. Final emplacement of the Dongqiao ophiolite appears from published $^{39}Ar/^{40}Ar$ constraints to be considerably younger. An upper age for emplacement would appear to be 85±2 Ma, which was obtained by $^{39}Ar/^{40}Ar$ on a dacite clast extracted from a conglomerate overthrust by an ophiolite klippe east of Gyanco (Coulon *et al.* 1986) even though the same publication quotes a minimum emplacement age of 90±2 Ma from plagioclase extracted from andesite lava unconformably overlying the ophiolite north of Pung Co.

(b) Rb–Sr *whole rock data*

Five whole granodiorite–granite samples from the Mo Tian Ling intrusion fall on an errorchron corresponding to an age of 129±26 Ma (MSWD 45), $^{87}Sr/^{86}Sr = 0.7065 \pm 5$, within error of a biotite K/Ar age of 117 Ma (table 3). The intrusion is therefore coeval with the Baingoin–Amdo granites to the south and together they identify an early Cretaceous magmatic province in the northern Lhasa Terrane which has geochemical characteristics of a post-collision environment; this inference is supported by evidence for rapid uplift of the Baingoin granite (Harris, Xu, Lewis & Jin, this volume). These data imply that collision occurred during the early Cretaceous or end-Jurassic along the Banggong Suture. Palaeontological constraints require a pre-late Jurassic obduction age for the Dongqiao ophiolite (Smith & Xu, this volume). The mid-Cretaceous emplacement ages determined from $^{39}Ar/^{40}Ar$ studies (Coulon *et al.* 1986) therefore record post-collision imbrication of the ophiolite nappe, which was obducted in early or mid Jurassic times prior to collision in the early Cretaceous or end-Jurassic.

Six whole rock samples of the Pung Co granodiorite (G101, figure 3) provide an errorchron age of 44±20 Ma (MSWD 6) and initial $^{87}Sr/^{86}Sr$ of 0.7102±5. This age is not easy to interpret. The geochemistry of the granodiorite shows an enrichment of LIL elements similar to that of other tonalites and granodiorites in the northern Lhasa Terrane which predate the Cretaceous Baingoin granite (Harris, Xu, Lewis & Jin, this volume) and indicates an origin from an active or recently active, continental margin. Either the Pung Co granodiorite is a

Table 3. Geochronological and stable isotope data from the Tibetan Plateau

	U–Pb[1] zircon (Ma)	Rb–Sr age (Ma)	isochron $^{87}Sr/^{86}Sr$	Rb–Sr[1] biotite (Ma)	K–Ar[2] biotite (Ma)	$^{18}\delta O_{smow}$[2] whole rock (‰)
Lhasa Terrane						
Pung Co	—	—	—	—	—	—
G101 (granodiorite)	—	44±20	0.7102±5[2]	—	—	7.2
G100 (granite)	—	—	—	—	123±1	—
Mo Tian Ling	—	—	—	—	—	—
G111–115 (granodiorite)	—	126±26	0.7065±5[1]	—	117±2	7.6
Qiangtang Terrane						
Fenghuoshan	—	—	—	—	—	—
G141 (syenite)	—	—	—	—	31±1	11.2
Kunlun Terrane						
Wudaoliang	—	—	—	—	—	—
G142 (tonalite)	—	—	—	—	228±4	9.3
Xidatan	—	—	—	—	—	—
G206 (granite gneiss)	—	194±17	0.7083±2[1]	120	130±2	10.0
Naij Tal	—	—	—	—	—	—
G236 (granite)	—	198±56	0.7097±4[1]	140	168±3	—
Wanbaugou	—	—	—	—	—	—
G222 (granite)	—	—	—	—	431±7	10.4
Golmud Hydro	—	—	—	—	—	—
G244,245 (granite)	—	257±21	0.7098±20[1]	252	270±5	8.8
G248 (granodiorite)	—	—	—	—	251±4	9.9
G247 (tonalite)	—	—	—	—	246±4	10.2
Golmud East	—	—	—	—	—	—
G273 (granodiorite)	240±6	—	—	226	—	8.7
Duo Ya He	—	—	—	—	—	—
G266 (granodiorite)	—	—	—	241	—	6.5

[1] data from Department of Earth Sciences, Open University.
[2] data from Academia Sinica, Beijing.

Paleogene intrusion or it is a Cretaceous post-collision body related to the Banggong Suture, coeval with the Baingoin and Mo Tian Ling plutons. In the first case the isochron age is primary and in the second it has undergone post-magmatic isotopic re-equilibration reducing its apparent age. The large distance from an active Eocene plate margin (250 km north of the Zangbo Suture), the large proportional error on its age, its high initial $^{87}Sr/^{86}Sr$ and the geochemical similarity between this and known Cretaceous bodies all support the latter interpretation. A K–Ar age of 91 Ma from the peraluminous granite which intrudes the granodiorite supports a Cretaceous age of emplacement. The Rb/Sr isotopic system may have been partially reset during late Cretaceous tectonism resulting in a spurious errorchron 'age'.

(*c*) Sr–Nd *systematics*

The Mo Tian Ling intrusion (G111–G115, figure 3) is a Cretaceous granodiorite with slightly negative $\varepsilon_{Nd}(T)$ lying within the field of I-type granites (figure 2). Model Nd ages of ~ 850 Ma confirm a crustal component in the petrogenesis of the intrusion. These data could be interpreted either as a crustal melt of ~ 850 Ma crust, or a mantle melt with assimilation of crust older than 850 Ma.

The Cretaceous two-mica granite from Baingoin (G71, figure 3) has a higher $\varepsilon_{Sr}(T)$, lower $\varepsilon_{Nd}(T)$ and older model Nd age (1402 Ma) than the coeval Mo Tian Ling intrusion. The very

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

high Rb/Zr ratio of this sample indicates an origin from crustal melting and its high Sm/Nd may therefore reflect fractionation during anatexis which leads to an anomalously high model Nd age. The similarity in initial $^{143}Nd/^{144}Nd$ of the Nyainqentanglha and the Baingoin granites suggests that both result from anatexis of a mid-Proterozoic crust ($\sim$ 1000 Ma). Assuming the Mo Tian Ling intrusion results from assimilation of crust of this age, it requires about 60% of such crustal material, somewhat higher than that inferred from Gangdise samples. Like many post-collision intrusions, the granodiorite has a geochemistry indicative of a source in a hydrated mantle wedge above a subduction zone, but it presumably ascended through tectonically thickened crust. The high crustal component compared with magmas formed at an active continental margin, such as the Gangdise Belt, is therefore to be expected.

The oldest known basement from the Lhasa Terrane, the Amdo gneisses, was analysed (G118, figure 3) to evaluate its contribution to the Cretaceous magmatic event. The range of model Nd ages for the Amdo orthogneisses (1242–1646 Ma) is older than that of other analysed samples from the Lhasa Terrane (figure 4), and the $\varepsilon_{Sr}(T)$–$\varepsilon_{Nd}(T)$ plot rules out the gneisses as possible sources for more recent magmatism. Assuming a Cambrian age of gneiss emplacement from zircon data (Xu *et al.* 1985) it provides Sr and Nd isotope ratios strongly indicative of a crustal source for the orthogneisses (figure 2) with an estimated $^{87}Rb/^{86}Sr$ in the source of 1.3.

4. Late Permian–Early Jurassic magmatism in the Kunlun Terrane

(*a*) *Introduction*

The northern margin of the Kunlun Terrane is marked by the uplifted syn-tectonic granitic batholith of the Kunlun Mountains. South of the batholith several post-tectonic granites are intruded and an orthogneiss is emplaced north of the Xidatan Fault. Geochemically the granites are calc-alkaline to calcic with trace elements indicative of formation either at an active continental margin, or in a post-collision setting. The southern limit of the Kunlun Terrane is marked by the Jinsha Suture, poorly represented in the Geotraverse region by an inlier of ultramafics and gabbros. Evidence for northward underthrusting along this possible plate margin comes from the southward-facing recumbancy of the structures in the south of the terrane, and Jurassic molasse, derived from the north, deposited south of the suture. There are no published geochronological data from this terrane, but previous stratigraphic studies favour a Permo-Triassic age for closure along the Jinsha suture (Chang & Pan 1981). The batholith intrudes Permian sediment.

(*b*) *Geochronology*

Five whole rock suites were selected for Rb–Sr whole-rock isochron studies. Of these, the Golmud East granodiorite and the Duo Ya He granodiorite from the syn-tectonic batholith have too little variation in Rb/Sr to yield useful whole rock ages. Seven samples from the Xidatan orthogneiss (G206 figure 5) fall on an errorchron with an 'age' of 189 ± 7 Ma (MSWD 19), and an initial $^{87}Sr/^{86}Sr$ of 0.7083 ± 2. Since this suite of gneisses includes two rock-types (biotite granite gneiss and leucogneiss) which have different geochemical characteristics and distinct model ages (see next section) it may be more realistic to estimate the age from the four biotite granite gneiss samples which have similar trace element signatures and similar model Nd ages. This results in an age of 194 ± 17 Ma (MSWD 25), $^{87}Sr/^{86}Sr$ of

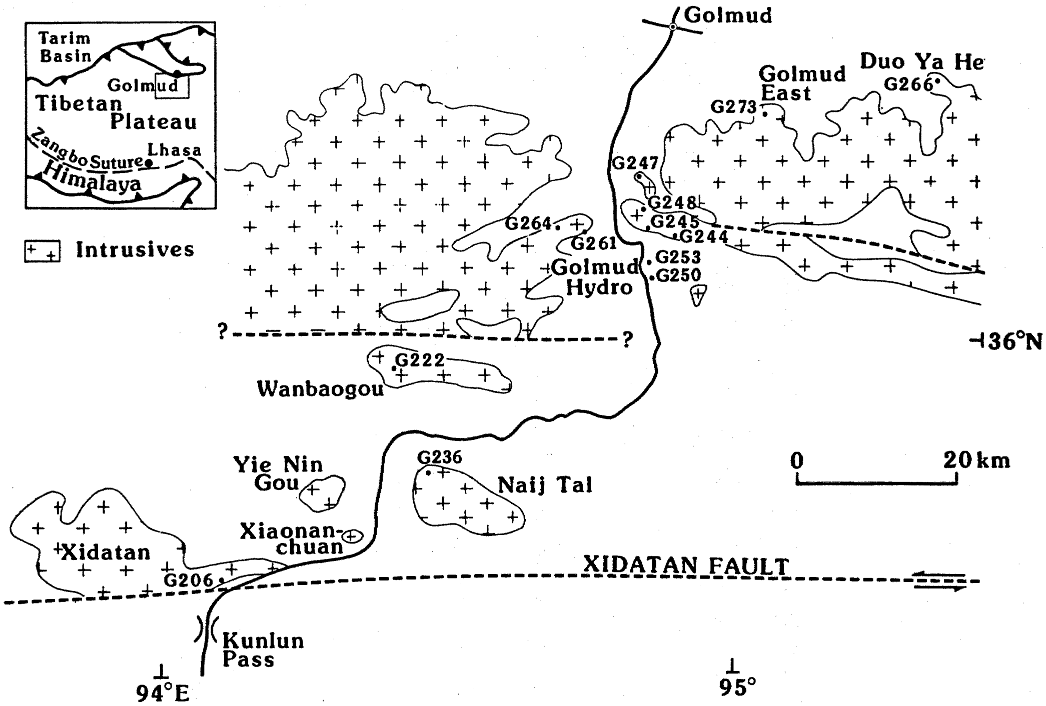

FIGURE 5. Sample location map for igneous samples selected for isotopic analysis from the Kunlun Terrane.

0.7083 ± 2, and the similarity of these data with the age and initial ratio derived from all Xidatan samples implies the same, or geochemically similar, sources for both gneisses. A similar but poorly constrained age of 198 ± 56 Ma (MSWD 140) and an initial $^{87}Sr/^{86}Sr$ of 0.7097 ± 4 has been obtained for five samples of the post-tectonic Naij Tal granite (G236, figure 5), the large uncertainty resulting from a small spread in Rb/Sr ratios. The syn-tectonic Golmud Hydro granite has also proved difficult to date by whole rock isochron. A total of 6 samples from G244–G245 (figure 5) give an age of 257 ± 26 Ma (MSWD 44), initial $^{87}Sr/^{86}Sr$ 0.710 ± 2. To determine the age of the Golmud East granodiorite, three populations of zircons were analysed and found to give a virtually concordant age of 240 ± 6 Ma (table 4). The syn-tectonic batholith was therefore emplaced from 270–240 Ma (this range is supported by K–Ar ages from the Golmud Hydro complex) and the post tectonic intrusions to the south from 200–190 Ma. K–Ar data from the Wanbaogou granite, which lies south of the Kunlun batholith, indicate an early Palaeozoic age (431 Ma), and this result is supported by preliminary Rb–Sr data. A post-tectonic tonalite plug, emplaced into the Triassic accretionary prism 100 km south of the Kunlun Pass near Wudaoliang, is dated at 213 Ma by the K/Ar method and clearly post-dates collisional deformation in the southern Kunlun Terrane.

In an attempt to constrain further the timing of events in the Kunlun Shan, biotite separates from five suites were analysed for Rb–Sr isotopes. Since the closure temperature of biotites is 300–350 °C (Dodson 1979), the data obtained by the method record the last time the rock cooled through this temperature. The Golmud Hydro and Golmud East intrusions have indistinguishable emplacement and mica ages (table 3). However, the Naij Tal and Xidatan suites give considerably younger biotite-whole rock ages of 140 Ma and 120 Ma respectively despite their early Jurassic intrusion ages. The Xidatan gneisses are strongly foliated parallel

Table 4. U–Pb isotopic data from zircons from Golmud East granodiorite (G273)

Sample	Grain characteristics	Uranium 10^{-12}M	Radiogenic Pb[1] 10^{-12}M	Common Pb 10^{-12}M	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$ Apparent ages (Ma)	$^{207}Pb/^{208}U$ Apparent ages (Ma)
G273–4	0.125–0.063 mm Non-mag at 3–10° Length/width = 4/1	268.5	12.738	0.902	0.03832	0.26753	0.05029	242.4	239.3
G273–5	0.125–0.063 mm Non-mag at 3–10° Length/width = 2.5/1	243.3	11.409	0.456	0.03852	0.26537	0.04996	243.6	239.0
G273–6	0.125–0.063 mm Non-mag at 3–10° Length/width = 2.0/1	546.8	24.585	1.466	0.03771	0.25952	0.04991	238.6	234.3

[1] corrected for common Pb. 206/204 = 17.48, 207/204 = 15.50, 206/204 = 37.21.
Analyst Xu Ronghua.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

to the east-trending Xidatan Fault with a recrystallized mica fabric and it is likely the mica age dates the penetrative fabric in this rock. Since the fabric and the fault are parallel, it raises the intriguing possibility that the micas record the time of early movement on this fault zone. The Naij Tal pluton is some 15 km north of the fault, does not have a strong fabric, and perhaps the isotopes are only partially reset giving a somewhat older age (140 Ma). K–Ar mica ages for these two bodies lie in the range 130–170 Ma. Since this range of mineral ages from two isotopic systems overlaps with the inferred end-Jurassic collision along the Banggong Suture it is possible that the fault was initiated, or at least reactivated, by collision between the Lhasa and Qiangtang terranes.

(*c*) Sr–Nd *systematics*

Model Nd ages of fifteen samples from the Kunlun granites have been determined (table 5). Model ages vary from 920–1880 Ma, with wide variations being recorded from those plutons which have a distinctive crustal melt geochemistry. For example, within the Xidatan gneisses the biotite granite gneisses have younger model Nd ages ($\sim$ 1000 Ma) than the leucogneisses (1600–1900 Ma). The high model Nd ages are again associated, not with low $^{143}Nd/^{144}Nd$, but with high Sm/Nd, with silica contents > 76 wt % and with elevated Rb/Zr indicative of small volume partial melts. The implication is that for crustally-derived granitic samples with $^{147}Sm/^{144}Nd > 0.14$, model ages may be too high due to Sm/Nd fractionation (see section 2*b*). In the case of the Xidatan gneisses, the best estimate of the source age is probably $\sim$ 1000 Ma, indicated by the biotite gneisses. The Golmud Hydro granite also has high model ages associated with high $^{147}Sm/^{144}Nd$ samples with elevated Rb/Zr. In this case, best estimate of source model age lies in the range 1100–1250 Ma.

The $\varepsilon_{Nd}(T)$–$\varepsilon_{Sr}(T)$ plot (figure 6) indicates that all Kunlun intrusions have negative $\varepsilon_{Nd}(T)$ and strongly positive $\varepsilon_{Sr}(T)$ indicating a high crustal component. The data are also displaced to higher values of $\varepsilon_{Sr}(T)$ compared with Lhasa Terrane samples which indicates a higher

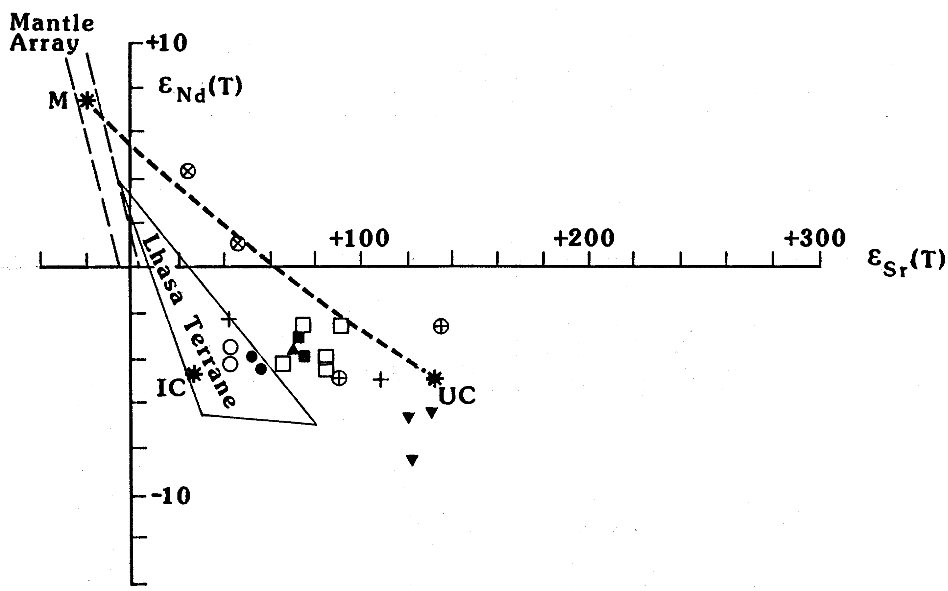

FIGURE 6. $\varepsilon_{Sr}(T)$–$\varepsilon_{Nd}(T)$ plot for samples from Kunlun Terrane. ● = Xidatan (biotite gneiss), ○ = Xidatan (leucogneiss), ■ = Naij Tal, □ = Golmud Hydro, ▲ = Golmud East, ▼ = Duo Ya He, + = Triassic (?) Volcanics, ⊕ = Triassic (?) Dyke, ⊗ = dykes intruding Devonian Volcanics. UC, IC, M indicate upper crust, intermediate crust and upper mantle at 240 Ma, crustal extraction at 1100 Ma. Dashed-line shows mixing curve between average upper crust and depleted mantle. Crustal parameters from Weaver & Tarney 1980.

TABLE 5. SR–ND DATA FROM IGNEOUS SAMPLES, KUNLUN TERRANE

Locality		Sample	Age (Ma)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	$\varepsilon_{Sr}(T)$	$^{143}Nd/^{144}Nd$	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$\varepsilon_{Nd}(T)$	T_{DM} Ma
Xidatan	Biotite gneiss	G206A		0.70989	0.58	+54	0.51230±1	7.10	47.6	0.090	−3.9	921
	—	G206B	194±17	0.71185	1.22	+57	0.51229±1	6.60	40.3	0.099	−4.5	1016
	Leucogneiss	G206C		0.72625	6.78	+44	0.51239±2	3.00	11.4	0.160	−4.1	(1880)
	—	G206D		0.72747	7.25	+43	0.51240±2	2.80	11.2	0.151	−3.6	(1586)
Naij Tal	Granite	G236D	198±56	0.71130	0.55	+75	0.51231±1	4.22	26.0	0.098	−3.9	1020
	—	G236E		0.71248	1.04	+72	0.51233±1	3.44	20.0	0.104	−3.0	970
Golmud Hydro	Granite	G244A		0.72384	3.71	+83	0.51224±2	3.90	21.6	0.109	−4.9	1181
	—	G245A		0.74425	9.73	+61	0.51231±7	3.07	12.9	0.144	−4.7	(1610)
	—	G245C	257±26	0.74576	9.76	+82	0.51230±4	2.72	12.0	0.140	−4.8	(1470)
	—	G245F		0.72786	5.04	+71	0.51239±3	2.60	12.7	0.130	−2.7	1244
	—	G261B		0.71858	2.08	+93	0.51238±1	5.20	25.7	0.122	−2.6	1108
Golmud East	Granodiorite	G273C	240±6	0.71181	0.68	+72	0.51229±1	3.80	26.1	0.089	−3.6	940
North Kunlun	Granodiorite	G266A		0.71727	1.22	+124	0.51208±1	5.50	34.8	0.096	−8.4	1250
	—	G266C	240⁽¹⁾	0.71744	1.19	+132	0.51215±1	5.00	25.8	0.117	−6.4	1420
	—	G266E		0.71678	1.10	+122	0.51215±2	4.90	29.0	0.102	−6.6	1230
Dacite flow	—	G250A		0.71710	1.52	+108	0.51223±2	7.90	35.8	0.133	−6.0	1546
Andesite dyke	—	G250C	240⁽¹⁾	0.71305	0.71	+90	0.51230±1	6.10	25.1	0.147	−5.1	1700
Andesite flow	—	G250F		0.70887	0.50	+40	0.51245±2	6.40	26.5	0.147	−2.1	1345
Basalt dyke		G253Y		0.72666	3.63	+141	0.51241±1	12.00	51.2	0.142	−2.8	1341
Rhyolite dyke	—	G253H	384⁽²⁾	0.70938	0.31	+49	0.51251±2	3.10	15.3	0.123	+1.2	899
Basalt dyke	—	G253I		0.71506	1.65	+26	0.51275±1	5.10	19.9	0.155	+4.3	775

(1) Assumed from Golmud East zircon age
(2) Assumed from stratigraphic evidence
T_{DM} values in parentheses indicate possible Sm/Nd fractionation of sample
Analyst C. L. Lewis

Rb/Sr in the source. If it is assumed that the crustal source has a model age of 1100 Ma (taken as an average from Kunlun samples with $^{147}Sm/^{144}Nd < 0.14$), and anatexis occurred at 240 Ma, then the isotopic ratios of crust with average Rb/Sr and Sm/Nd for upper and intermediate crust are given by UC and IC respectively in figure 6. Naij Tal, Golmud Hydro, Golmud East and Xidatan intrusives have somewhat lower Rb/Sr sources than average upper crust. Some samples lie close to a mixing curve between upper crust and depleted mantle, and this could either indicate a shorter period of crustal residency in the source or up to 20% mantle component in the granite petrogenesis. The Duo Ya He granodiorites are displaced from the array of other Kunlun data to lower $\varepsilon_{Nd}(T)$ values suggesting a slightly older crustal source.

Six volcanic and hypabyssal samples have been analysed for Sr–Nd isotopes from the Dagangou Formation south of the syn-tectonic Kunlun batholith. Interpretation of these results is uncertain, both because distinction between flows and dykes is unclear, and because it is not known whether the formation comprises two distinct suites. Dykes and flows from a fault-bounded block (G250) have isotopic characteristics similar to those of the Permo-Triassic batholith and may be the extrusive equivalent (figure 6). Dykes intruding a suite with known Devonian age (G253) have younger model Nd ages and a large mantle component.

5. Oxygen isotope data

A reconnaissance study of oxygen isotopes from 15 granitoid whole rock samples has been undertaken (table 3) and compared with published data from the Gangdise Belt and High Himalayan leucogranites (Blattner *et al.* 1983; Debon *et al.* 1986). There is a general small increase in $\delta^{18}O$ with silica content for the Gangdise Belt (figure 7) which is consistent with assimilation and fractional crystallization processes. The leucogranites show high $\delta^{18}O$ which together with high initial $^{87}Sr/^{86}Sr$, indicate crustal melting. Data presented in this study show that samples from Pung Co and Mo Tian Ling in the northern Lhasa Terrane lie within the

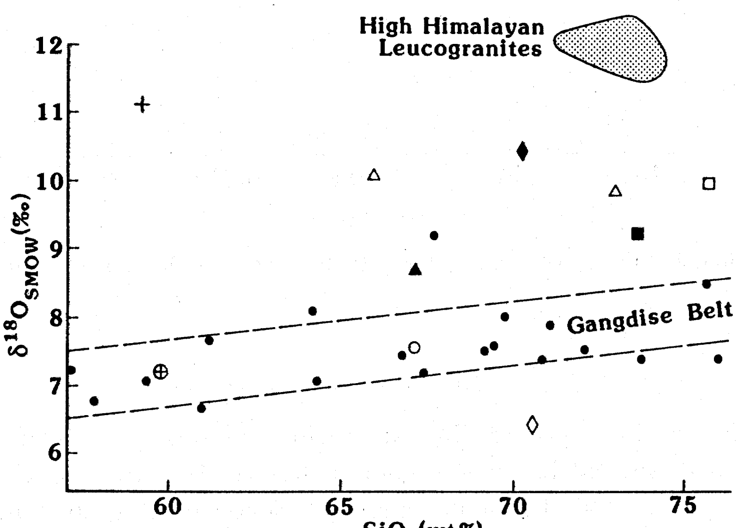

Figure 7. Variation of $\delta^{18}O_{SMOW}$ with silica content. ● = Gangdese Belt, ○ = Mo Tian Ling, ⊕ = Pung Co, + = Fenguoshan syenite, □ = Xidatan, ■ = Naij Tal, △ = Golmud Hydro, ▲ = Golmud East, ◇ = Duo Ya He, ◆ = Wanbaogou. Data from table 3. Blattner *et al.* 1983, Debon *et al.* 1986.

Gangdise trend. Strong evidence either for a crustal contribution or extensive fluid/rock interaction comes from the high $\delta^{18}O$ values of the Fenghuoshan microsyenite from the Qiangtang terrane, and the granitic intrusions of the Kunlun (with the exception of the Duo Ya He granodiorite).

Samples from the Gangdise Belt show reasonable correlation between $\delta^{18}O$ and initial $^{87}Sr/^{86}Sr$ (coefficient of 0.83 for seven samples) (figure 8) which implies that these data record primary genetic processes and is consistent with crustal assimilation and fractional crystallization. Assimilation or reworking of continental crust causes an increase in both parameters as observed in the Xidatan, Naij Tal, Wanbaogou and Golmud intrusions from the Kunlun. The Pung Co granodiorite (G101) from the northern Lhasa Terrane has mantle oxygen values but elevated strontium ratios and this supports the evidence (section 3*b*) for post-magmatic re-equilibration which not only reduces the apparent age, but also elevates the initial ratio. Interestingly the Duo Ya He granodiorite records even higher strontium ratios at low $\delta^{18}O$. It is possible that this facies within the Kunlun batholith represents a much older granitic inlier. Supporting evidence comes from its strong foliation and low $^{143}Nd/^{144}Nd$ indicative of an older source region than other analysed intrusions from the Kunlun batholith. In order to reduce the initial $^{87}Sr/^{86}Sr$ to 0.707, a value within the range typical of mantle-derived magmas, an intrusion age of ~ 600 Ma is required. It therefore remains equivocal that the Duo Ya He granodiorite is part of the Triassic magmatic event.

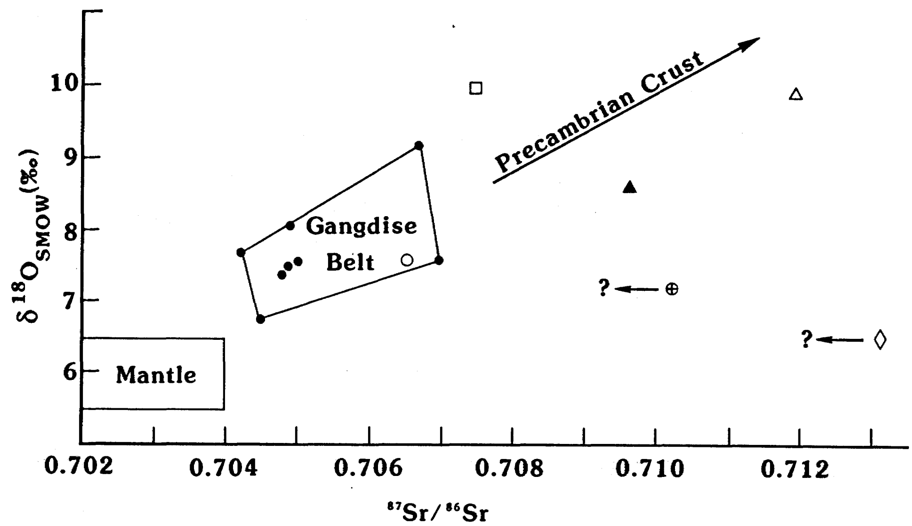

FIGURE 8. Variation of $\delta^{18}O_{SMOW}$ with initial $^{87}Sr/^{86}Sr$. Symbols as for figure 7. Data from table 3.

6. Model Nd ages of sediments

Nd model ages of fine-grained clastic sediments provide an indication of average age of their source regions, provided Sm/Nd has not fractionated since the sediment progenitors were extracted from the mantle. This technique has been successfully applied to Phanerozoic sediments to identify periods of crustal growth and orogenesis (Michard *et al.* 1985) and periods of ocean closure (Davies *et al.* 1985). In this study Sm/Nd data from sediments from critical horizons within the Lhasa, Qiangtang and Kunlun terranes (figure 9) have been analysed to

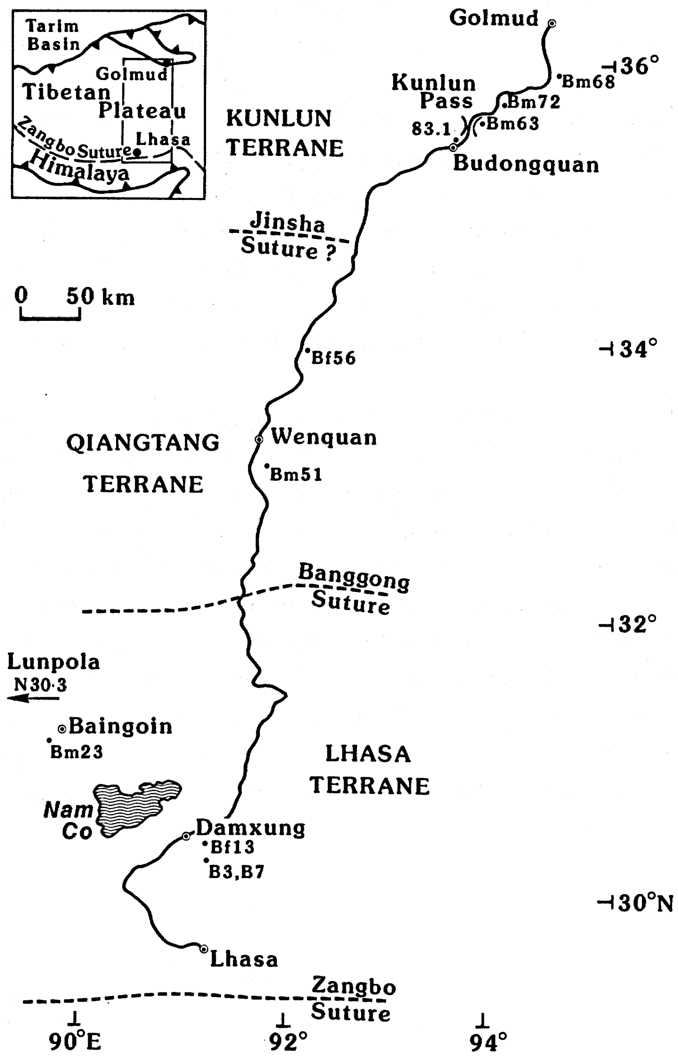

FIGURE 9. Sample location map for samples of sediment selected for Nd isotope analysis.

determine variations of source region age with time and hence possible periods of ocean closure which allow new source regions to become available for erosion. Such a technique will only be successful if the colliding plates have uplifted regions of contrasting average ages.

Of the eleven analysed samples, nine define a trend indicating a general increase in ε_{Nd} with decreasing age of sedimentation (figure 10). This means that source region ages become younger, relative to bulk earth, in the younger sediments.

Within the Lhasa Terrane the Late Carboniferous drop-stone glacial deposits (B7) require significantly older Precambrian sources regions than the overlying siltstones (B3) which identifies the availability of older regions in Gondwanaland for erosion during Carboniferous glaciation. The significantly older model age is consistent with the drop-stones being transported from an Archean land-mass to the south and deposited in relatively young terrane.

Two Lower Cretaceous to mid-Jurassic sediments from either side of the Banggong Suture indicate similar model ages. In this case it is not possible to confirm the time of collision since both plates apparently provided source regions of similar age prior to collision.

In the north of the Qiangtang terrane, the Upper Permian shale (Bf56) has a significantly younger model age than either the mid Carboniferous shale (Bm72) or the Upper Jurassic silt (83.1) of the southern Kunlun. Transport directions in Upper Permian strata are from the north, but adjacent strata contain numerous tuffaceous horizons and the shales are overlain by Permian volcanics. The young model age of the Permian shale is therefore attributed to magmatism within the Qiangtang plate and not to an influx of material from a pre-Upper Permian collision with younger source regions to the north. Since juvenile volcano-sedimentary detritus was apparently derived within the Qiangtang Terrane, these data do not help identify the time of collision with a rising younger source region to the north. In any event the bulk of Kunlun magmatism probably occurred around 240 Ma and could not affect pre-Triassic sediments.

The general trend of model age with sedimentation age seen in the Tibetan Plateau (figure 10) is contrary to trends observed in studies from Australia and from Britain. The trend of Australian shales, representative of at least part of Gondwana, is of a slight decrease in ε_{Nd} in young sediments during the Phanerozoic (Allègre & Rousseau 1984). In British sediments the relatively sharp decrease in ε_{Nd} with decreasing sedimentation age is accredited to detritus from the Precambrian terrane to the north after closure of the Iapetus Ocean (Davies *et al.* 1985). The reverse trend shown by the Tibetan sediments has been recorded in late Proterozoic sediments from the Damara Belt of Namibia (McDermott 1987). Such a trend is remarkable since continuous reworking of crust with no introduction of younger material by either magmatic or tectonic processes will always lead to a decrease in ε_{Nd} in younger sediments as shown by the crustal reworking vector of figure 10. The reverse trend can be explained in one of two ways.

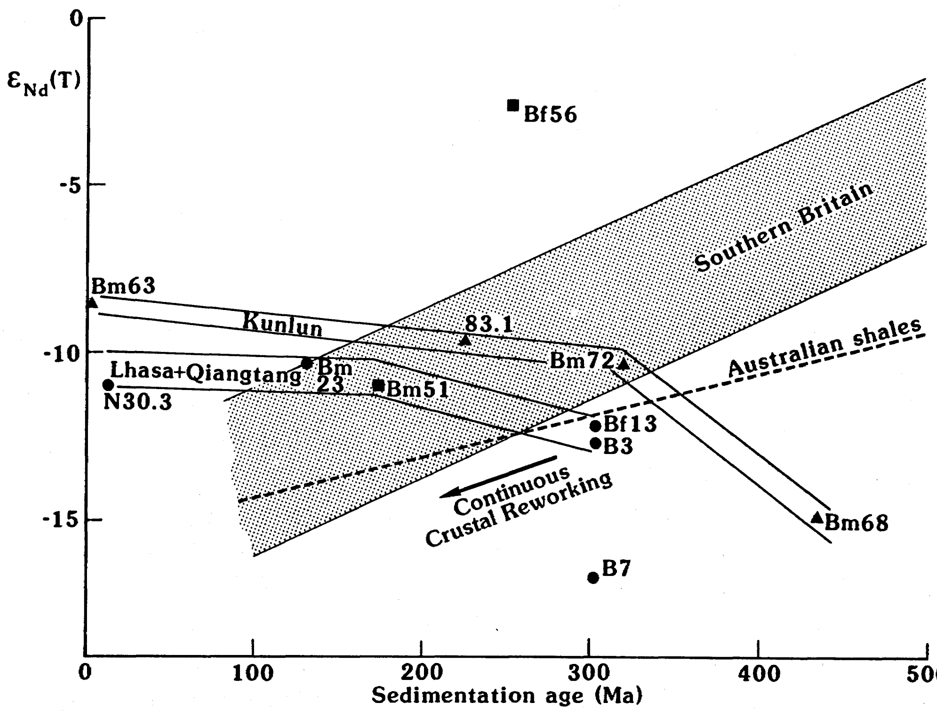

FIGURE 10. Variation of $\varepsilon_{Nd}(T)$ with sedimentation age for sediments from the Tibetan Plateau. ● = Lhasa, ■ = Qiangtang, ▲ = Kunlun Terranes. Shaded region marks evolution of sediments from southern Britain (Davies *et al.* 1985), dashed line indicates shale data from Australia (Allègre & Rousseau 1984).

Table 6. Nd isotopic data from sediments

Locality		Sample	Sedimentation Age		$^{143}Nd/^{144}Nd$	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$\epsilon_{Nd}(T)$	T_{DM} Ma
Lhasa Terrane										
Lhasa	Laminated siltstone	B3	Late Carb.	303±17	0.51183±1	6.32	33.3	0.115	−12.6	1873
	Glacial (Drop-stone)	B7	Late Carb.	303±17	0.51161±1	2.09	11.6	0.109	−16.7	2099
Damxung	Siltstone	Bf13	Late Carb.	303±17	0.51185±1	5.75	30.2	0.115	−12.2	1855
Baingoin	Estuarine siltstone	Bm23	Lower Cret.	131±7	0.51206±1	5.58	25.8	0.131	−10.3	1823
Lunpola	Lacustrine siltstone	N30.3	Neogene	13±11	0.51207±1	6.11	31.1	0.119	−10.9	1558
Qiangtang Terrane										
Kaixingling	Shale	Bf56	Upper Perm.	258±5	0.51241±1	6.14	27.3	0.136	−2.5	1257
Wenquan	Plant shale	Bm51	Mid. Jur.	175±12	0.51199±2	5.63	29.8	0.114	−10.8	1613
Kunlun Terrane										
N. Kunlun	Silty limestone	Bm68	Ord./Sil.	435±25	0.51169±2	2.36	10.8	0.132	−14.9	2546
Xidatan	Shale	Bm72	Mid. Carb.	320±15	0.51198±1	11.29	50.6	0.135	−10.3	2067
Budongquan	Siltstone	83.1	Triassic	226±17	0.51204±1	5.92	29.3	0.122	−9.6	1681
Kunlun Pass	Lacustrine Siltstone	Bm63	Quaternary	0.8±0.8	0.51220±1	3.19	15.8	0.122	−8.5	1402

Analyst Xu Ronghua

(1) The terranes which constitute the plateau are sites of rapid crustal growth during the Phanerozoic providing juvenile magmatic material to the sediment. About 25 % crustal growth is required in Tibet during the Phanerozoic assuming an initial crust of 2000 Ma average age from the average age of upper crust (Goldstein *et al.* 1984).

(2) A relatively young source region (late Proterozoic) was progressively uplifted and eroded more rapidly than older source regions during most of the Phanerozoic.

There is no evidence in the preserved fragments of crust now exposed for significant new crust during the last 500 Ma. The magmatic rocks which are exposed have a strong crustal component and the major opportunity for crustal growth came only in the last 40 Ma with the evolution of the Gangdise Belt. The decrease in age of sedimentary source regions from the Carboniferous to the Jurassic would seem to result from preferentially-uplifted juvenile material. Certainly, in the Lhasa Terrane, uplift of a young source region is required which predates not only the Himalayan orogeny, but also closure of the Banggong Suture. After closure of the Banggong Suture, the uplifted Kunlun Mountains, which represent sites of voluminous magmatism during Triassic times and possibly earlier, provide a relatively young northerly source from the southern Kunlun to the Qiangtang and Lhasa terranes.

The two samples of recent sedimentation (Neogene silts from the Lhasa Terrane and Quaternary silts from the Kunlun) give ε_{Nd} values of -10.9 and -8.5. The slightly younger model age for the northern deposits may reflect the proximity of the uplifted Kunlun batholith. These values are similar to that of sediment from the Yangtze River (-10.9) which has its source in Tibet (Goldstein *et al.* 1984). They are in strong contrast to sediments derived from either juvenile continental crust (such as Nile sediments $\varepsilon_{Nd} = -3.3$) or to those derived from predominantly Archaean continental crust (such as Congo sediments $\varepsilon_{Nd} = +16.1$). Uplifted regions of the Tibetan Plateau therefore have average model Nd ages of 1400–1600 Ma, somewhat younger than those of average continental crust (2000 Ma). This can be accounted for either by widespread mantle-derived magmatism in Tibet not hitherto sampled or by tectonic processes which have selectively uplifted younger terranes.

7. Discussion and conclusions

A compilation of available geochronological data from the Lhasa to Golmud section across the Tibetan Plateau (figure 11) indicates progressively younger periods of intrusive magmatism from north to south, associated with successively younger ocean closures. In the north of the plateau the Kunlun batholith was emplaced at a continental margin during active subduction in late Permian–mid Triassic times (260–240 Ma) and south of the batholith granites were emplaced in a post-collision environment in the early Jurassic (200–190 Ma). Micas from intrusions near the Xidatan Fault record distinctly younger ages (140–120 Ma) possibly due to tectonism associated with closure of the Banggong Suture. South of the Banggong Suture in the northern Lhasa Terrane, Cretaceous post-collision intrusions (130–110 Ma) slightly pre-date post-collision volcanism (110–70 Ma). In the southern Lhasa Terrane magmatism is predominantly Eocene (60–40 Ma), pre-dating collision between the Himalayan and Lhasa terranes, although Cretaceous plutonism ($\sim$ 90 Ma) WSW of Lhasa records an earlier period of subduction.

Nd model ages from sediments exposed in all three crustal fragments define a trend of increasing ε_{Nd} with decreasing age of sedimentation. The samples define a band which repre-

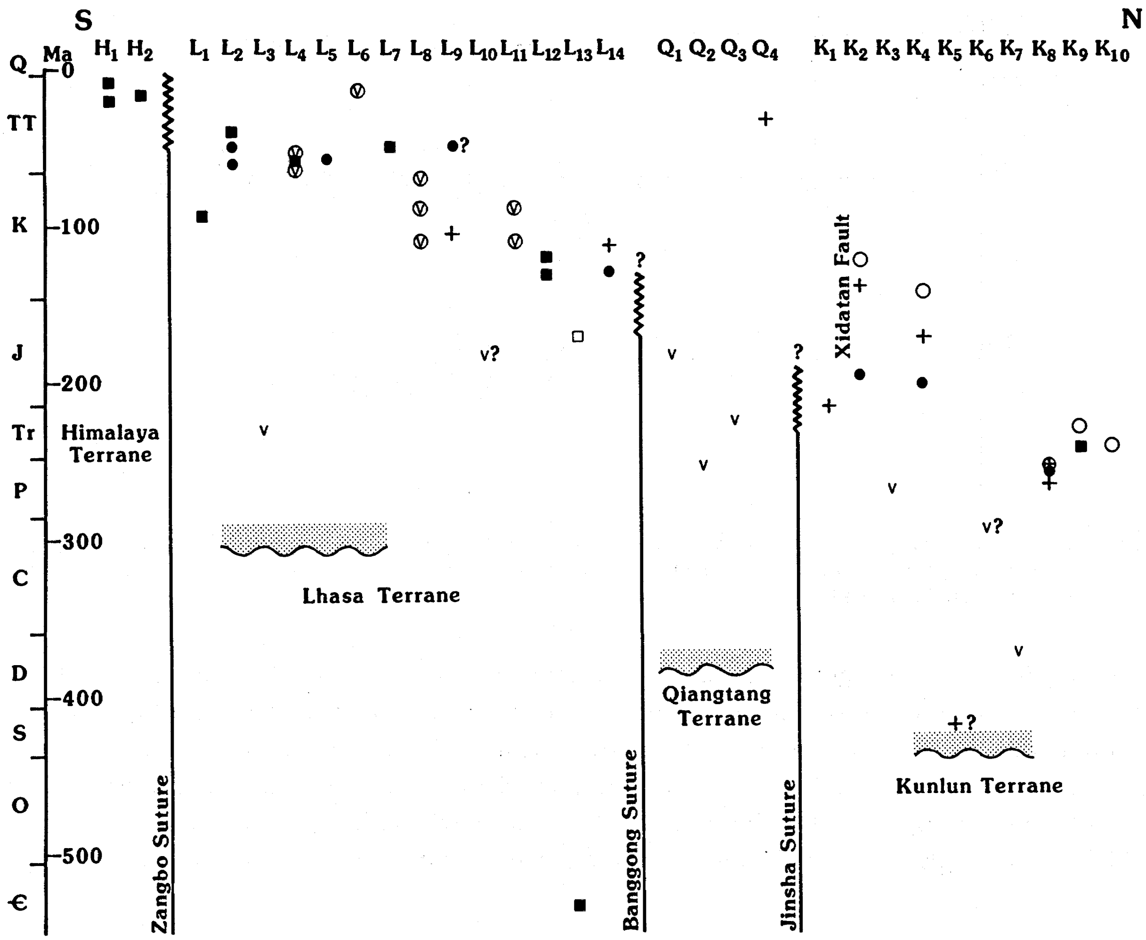

FIGURE 11. Compilation of geochronological data in geographic sequence from south to north along geotraverse route (extended south of the Zangbo suture). ■ = U–Pb monazite or zircon age, □ = U–Pb sphene age, ● = Rb–Sr isochron age, ○ = Rb–Sr biotite age, + = K–Ar biotite age, ⓥ = $^{39}Ar/^{40}Ar$ age on volcanics, v = undated volcanics. Shading indicates oldest fossiliferous strata for each terrane. H_1 = High Himalaya, H_2 = North Himalaya, L1 = Dazhuka, L2 = Quxu–Lhasa, L3 = Dagze, L4 = Linzizong Formation, L5 = Yangbajain, L6 = Macquiang, L7 = Nyainqentanglha, L8 = Nam Co, L9 = Pung Co, L10 = Nagqu, L11 = Dongqiao, L12 = Baingoin-Amdo, L13 = Amdo (basement), L14 = Mo Tian Ling, Q1 = Yanshiping Group, Q2 = Kaixingling Group, Q3 = Batang Group, Q4 = Fenghuoshan, K1 = Wudaoliang, K2 = Xidatan, K3 = Wanbaogou Group, K4 = Naij Tal, K5 = Wanbaogou, K6, K7 = Dagangou Formation, K8 = Golmud Hydro, K9 = Golmud East, K10 = Duo Ya He.

sents Nd data for average Tibetan crust exposed during the Phanerozoic (figure 12). $\varepsilon_{Nd}(T)$ from igneous samples lie in an envelope constrained by a depleted mantle reservoir and the sediment data. Hence on the basis of Nd data alone, magmagenesis can be modelled from mixing upper crustal and mantle end-members. Considerations of Sr–Nd systematics however, indicate that the Kunlun granites result predominantly from anatexis of upper–intermediate mid-Proterozoic crust whereas peraluminous Cretaceous plutons from the northern Lhasa terrane and Eocene plutons from the Nyainqentanglha Shan result from melting crustal sources of similar age and intermediate compositions. Calc-alkaline intrusions from the northern Lhasa Terrane and from the Gangdise Belt have a mantle signature, but require 30–60% assimilation of crustal material.

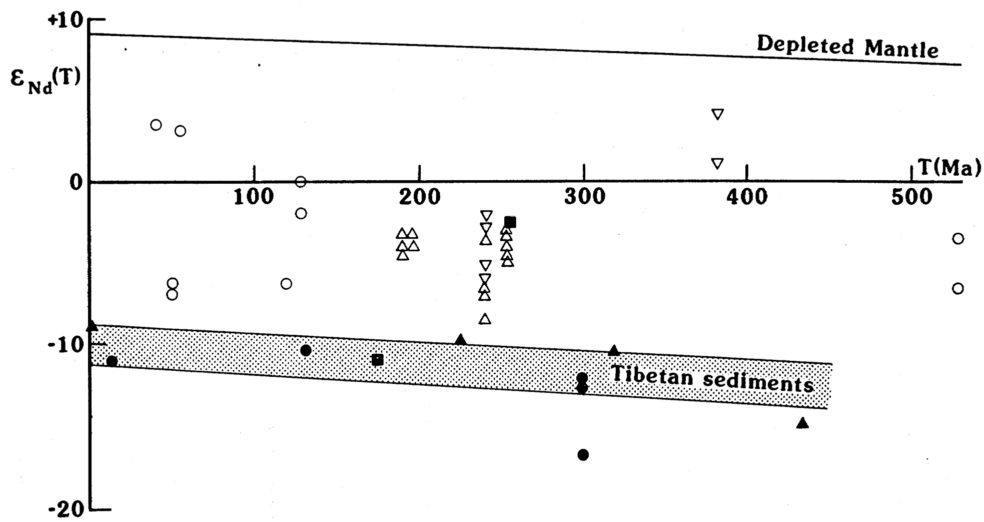

FIGURE 12. Variation of $\varepsilon_{Nd}(T)$ with time for samples from Tibetan Plateau. Open symbols indicate igneous samples and filled symbols sediment data (see figure 10 for legend). ▽ = volcanics from Kunlun Terrane. Depleted mantle from De Paolo 1981.

From the analysed samples, there is no evidence that crustal growth occurred on a large-scale during the Phanerozoic in any of the three terranes, and all intrusions result from partial or total crustal reworking. Indeed a distinctive feature of intrusions from the Tibetan Plateau is that, irrespective of age, they have a substantial crustal component in their petrogenesis. This raises the intriguing possibility that anomalously thickened continental crust is a characteristic which considerably predates the most recent (Eocene) collision recorded in the rocks from the plateau.

Peter van Calsteren and Andy Gledhill were responsible for the smooth running of the mass spectrometer and for chemical separation. Isotopic analytical facilities at the Open University are supported by NERC. We thank John Taylor for drafting the figures and Marilyn Leggett for typing the manuscript.

REFERENCES

Allègre, C. J. & Ben Othman, D. 1980 Nd and Sr isotopic relationship in granitoid rocks and continental crust development: a chemical approach to orogenesis. *Nature, Lond.* **286**, 335–342.
Allègre, C. J. & Rousseau, D. 1984 The growth of continent through geological time studied by Nd and isotope analysis of shales. *Earth planet. Sci. Lett.* **67**, 19–34.
Blattner, P., Dietrich, V. & Gansser, A. 1983 Contrasting ^{18}O enrichment and origin of High Himalayan and Transhimalayan intrusives. *Earth planet. Sci. Lett.* **65**, 276–286.
Casnedi, R., Desio, A., Forcelle, F., Nicoletti, M. & Petrucciani, C. 1978 Absolute age of some granitoid rocks between Hindu Raj and Gilgit River. *Rend. Sci. fis. mat. e nat.* **64**, 204–210.
Chang Chengfa & Pan Yushen 1981 A brief discussion on the tectonic evolution of the Qinghai-Xizang plateau. *Proceedings on Qinghai-Xizang (Tibet) Plateau*, **1**, 1–18. Beijing.
Chang Chengfa *et al.* 1986 Preliminary conclusions of the Royal Society and Academia Sinica 1985 geotraverse of Tibet. *Nature, Lond.* **323**, 501–507.
Coulon, C., Maluski, H., Bollinger, C. & Wang, S. 1986 Mesozoic and Cenozoic volcanic rocks from central and southern Tibet: ^{39}Ar-^{40}Ar dating, petrological characteristics and geodynamical significance. *Earth planet. Sci. Lett.* **80**, 281–302.
Davies, G., Gledhill, A. & Hawkesworth, C. 1985 Upper crustal recycling in southern Britain: evidence from Nd and Sr isotopes. *Earth planet. Sci. Lett.* **75**, 1–12.

Debon, F., Sonet, J., Lin Guohue, Jin Chengwei & Xu Ronghua 1982 Caractères chimico-mineralogiques et datations par Rb–Sr des trois ceintures plutoniques du Tibet meridional. *C. R. Acad Sci Paris* **295**, 213–218.

Debon, F., Le Fort, P., Sheppard, S. M. F. & Sonet J. 1986 The four plutonic belts of the Transhimalaya-Himalaya: a chemical, mineralogical, isotopic and chronological synthesis along a Tibet-Nepal section. *J. Petrol.* **27**, 219–250.

Debon, F., Le Fort, P., Dantel, D., Sonet, J. & Zimmermann, J. L. 1987 Granites of western Karakorum and northern Kohistan (Pakistan): A composite Mid-Cretaceous to Upper Cenozoic magmatism. *Lithos* **20**, 19–40.

De Paolo, D. J. 1981 Nd isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. *Nature, Lond.* **291**, 193–196.

Dodson, M. H. 1979 The theory of cooling ages. In *Lectures in isotope geology* (ed. E. Jager and J. C. Hunziker), pp. 194–202. Heidelberg: Springer-Verlag.

Duyverman, H. J., Harris, N. B. W. & Hawkesworth, C. J. 1982 Crustal accretion in the Pan African: Nd and Sr isotope evidence from that Arabian Shield. *Earth planet. Sci. Lett.* **59**, 315–326.

Gariepy, C., Allègre, C. J. & Xu Ronghua 1985 The Pb isotope geochemistry of granitoids from the Himalaya-Tibet collision zone: implications for crustal evolution. *Earth planet. Sci. Lett.* **74**, 220–234.

Goldstein, S. L., O'Nions, R. K. & Hamilton, P. J. 1984 A Sm-Nd isotopic study of atmospheric dusts and particuiates from major river systems. *Earth planet. Sci. Lett.* **70**, 221–236.

Hawkesworth, C. J., Kramers, J. D. & Miller, R. McG. 1981 Old model Nd ages in Namibian Pan-African rocks. *Nature, Lond.* **289**, 278–282.

Honneger, K., Dietrich, V., Frank, W., Gansser, A., Thoni, M. & Trommsdorff, W. 1982 Magmatism and metamorphism in the Ladakh Himalayas (the Indus-Tsangpo suture zone). *Earth planet. Sci. Lett.* **60**, 253–292.

Maluski, H., Proust, F. & Xiao, X. C. 1982 $^{39}Ar/^{40}Ar$ dating of the Trans-Himalayan calc-alkaline magmatism of southern Tibet. *Nature, Lond.* **298**, 152–154.

McCulloch, M. T. & Chappell, B. W. 1982 Nd isotopic characteristics of S and I-type granites. *Earth planet. Sci. Lett.* **58**, 51–64.

McDermott, F. 1987 Granite petrogenetic crustal evolution studies in the Damara Pan-African orogenic belt, Namibia. Unpubl. Ph.D. thesis, Open University.

Michard, A., Gurnet, P., Soudant, M. & Albarede, F. 1985 Nd isotopes in French Phanerozoic shales: external vs. internal aspects of crustal evolution. *Geochim. cosmochim. Acta.* **49**, 101–610.

Petterson, M. G. & Windley, B. F. 1985 Rb–Sr dating of the Kohistan arc batholith in the Trans-Himalaya of north Pakistan and tectonic implications. *Earth planet. Sci. Lett.* **74**, 45–57.

Scharer, U., Hamet, J. & Allègre, C. J. 1983 The Transhimalaya (Gangdese) plutonism in the Ladakh region: an U–Pb and Rb/Sr study. *Earth planet. Sci. Lett.* **67**, 327–339.

Scharer, U., Xu Ronghua & Allègre, C. J. 1984 U–Pb geochronology of the Gangdese (Transhimalaya) plutonism in the Lhasa-Xigaze region, Tibet. *Earth planet. Sci. Lett.* **67**, 311–320.

Weaver, B. L. & Tarney, J. 1980 Continental crust composition and nature of the lower crust: constraints from mantle Nd–Sr isotope correlation. *Nature, Lond.* **286**, 342–346.

Xu Ronghua & Jin Chengwei 1984 A geochronological study of the Quxu batholith, Xizang. *Sci. Geol. Sinica*, 414–422.

Xu Ronghua, Scharer, U. & Allègre, C. J. 1985 Magmatism and metamorphism in the Lhasa Block (Tibet): a geochronological study. *J. Geol.* **93**, 41–57.