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Sr, Nd and O isotopic characterization of the Gophu La and Gumburanjun leucogranites (High Himalaya)

by *Giorgio Ferrara*[1], *Bruno Lombardo*[2], *Sonia Tonarini*[1] and *Bruno Turi*[3]

Abstract

The petrographical and compositional homogeneity of the Miocene tourmaline leucogranites of the High Himalaya at the scale of the whole mountain belt is accompanied by large variations in isotopic and trace-element ratios at the scale of a single pluton or even of the single outcrop. In this paper we discuss the results of an isotopic study (Sr, Nd and O) on two such plutons, the Gophu La granite of the eastern Himalaya and the Gumburanjun granite of the northwest Himalaya. In both plutons, initial $^{87}Sr/^{86}Sr$ isotope ratios (Sr_i) are very high (from .742 to .776) and Nd isotope ratios very low (ε_{Nd} from –12 to –14). $\delta^{18}O$ values in Gophu La range from 11.4 to 12.6‰. Such values are in the same range as those obtained on other Himalayan leucogranites, particularly on the Manaslu granite of central Nepal, and point to a purely crustal origin for these magmas. Independently of provenance, our data can be subdivided into two groups, each with a different geochemical signature.

The first group includes most Gophu La samples and is characterized by very high Sr_i (.772–.776), $^{143}Nd/^{144}Nd$ ratios ranging only between .51193 and .51196, and by Rb/Sr ratios between 2 and 8. The second group includes all Gumburanjun but one sample and has $^{87}Sr/^{86}Sr$ initial ratios between .742 and .754, $^{143}Nd/^{144}Nd$ ratios between .51189 and .51204, and Rb/Sr ratios ranging only between 2 and 5. From the available data, most Himalayan leucogranites, including Manaslu, appear to have isotopic signatures like that of group 2. Some, including Gophu La and Gumburanjun, have both signatures, a few apparently only have the high Sr_i signature. An origin from partial melting of an isotopically heterogeneous, metasedimentary source is likely for the relatively low Sr_i magmas, whereas an origin from a 500 Ma old granitoid from an igneous protolith is more likely for the high Sr_i granites. The common occurrence of magmas with both low and high $^{87}Sr/^{86}Sr$ initial ratios in a single pluton (e.g. Gophu La) suggest a close association of the two parent materials in a single source region.

Keywords: Leucogranites, $^{87}Sr/^{86}Sr$ ratio, Nd data, $\delta^{18}O$ values, High Himalaya, Gophu La, Gumburanjun, Bhutan, Zanskar.

Introduction

Unlike most leucogranites, which are derived through fractional crystallization from granite liquids retaining a mantle-derived component, the Miocene leucogranites of the Himalaya are purely upper-crustal melts of very constant composition, closely approaching compositions of "minimum" melts in the haplogranite system. Recent studies of radiogenic and stable isotope variations in the Himalayan leucogranites (Vidal et al., 1982; Blattner et al., 1983; Ferrara et al., 1983; Deniel et al., 1987; France-Lanord et al., 1988) have shown that the isotopic heterogeneity commonly observed even at the metre scale in such granites does not result from the action of fluids, but rather reflects initial isotopic heterogeneity of the source material which has not been obliterated by magmatic processes. It has been thus possible to evaluate compositions of the source regions and put constraints on geological models for the generation of the leucogranite plutons, particularly for the Manaslu granite of central Nepal (Deniel et al., 1987; France-Lanord et al., 1988).

In the present study $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and $\delta^{18}O$ variations have been used to investigate the

[1] Istituto di Geocronologia e Geochimica Isotopica, CNR, Via C. Maffi, 36, I-56100 Pisa.
[2] Centro di Studio sulla Geodinamina delle catene collisionali, CNR, c/o Dipartimento di Scienze della Terra, Via Valperga Caluso, 37, I-10125 Torino.
[3] Dipartimento di Scienze della Terra, Università «La Sapienza» di Roma, P.le A. Moro, I-00185 Roma.

origin of the Gophu La and Gumburanjun granites of the Bhutan and NW Himalaya, respectively. We also considered it important to compare our results with those on the Manaslu pluton and other less well documented Himalaya granites, in an attempt to assess the regularity and continuity of the isotopic variations and their implications on age determinations with Rb/Sr whole-rock isochrons.

Geological setting and age of the Gophu La and Gumburanjun granites

GEOLOGICAL SETTING

Leucogranite plutons occur along the entire length of the High Himalaya (Fig. 1) from Bhutan to the western Nanga Parbat syntaxis as a belt of about a dozen major lens-shaped plutons and probably twice as many smaller bodies and sheets (DIETRICH and GANSSER, 1981, Fig. 1; LE FORT et al., 1987, Tab. 1). The largest plutons are Mönlakarchung-Pasalum in Bhutan, Everest-Makalu, Manaslu and Mugu-Mustang in Nepal, and Badrinath Bhagirathi-Garhwal in India. The granite bodies are preferentially emplaced at, or close to a major structural (and metamorphic) discontinuity, which superposes low-grade metasediments of Late Proterozoic age (Haimantas) to the amphibolite-facies High Himalaya Crystallines, but some of them, including Gophu La, occur well in the latter.

Another belt of two mica adamellites, the North Himalaya belt, or Lhagoi Kangri belt of the Chinese authors, occurs some 60 km to the north of the High Himalaya belt. These plutons closely resemble those of the High Himalaya mineralogically, chemically and isotopically (DEBON et al., 1986) but have been emplaced as rising diapirs in the Tibetan sedimentary series, i.e. at higher structural levels than the High Himalaya granites.

The *Gophu La* granite crops out in Lunana, a remote and sparsely populated valley of northern Bhutan (Fig. 2). It is the second largest granite body of Bhutan, with an outcrop surface of 300 km^2, the largest being the Mönlakarchung-Pasalum body, 20 km to the east of Gophu La (DIETRICH and GANSSER, 1981; GANSSER, 1983).

Like other Himalayan leucogranites, the Gophu La body is lens-shaped and apparently rootless, its floor being exposed in the valley leading from Thamza, the highest village in Lunana, to Gophu La, a high mountain pass connecting Lunana with Mangde Chu and central Bhutan.

The Gophu La granite is broadly concordant with the regional structures and the metamorphic foliation of the enclosing gneisses, though the contact may often be discordant at smaller scales (GANSSER, 1983). Country rocks are migmatitic gneisses and amphibolite-facies metasediments of the High Himalaya Crystallines, gently dipping to the north and folded in large, open, antiforms and synforms, which also fold the Main Central Thrust.

Migmatitic gneisses and migmatites are predominant in the high mountain range dividing Lunana from southern Tibet, whereas the metasediments crop out as a thick band on both sides of middle and lower Lunana (Fig. 2). The metasedimentary rocks are garnet-biotite psammite gneisses, with bands of marble and amphibolite, and locally thick intercalations of biotite-muscovite granite (GANSSER, 1983, p. 84). The migmatitic gneisses are of quartzo-feldspathic composition, with biotite, garnet and sillimanite as minor components, and contain pods of biotite-muscovite granite. Mobilized biotite-muscovite granites with large cordierite crystals and rare andalusite are common just west of Lunana in the biotite-garnet gneisses cropping out between the village of Laya and Masang Kang (GANSSER, 1983, p. 99).

The *Gumburanjun* pluton, so named after a sharp ridge in the headwaters of Kargyak Chu in SE Zanskar, is an order of magnitude smaller than Gophu La, with probably no more than 30 km^2 in surface outcrop, and intrudes a higher structural level of the High Himalaya Crystallines; (GAETANI et al., 1985) just below the contact with the overlying sedimentary rocks of the Tibetan nappes (Fig. 3). The pluton consists of a relatively homogenous core surrounded by a spectacular network of dikes, apparently following sets of fractures in country rocks, detached blocks of which can be seen "floating" in the granite (Fig. 4). Country rocks, as seen in the cliffs just N of Gumburanjun, are fine-grained biotite gneiss with transposed dikes of muscovite-garnet metagranite cut by dikes of muscovite-tourmaline garnet-leucogranite, passing upwards to fine-grained garnet-biotite gneiss with intercalations of garnet-staurolite-biotite micaschists (POGNANTE et al., 1987) The upper part of the sequence consists of distinctive biotite-muscovite-garnet phyllites, commonly with biotite porphyroblasts a few mm in size (the Budhi Schist facies of HEIM and GANSSER, 1939, p. 87–88) and of more massive biotite metagreywacke. A rather "cold" mylonite zone marks the contact with the apparently unmetamorphosed Karsha Dolomite, the lowermost unit of the Phugtal Nappe, in turn the lowermost Tibetan nappe (GAETANI et al., 1985).

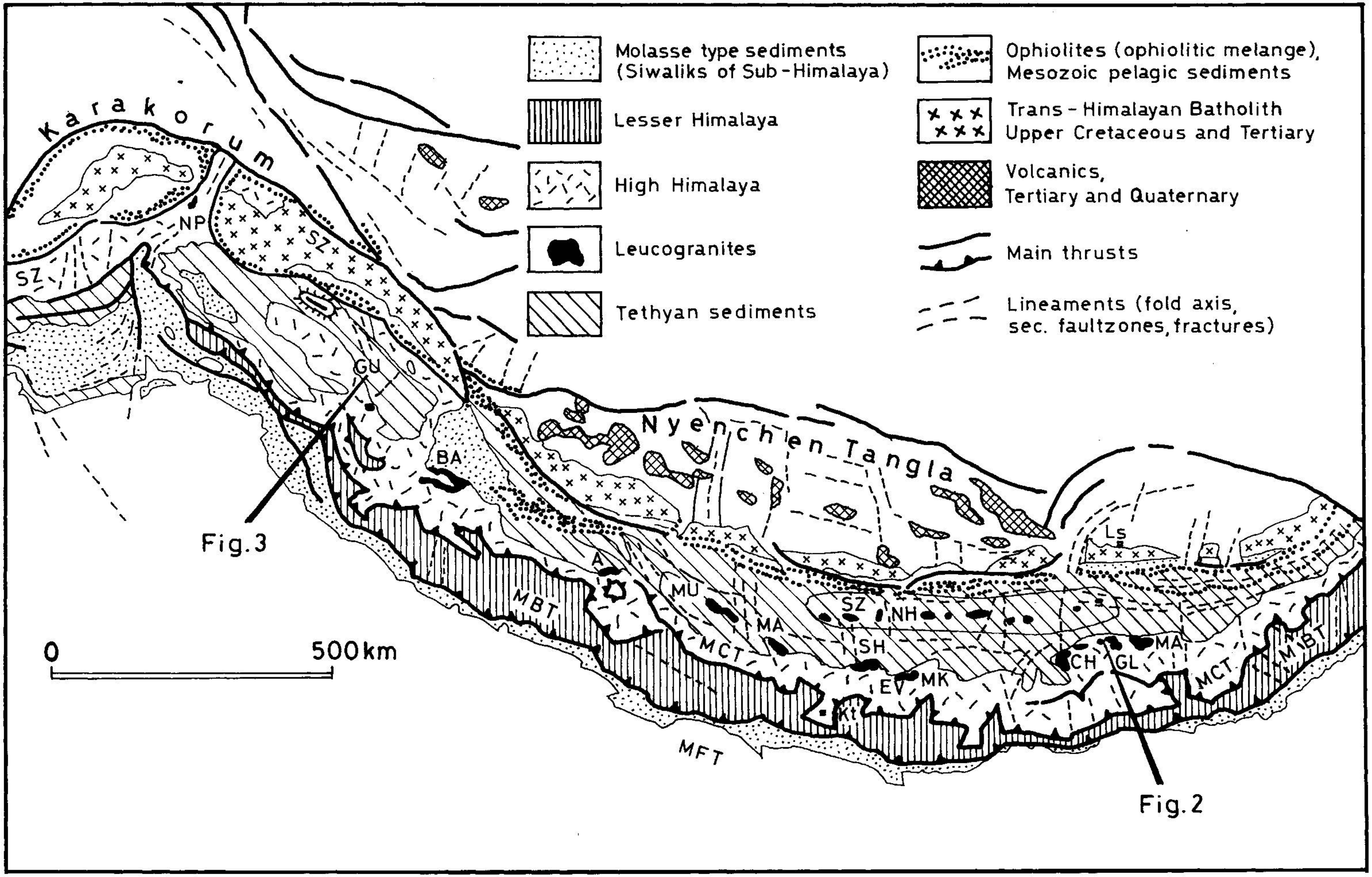

Fig. 1 Tectonic map of the Himalaya showing the major occurrences of Tertiary (Neogene) leucogranites after DIETRICH and GANSSER (1981). From NW to SE: NP = Nanga Parbat; GU = Gumburanjun; BA = Bhagirathi-Badrinath; A = Api; MU = Mustang; MA = Manaslu; SH = Shisha Pangma; EV = Everest; MK = Makalu; CH = Chomolhari and Chung La; GL = Gophu La; MA = Mönlakarchung-Pasalum; NH = North Himalaya Leucogranites. Kt = Kathmandu, Ls = Lhasa. Main structural units: SZ = Suture Zone (Indus/Yarlung Tsangpo); MCT = Main Central Thrust; MBT = Main Boundary Thrust; MFT = Main Frontal Thrust.

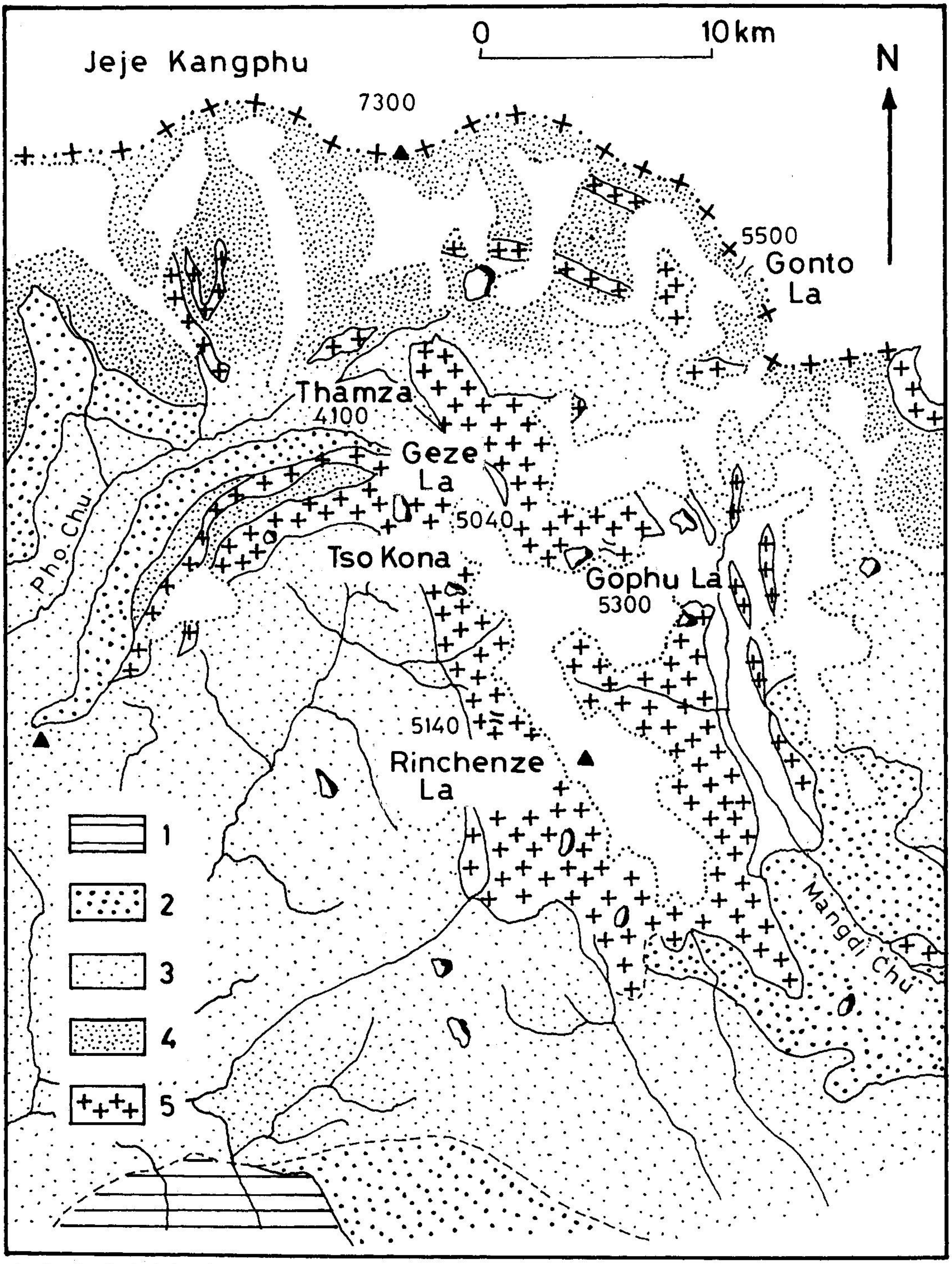

Fig. 2 Geological sketch map of the Gophu La region, from CASTELLI and LOMBARDO (1988), based on 1 : 500 000 Geological Map of the Bhutan Himalaya (GANSSER, 1983). 1 = low-grade phyllites and calc-schists of the Chekha Formation (Late Proterozoic?); 2 = metasediments; 3 = gneisses in general; 4 = migmatitic gneisses and migmatites; 5 = leucogranites.

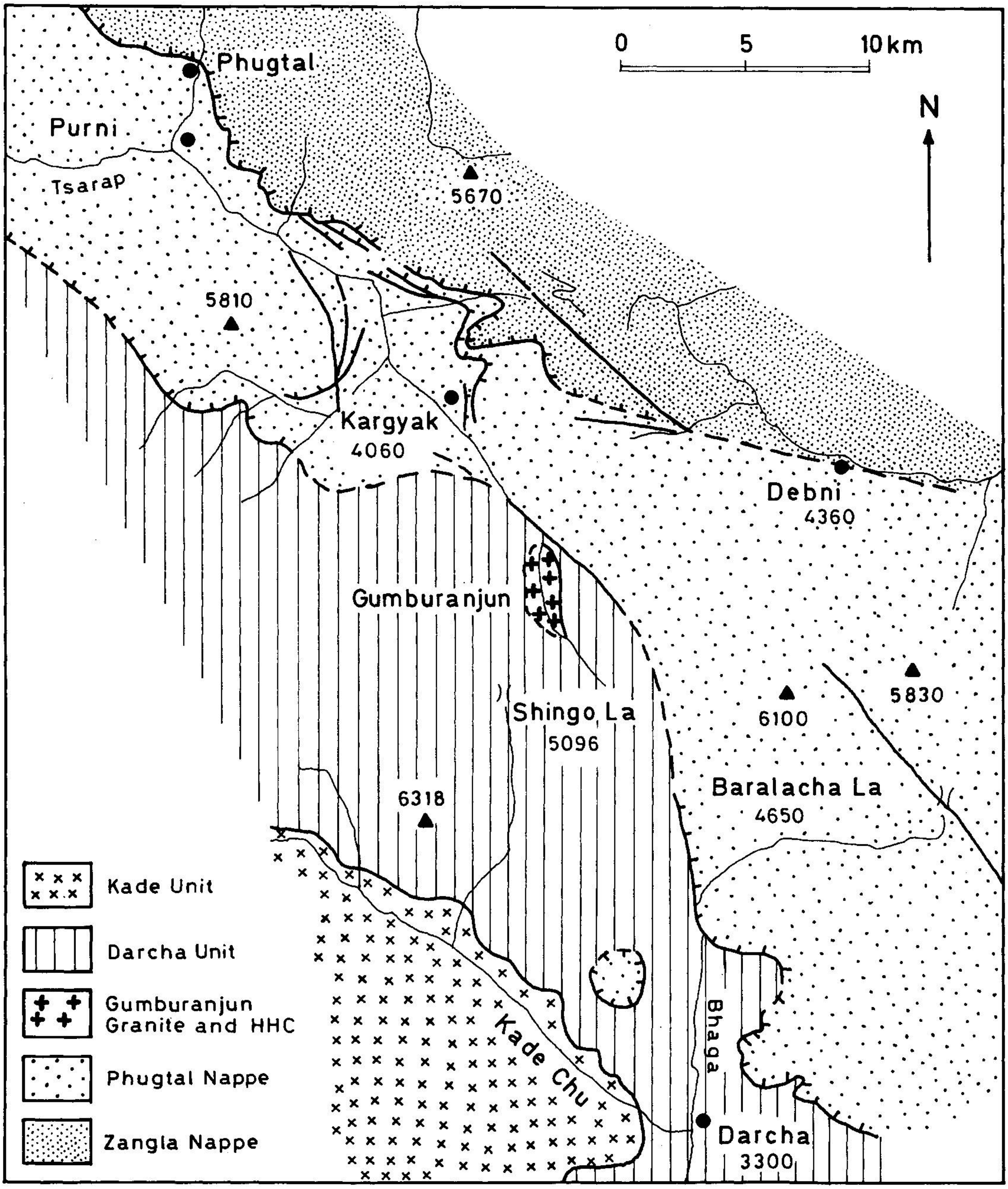

Fig. 3 Tectonic sketch map of Southeastern Zanskar and Northern Lahul (from GAETANI et al., 1985, simplified and slightly modified).

AGE

As is for most Himalayan leucogranites, Sr isotope heterogeneity precluded the use of the whole-rock isochron method to obtain a reliable age for the emplacement of the Gophu La and Gumburanjun granites. A minimum emplacement age is provided for Gophu La by Rb–Sr mineral ages on two samples, BH 17 from Tso Köna (Fig. 2) and BH 27 from a locality NW of Rinchenze La (Tab. 1). In BH 27 the muscovite- and biotite ages are identical (15.0 Ma), suggest-

Fig. 4 Gumburanjun from NW. In the center the H ridge; to the right the western face with the central couloir (photo courtesy M. Gaetani).

ing rapid closing of the Rb/Sr isotope systems, whereas in BH 17 the muscovite age (14.7 ± .2 Ma) is significantly older than the biotite age (14.0 ± .2 Ma), pointing to slower cooling in this part of the pluton. A $^{39}Ar/^{40}Ar$ study of K-feldspar from BH 17 (VILLA and LOMBARDO, 1986) indicated a minimum crystallization age of 18 Ma (Early Miocene) and a cooling rate for the granite of about 100 °C/Ma. A younger Rb–Sr biotite age (11 Ma: Middle Miocene) is reported by DIETRICH and GANSSER (1981) for the granite body of Chung La, about 100 km southwest of Gophu La, which intrudes the Late Proterozoic Chekha phyllites and calcschists.

In the *Gumburanjun* pluton, two samples (G1 and G10) from the same locality close to the center of the pluton, yielded almost identical Rb–Sr biotite ages (18.4 and 18.8 Ma, respectively) and a Rb–Sr muscovite age of 20.7 ± .3 Ma on G10 (Tab. 2), again suggesting a cooling rate of about 100 °C/Ma. A $^{39}Ar/^{40}Ar$ study of muscovite from the same samples (VILLA and ODDONE, 1988) yielded ages of 19.1 ± and 19.2 ± Ma, respectively.

Only another Rb–Sr mineral age seems to have been reported on leucogranite rocks of SE Zanskar, where SEARLE and FRYER (1986) obtained an age of 17.6 ± .2 Ma on biotite from a muscovite-tourmaline leucogranite collected E of Bardan Gompa, at the same structural level, but 50 km NW of Gumburanjun.

Petrography and bulk composition

PETROGRAPHY

The *Gophu La* pluton was sampled at three localities along the trail leading from Thamza to Pele La and the Thimphu-Tongsa road unnamed: Geze La, the Tso Köna lake and the camping ground NW of Rinchenze La (Fig. 2). The Gophu La granite is homogeneous and hololeucocratic

Tab. 1 Rb/Sr analyses of minerals from Gophu-La samples

Sample	Mineral	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma$	Age	$^{87}Sr/^{86}Sr_i$ (18 Ma)
BH17	Pl(+Qz)	25.2	66.9	1.09	.75314 ± 11		.7528
	Kf	755	130	16.9	.75662 ± 11		.7523
	Mu	932	14.3	190.7	.79241 ± 11	14.7 ± .2	
	Bt	1696	2.35	2189	1.18664 ± 31	14.0 ± .2	
BH27	Pl(+Kf)	301	86.4	10.14	.77493 ± 14		.7723
	Kf	1088	85.5	37.06	.78072 ± 14		.7713
	Mu	1122	3.44	961.1	.97702 ± 34	15.0 ± .3	
	Bt	1851	2.35	2411	1.28947 ± 26	15.1 ± .2	

(M' < 4.5). Grain size is fine at Geze La and Tso Köna and medium at Rinchenze La. Modal compositions straddle the boundary between the monzogranite and granodiorite fields of the QAP classification (Castelli and Lombardo, 1988), falling in the area of overlap of granitic compositions with sedimentary (S) and igneous (I) sources as defined by White and Chappell (1977).

Idiomorphic plagioclase, with oligoclase cores (An_{17}) and albite rims (An_5), is the most abundant constituent (36–39%), followed by quartz (29–32%), xenomorphic K-feldspar (21–23%), idiomorphic to interstitial phengitic muscovite (5–7%) and reddish-brown biotite (1–3%). A green biotite, probably formed by subsolidus reactions, occurs in a few samples. Characteristic accessory minerals are idiomorphic andalusite included in both plagioclase and muscovite, and sillimanite, nearly always replaced by fine grained white mica. Other accessory minerals are yellowish-brown, skeletal and zoned tourmaline, apatite, zircon and rare grains of opaque minerals.

The *Gumburanjun* pluton was sampled at two localities (Fig. 4): 1) at a 150 meter high section in the central couloir of the western face (# G1 ÷ G10) and 2) at the base of the northern ridge (G11 ÷ G16).

Like in the Gophu La granite modal compositions are dominated by plagioclase (35–40%) of oligoclase to albite composition, followed by quartz (about 30% in volume), K-feldspar (~20%) and muscovite (4–5%). Biotite is common but not abundant, with the exception of sample G8, in which biotite flakes up to 5–6 mm across define an igneous layering. Tourmaline is ubiquitous and more abundant than in Gophu La and may occur as the star-shaped clusters characteristic of many Himalayan leucogranites. Small crystals of pink garnet occur in samples both with biotite (G7, G8, G15) and without it (G12, G13), as well as in pegmatites with tourmaline, beryl, muscovite and unidentified Cu minerals.

BULK COMPOSITION

Average compositions and compositional ranges for the Gophu La and Gumburanjun granites are given in table 3 and compared with corresponding values in the Manaslu granite, one of the largest and the best studied Miocene pluton of the Himalaya. The notable homogeneity and small compositional range of the Miocene granites at the scale of the whole mountain belt (Manaslu is 550 km west of Gophu La and 800 km east of Gumburanjun) are obvious: all have high values of SiO_2, Al_2O_3 and alkalies, with low contents of total Fe and especially of MgO, yelding normative

Tab. 2 Rb/Sr analyses of minerals from Gumburanjun samples

Sample	Mineral	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma$	Age	$^{87}Sr/^{86}Sr_i$ (20 Ma)
G1	Pl(+Qz)	19.5	65.0	.873	.77287 ± 9		.7726
	Kf(+Qz)	145	127	3.33	.77340 ± 9		.7725
	Bt	1456	2.07	2158	1.33714 ± 13	18.4 ± .3	
G10	Kf	606	125	14.08	.75740 ± 8		.7534
	Mu	671	9.3	211	.81567 ± 17	20.7 ± .3	
	Bt	1713	2.43	2166	1.33172 ± 20	18.8 ± .3	

Tab. 3 Average compositions and compositional range of Himalayan leucogranites

			Manaslu			
	x(14)	Gophu La	x(201)	MSD	x(17)	Gumburanjun
SiO_2	73.46	72.31– 75.16	73.65	1.18	73.91	71.39– 75.36
TiO_2	0.12	0.07– 0.15	0.10	0.07	0.06	0.01– 0.09
Al_2O_3	14.87	14.20– 15.28	14.87	0.63	15.25	14.56– 16.99
Fe_2O_3tot	0.86	0.26– 1.06	0.84	0.20	0.85	0.46– 1.65
MnO	0.02	0.01– 0.03	0.03	0.01	0.03	0.01– 0.07
MgO	0.05	0.01– 0.13	0.11	0.09	0.17	0.11– 0.29
CaO	0.71	0.57– 0.88	0.47	0.37	0.59	0.43– 0.75
Na_2O	4.06	3.73– 4.33	4.05	0.34	4.16	2.96– 4.81
K_2O	4.78	4.11– 5.00	4.56	0.44	4.29	3.53– 5.77
P_2O_5	0.09	0.04– 0.14	0.13	—	0.18	0.07– 0.42
L.O.I.	1.00	0.66– 1.74	0.84	0.30	0.55	0.31– 0.83
Rb	357	295 –418	287		247	200 –296
Sr	74	52 – 98	76		83.6	47.8 –104.0
Rb/Sr	4.7	3.5 – 7.4	3.8		3.0	2.1 – 6.0
K/Rb	112.4	92.9 –135.6	133.4		146.0	120.5 –169.8

Sources of data
Gophu La: Castelli and Lombardo (1988, Tab. 5) and this paper (Tab. 5)
Manaslu: Le Fort et al. (1987, Tab. 2)
Gumburanjun: this paper (Appendix and Tab. 4)

compositions characteristic of peraluminous granites. Rb contents and Rb/Sr ratios are both high.

As noted by several authors (e.g. Dietrich and Gansser, 1981; Le Fort, 1981; Castelli and Lombardo, 1988), and experimentally demostrated by Bernard-Griffiths et al. (1985), such compositions are close to "minimum" melts, generated in a haplogranite system containing a few wt% of B_2O_3 and variable amounts of water in the fluid phase, which underwent some differentiation at the magmatic stage.

At the regional scale, a trend with increasing MgO and P_2O_5, and decreasing K_2O and Rb from east to west, which is apparent from the data of table 3, is probably due more to variations in relative proportions of different source rocks, than to differences in formation conditions, as we will show below.

Tab. 4 Rb/Sr and Nd isotopic data of the Gumburanjun granite

Sample	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma$	$^{87}Sr/^{86}Sr_i$ (20 Ma)	$^{143}Nd/^{144}Nd \pm 2\sigma$
G1	233	97.8	6.95	.77512 (6)	.7731	.511963 (41)
G2	221	67.4	9.53	.75597 (10)	.7533	
G3	249	72.1	10.05	.75445 (11)	.7516	
G4	272	100	7.91	.75561 (19)	.7533	
G5	296	66.9	12.86	.75682 (14)	.7532	
G6	252	81.2	9.02	.75531 (30)	.7528	
G7	285	47.8	17.34	.75681 (22)	.7419	
G8	242	72.5	9.73	.75416 (17)	.7514	
G9	232	84.2	8.02	.75145 (9)	.7492	.512015 (24)
G10	248	77.1	9.36	.75612 (5)	.7535	.511886 (23)
G11	284	97.3	8.49	.75637 (8)	.7540	
G12	217	73.0	8.62	.75356 (7)	.7511	.511931 (25)
G13	200	94.7	6.14	.75637 (5)	.7514	
G14	278	99.9	8.10	.75637 (5)	.7541	.512040 (23)
G15	223	104	6.24	.75280 (8)	.7510	
G16	229	102	6.53	.75511 (7)	.7533	
Z597	231	84	7.98	.75428 (8)	.7520	

Tab. 5 Rb/Sr, Nd and O isotopic data of the Gophu-La granite

Sample	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma$	$^{87}Sr/^{86}Sr_i$ (18 Ma)	$^{143}Nd/^{144}Nd \pm 2\sigma$	$\delta^{18}O$
BH 14 Geze La	360	70.1	14.97	.77779 (14)	.7740	.511932 (32)	12.42
BH 15 Geze La	329	94.3	10.15	.75513 (6)	.7525	.511975 (26)	11.38
BH 16 Geze La	380	68.5	16.16	.78060 (14)	.7765		12.58
BH 17 Tso Kona	323	89.2	10.50	.75461 (17)	.7519	.511992 (35)	11.45
BH 18 Tso Kona	295	66.6	12.88	.77494 (8)	.7716		11.91
BH 19 Tso Kona	418	98.2	12.41	.77779 (11)	.7746		12.10
BH 20 Tso Kona	347	94.4	10.68	.75440 (14)	.7517	.512004 (30)	11.78
BH 21 Tso Kona	320	88.9	10.46	.75613 (6)	.7535	.511928 (23)	12.08
BH 22 Tso Kona	329	89.6	10.66	.75731 (8)	.7555	.511995 (18)	12.03
BH 23 Tso Kona	396	62.9	18.40	.77642 (13)	.7717	.511954 (20)	11.70
BH 24 Rinchenze La	376	68.3	16.03	.77858 (10)	.7745		12.04
BH 25 Rinchenze La	347	57.1	17.72	.77656 (11)	.7721		11.95
BH 26 Rinchenze La	387	64.2	17.57	.77702 (11)	.7725	.511934 (18)	11.98
BH 27 Rinchenze La	385	52.4	21.41	.77664 (8)	.7711	.511939 (36)	12.55

Isotope geochemistry

Sr and Nd isotope ratios for the Gumburanjun and Gophu La granites are given in tables 4 and 5. Table 5 also gives $\delta^{18}O$ for the Gophu La granite. Sr isotope ratios have been corrected assuming an emplacement age of 20 Ma for Gumburanjun (Villa and Oddone, 1988) and 18 Ma for Gophu La (Villa and Lombardo, 1986). No age correction was applied to Nd isotope ratios, as in the other Miocene leucogranites of the Himalaya its value is not larger than 1.0–2.0 × 10^{-5} (Deniel et al. 1986, 1987).

Initial Sr isotope ratios (Sr_i) in the Gumburanjun granite are very uniform, as in 15 out of 17 samples, Sr_i range only between .749 and .754. The only two exceptions are sample G1, where Sr_i is much higher (.773) and sample G7, where it is lower (Sr_i = .742). Sr_i values in the Gophu La pluton have a bimodal distribution which is independent from the sampling locality: five samples (one from Geze La and four from Tso Köna) have Sr_i between .752 and .755, i.e. in the same range as most Gumburanjun samples, whereas the other nine samples (two from Geze La, three from Tso Köna and the four from Rinchenze La)

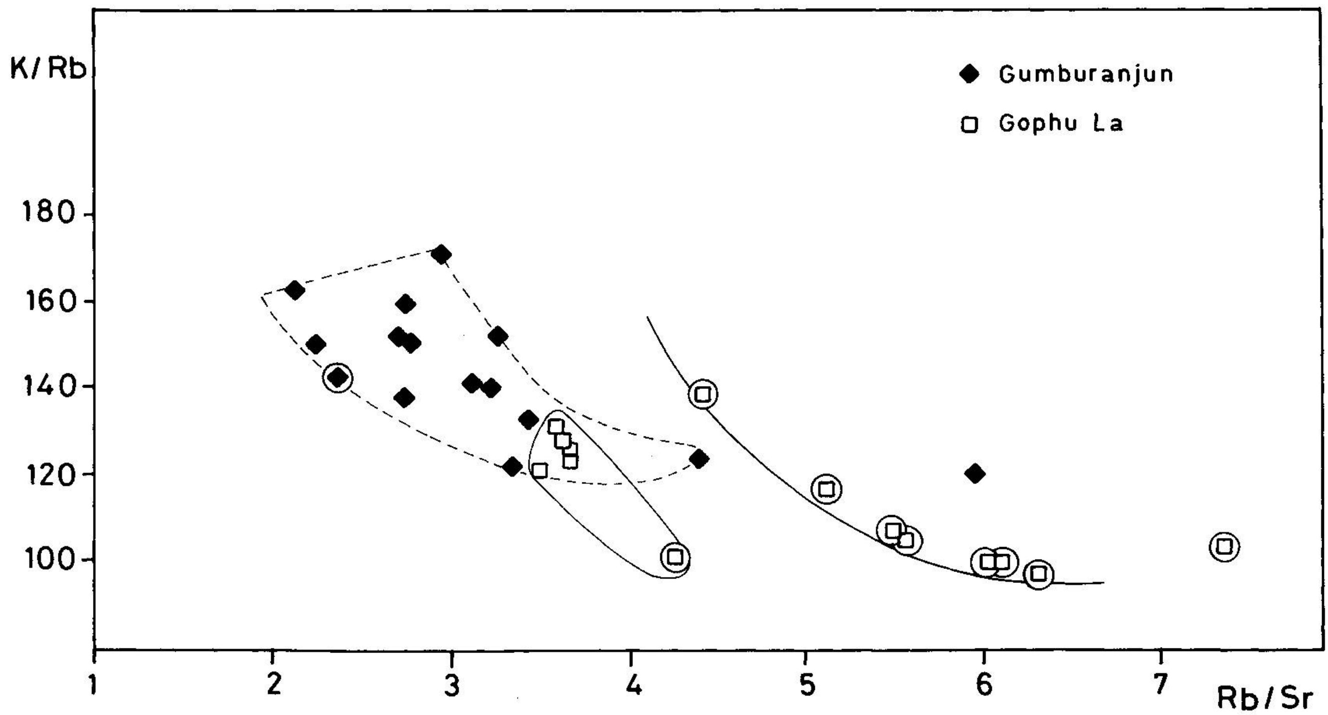

Fig. 5 K/Rb vs. Rb/Sr diagram for the Gophu La and Gumburanjun leucogranites. Data point within circles are relative to the samples with higher Sr isotopic initial composition.

have much higher Sr_i, specifically between .771 and .777. When Sr_i are plotted against Rb/Sr ratios (Fig. 5) the low Sr_i population displays relatively small variation of Rb/Sr ratios (2.0–4.5), whereas the spreading in Rb/Sr ratios of the high Sr_i population is fairly larger, from 4.0 to 7.5 in Gophu La and from 2.0 to 7.5 if Gumburanjun and the leucogranites from Bhutan analyzed by DENIEL et al. (1986) are also considered. In a plot of K/Rb against Rb/Sr (Fig. 6) the low Sr_i samples from Gophu La again tightly cluster together, falling in the middle of the field defined by the Gumburanjun samples, whereas the high Sr_i samples from Gophu La and, less clearly, also the Gumburanjun samples fall on hyperbolic trends of increasing Rb/Sr ratios and decreasing K/Rb ratios. These trends are consistent with those expected during fractional crystallization, when Rb is concentrated in the residual liquids, Rb/Sr ratios increase and K/Rb ratios fall (TAYLOR et al., 1967) but could also result from variations in the amount of partial melting. As noted by FERRARA et al. (1989), the second possibility seems to be ruled out by the observation that radiogenic Sr preferentially enter the liquid phases during incipient disequilibrium melting. In the high Sr_i population the samples which have the highest Rb/Sr ratios, also have the lowest Sr_i. The relations observed between Sr_i and Rb/Sr for all samples are reversed when Sr_i are plotted against P_2O_5, as all the samples with high Sr_i tend to cluster together at low values of P_2O_5, and it is the low Sr_i population which shows the largest spreading in P_2O_5 (Fig. 7). Following WHITE and CHAPPELL (1977) we interpret such a trend as reflecting progressively larger incorporation of refractory residua of parent material in a low P_2O_5 "minimum" melt.

In contrast to Sr isotope heterogeneity, Nd isotope ratios are highly uniform, ranging only between 0.51189 and 0.51204 in Gumburanjun and between 0.51193 and 0.51204 in Gophu La. If $^{143}Nd/^{144}Nd$ ratios are plotted against Sr_i (Fig. 8) some spreading is observed in the low Sr_i population, whereas the high Sr_i samples are tightly grouped, together with the Bhutan granites studied by DENIEL et al. (1986). Variations in the Nd isotope ratios of the low Sr_i samples could be explained by different contents of restite phases such as apatite, but P_2O_5 contents in both Sr_i

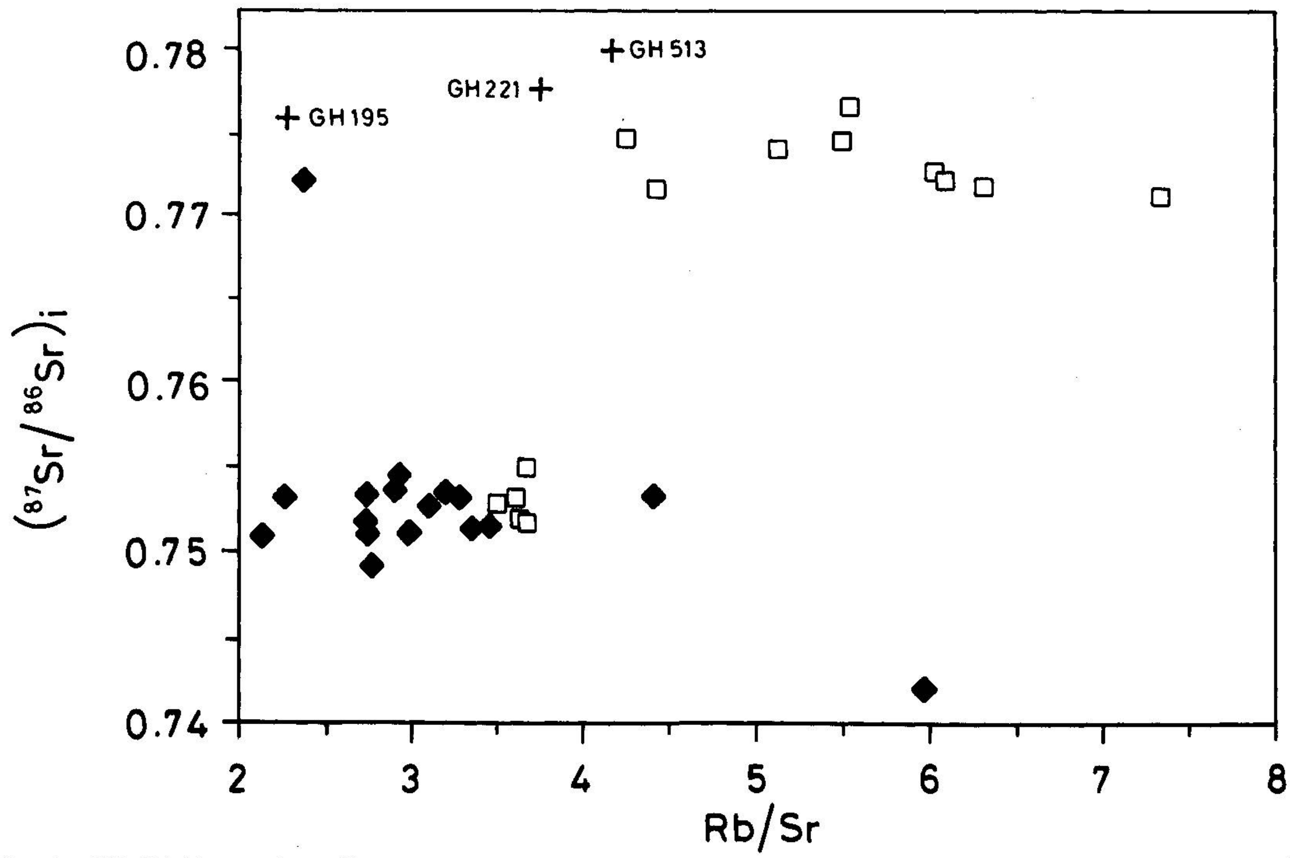

Fig. 6 ($^{87}Sr/^{86}Sr$)i vs. Rb/Sr diagram for the Gophu La (open squares) and Gumburanjun (closed diamonds). Crosses are Bhutan granites from DIETRICH and GANSSER (1981).

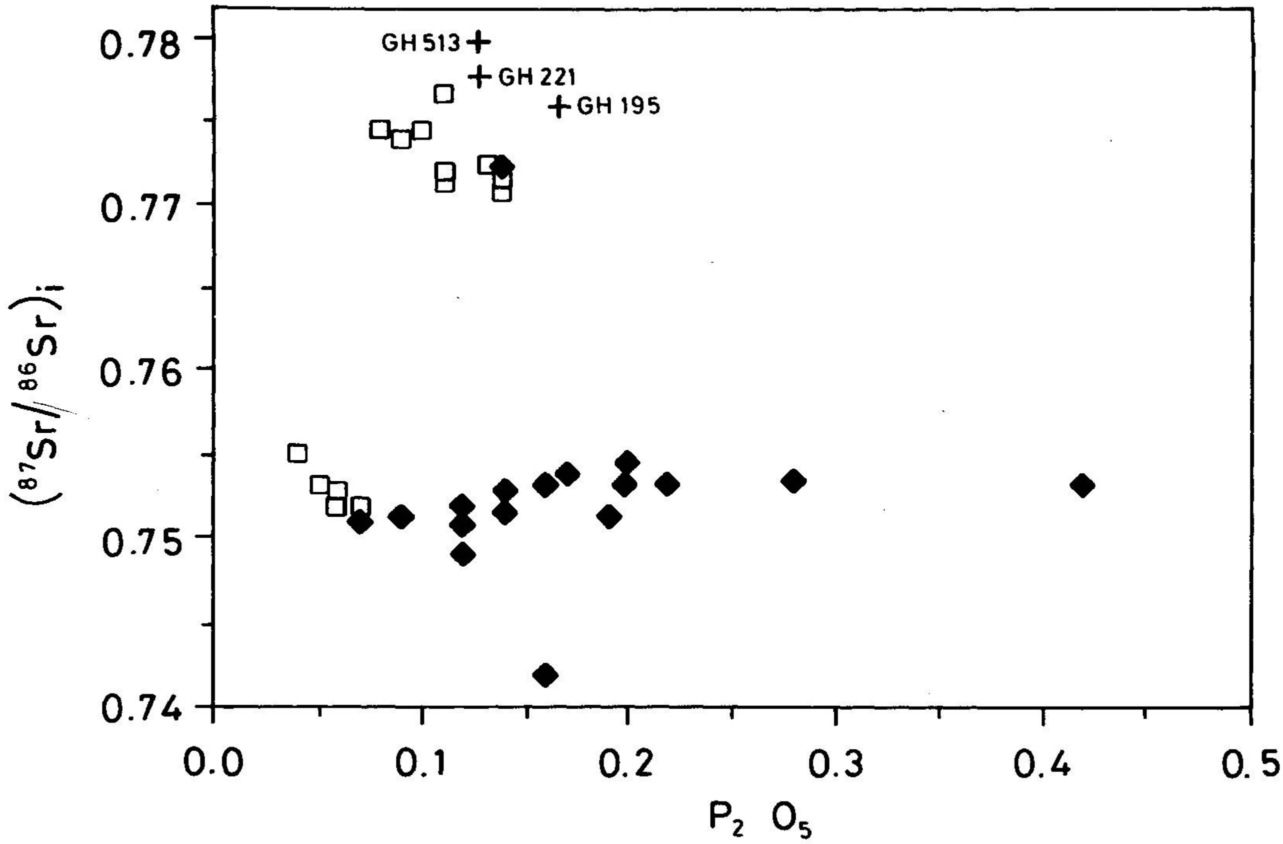

Fig. 7 $(^{87}Sr/^{86}Sr)_i$ vs. P_2O_5 diagram for the Gophu La and Gumburanjun granites. Symbols as in Fig. 6.

groups are totally unrelated with the Nd isotope composition (Fig. 9). Assuming that the Nd isotope variations in the low Sr_i granites directly reflect variations of this ratio in the parent rocks, as demonstrated for the Manaslu granite by VIDAL et al. (1984), a better explanation seems to be isotope heterogeneity of source material, with admixing of a quartz-rich end member of low ε_{Nd} with a pelitic end member of higher ε_{Nd} (FRANCE-LANORD et al., 1988). Conversely, the absence of significant variation in the Nd isotope ratios of the high Sr_i granites implies that the source region(s) of these melts must have been homogeneous with respect to Nd.

The Gophu La samples dispay a narrow range of $\delta^{18}O$ (11.4–12.6‰, mean 12‰, see Fig. 10) with a tendency for lower values in the low Sr_i group ($\bar{x}$ = 11.74, range 11.38–12.08) and for higher values in the high Sr_i group ($\bar{x}$ = 12.14, range 11.70–12.58). Such $\delta^{18}O$ values are comparable to those found by BLATTNER et al. (1983) on other Bhutan leucogranites (average of 7 samples: $\delta^{18}O$ = 11.51‰, range 9.5–12.4) and by FRANCE-LANORD et al. (1988) on the Manaslu granite (average of 11 samples: $\delta^{18}O$ = 11.95‰, range 10.9–12.8).

Discussion: Implications of isotope systematics for the petrogenesis of Himalayan leucogranites

A close similarity in bulk composition between the Gophu La and Gumburanjun granites, more than 1300 km apart, and of both with the Manaslu granite, is obvious from the data presented above, the main difference being the higher Rb contents and Rb/Sr ratios of Gophu La. On the other hand Sr_i, regardless of provenance, clearly fall in two separate groups. A first group (1) is characterized by Sr_i between 0.772 and 0.776, $^{143}Nd/^{144}Nd$ ratios between 0.51193 and 0.51196, and by Rb/Sr ratios between 2 and 8. Leucogranites with such high Sr_i are apparently predominant in Bhutan, as all the samples analyzed by DIETRICH and GANSSER (1981, Tab. 3) and DENIEL et al. (1986, Tab. 1) have Sr_i in this range, but also occur in the Mt. Everest region (Lhotse Nup Glacier: FERRARA et al., 1983, DENIEL et al., 1986), the Bhagirathi-Badrinath pluton of Garhwal (DENIEL et al., 1986; STERN et al., 1989) and in the Chenab valley of Western Himalaya (SEARLE and FRYER, 1986, Tab. 3). Only one sample (G1) from the Gumburanjun pluton belongs to this group, whereas 9 out of 14 Gophu La samples belong to it. $^{143}Nd/$

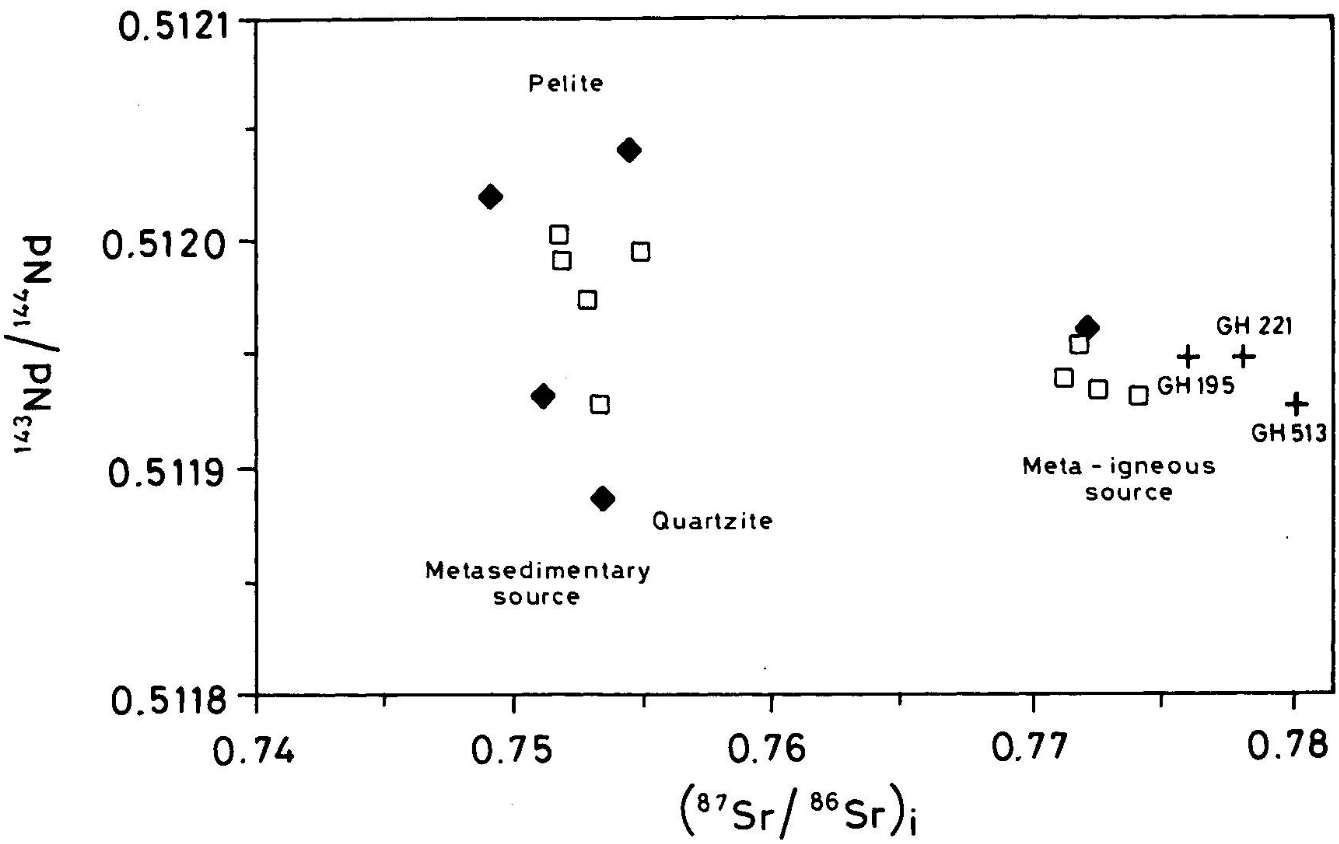

Fig. 8 $^{143}Nd/^{144}Nd$ vs. $(^{87}Sr/^{86}Sr)i$. Symbols as in Fig. 6. Nd isotope ratios for Bhutan leucogranites (+) are from DENIEL et al. (1986). Two likely parent rock compositions are identified as well as the dominant component in sedimentary quartz-feldspar-phyllosilicate mixtures. See text for discussion.

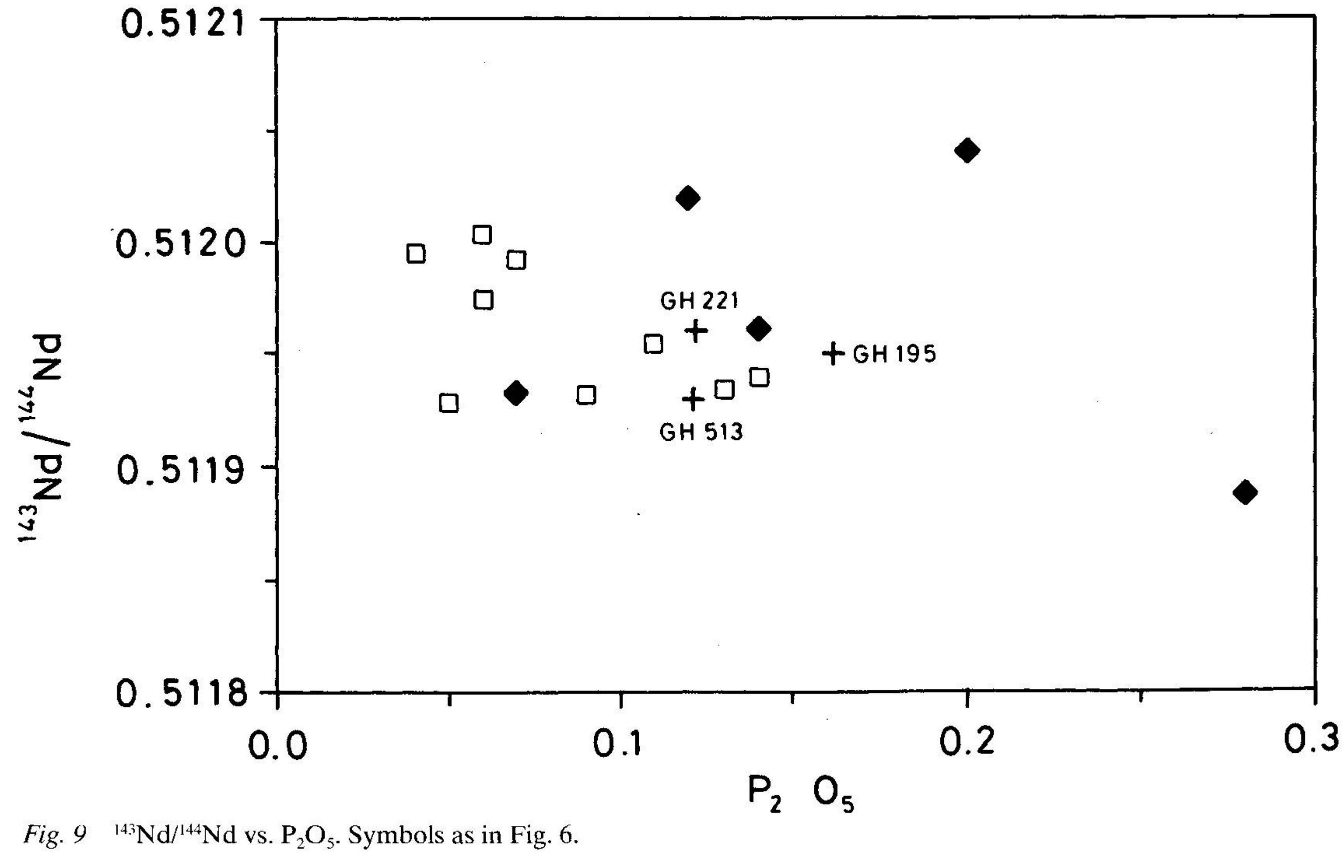

Fig. 9 $^{143}Nd/^{144}Nd$ vs. P_2O_5. Symbols as in Fig. 6.

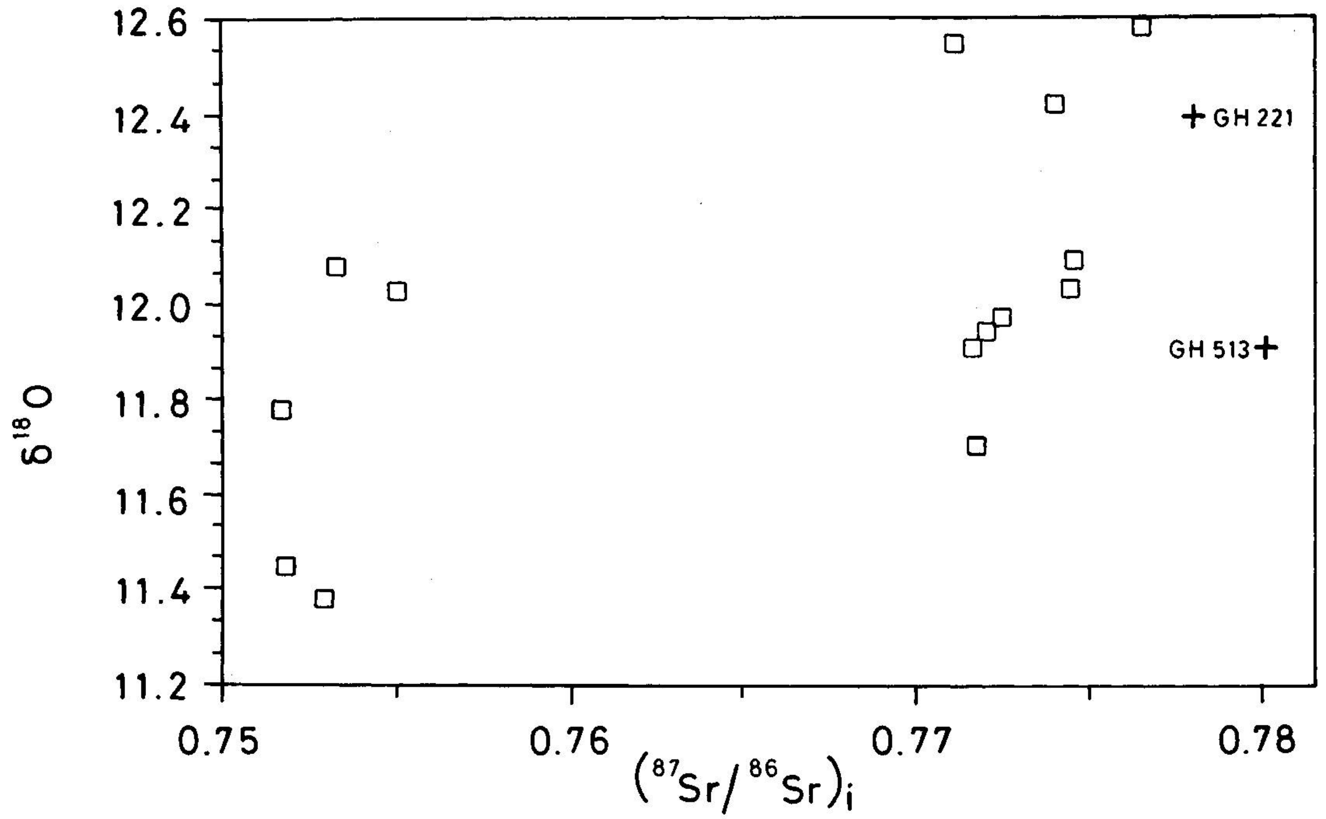

Fig. 10 Plot of $\delta^{18}O$ vs. $(^{87}Sr/^{86}Sr)i$ for the Gophu La leucogranites (open squares). Crosses are Bhutan granites from BLATTNER et al. (1983).

^{144}Nd ratios measured by DENIEL et al. (1986, Tab. III), on the high Sr_i granites from Bhutan and the Badrinath pluton are in the same range we measured on such granite in Gophu La and Gumburanjun (0.51192–0.51196, 0.51190–0.51194 with the age correction).

The second group (2) has Sr_i typical of most Himalayan leucogranites (0.742–0.754, Rb/Sr ratios between 2 and 5, and $^{143}Nd/^{144}Nd$ ratios between 0.51189 and 0.51204. This group includes all Gumburanjun samples but one and five samples from Gophu La. Other low Sr_i granites are Nuptse (FERRARA et al., 1983) and especially Manaslu (DENIEL et al., 1987), in which Sr_i are mostly between 0.740 and 0.754 (but between 0.760 and 0.763 in a 160 m section in the west-central part).

Both in Gumburanjun and Gophu La petrographical and mineralogical evidence suggests that hydrothermal alteration has been low, or non-existent, as in the Bhutan leucogranites studied by BLATTNER et al. (1983) and especially in the Manaslu granite, where FRANCE-LANORD et al. (1988) were able to show that H- and O-isotope fractionations among minerals are consistent with high temperature equilibrium and, for O, with closed system evolution. Also, Sr_i of minerals, in particular of K-feldspar, in Gumburanjun and Gophu La are in equilibrium with those of the host granites, which may be thus considered to preserve the Sr isotope signature of parent rocks. Nd isotope compositions can be likewise assumed to be close to $^{143}Nd/^{144}Nd$ ratios of parent rocks, as it is known that this ratio is not affected by fractionation during anatexis of crustal material (DE PAOLO and WASSERBURG, 1976). Conversely, the Sm/Nd ratio, which should not be significantly changed by crustal processes (DE PAOLO and WASSERBURG, 1976; ALLÈGRE and BEN OTHMAN, 1980) is known to be fractionated during formation of leucogranite magmas (BERNARD-GRIFFITHS et al., 1985) and in the Manaslu granite (DENIEL et al., 1987) it is significantly higher than the crustal average of DE PAOLO and WASSERBURG. These features could be due to extraction of accessory REE-rich minerals (monazite) as suggested by VIDAL et al. (1984).

Detailed geochemical investigations, summarized by DENIEL et al. (1987) and FRANCE-LANORD et al. (1988) have shown that the best candidate as source material of the Manaslu granite is Formation 1 (F1), a thick quartz-pelitic sequence forming the base of the High Himalaya Crystallines in Central Nepal (LE FORT, 1981). Isotopic variations in Formation 1 at the time of melting were preserved during emplacement and crystallization of leucogranite magma, whose isotope compositions bear the inherited signature of F1 and are related to the original mineralogical constitution of the parent sediments. In particular, variations in ε_{Nd} are directly linked to ε_{Nd} differences in the sedimentary precursors of F1 and the spreading in Sr_i reflects the variability of Rb contents in source material, whereas $\delta^{18}O$ variations reflect the initially $\delta^{18}O$ values of the sediments which were smoothed out during diagenesis and metamorphism (FRANCE-LANORD et al., 1988).

In view of the close isotopic similarity between Manaslu and our low Sr_i granites (group 2) we suggest that an origin from partial melting of an isotopically heterogeneous metasedimentary protolith like F1 is also likely for the low-Sr_i leucogranite magma in Gumburanjun and Gophu La. In contrast, the origin of the high Sr_i granites (group 1) seems to be better explained by partial melting of a source region susceptible of yielding large amounts of melts close to "minimum" compositions, with uniform Nd isotope ratios and high, but strongly variable, Sr isotope ratios. This last feature could a) reflect variations in Rb/Sr ratios of source rocks, hence different contents of inherited radiogenic ^{87}Sr, or b) simply be caused by different degrees of mixing between a "minimum" melt and restite material. In view of the observed isotopic equilibrium between the minerals of the high-Sr_i samples, we favour the first hypothesis and assume that Sr isotope heterogeneity in this group is inherited from source rocks.

$^{87}Sr/^{86}Sr$ evolutionary diagrams of the High Himalaya Crystallines (HONEGGER et al., 1982; VIDAL et al., 1982; BORTOLANI et al., 1983) suggest that the best candidate as parent material of the high Sr_i magmas may be igneous, rather than metasedimentary, and be represented by the so called "500 Ma Intrusives", i.e. the lower Palaeozoic metagranites and orthogneisses which are present all along the High Himalaya and may be locally more abundant than paragneisses. Geochemical investigations of such rocks are still scarce (see LE FORT et al., 1986 for a review and references; also POGNANTE et al., 1990), but enough information is available to indicate that they can have Sr isotope ratios at 20 Ma high enough to generate the high Sr_i leucogranite magmas, though they are not so radiogenic as the older 1800 Ma intrusives also present in the Himalaya, e.g. in the Berinags of the Larji-Kulu-Rampur Window, NW Himalaya (FRANK et al., 1977). However, the common occurrence of magmas with both low and high Sr_i, in a single pluton (e.g. Gophu La and Gumburanjun) points to a close association of the two parent materials in a single source region, as is actually the case in areas so far apart as Bhutan (GANSSER, 1983), the Mount Everest region (BORTOLANI et al., 1983) and Zanskar (POGNANTE et al., 1990). Such a source region could produce isotopically heterogeneous magmas of very uniform chemical composition, in which ε_{Nd} would be positively correlated with $^{87}Sr/^{86}Sr$ ratios (like in Manaslu: VIDAL et al., 1984; DENIEL et al., 1987) as a result of mixing between two end member compositions reflecting two different types of source rock.

Summary and conclusions

1) Isotopic measurements on the Gophu La granite of Bhutan and the Gumburanjun granite of Zanskar confirm the existence of isotopic inhomogeneity at the scale of a single pluton, or even of the single outcrop in the Miocene leucogranites of the High Himalaya.

2) Independently of provenance, whether from Gophu La or Gumburanjun, or from individual outcrops in the two plutons, our data cluster in two groups, each with a different geochemical signature.

A first group of samples is characterized by $^{87}Sr/^{86}Sr$ initial ratios between 0.772 and 0.776, by $^{143}Nd/^{144}Nd$ ratios between 0.51193 and 0.51196 and by Rb/Sr ratios between 2 and 8. Leucogranites with such high Sr_i are apparently predominant in Bhutan, but also occur in the Mt. Everest region, in the Mugu-Mustang batholith of Western Nepal, in the Bhagirath-Badrinath pluton of Garhwal and in the Chenab Valley of Western Himalaya. Nine out of fourteen samples of Gophu La, but only one sample from Gumburanjun, belong to this group.

The second group has Sr_i in the same range as most Himalayan leucogranites (0.742–0.754), Rb/Sr ratios between 2 and 5, $^{143}Nd/^{144}Nd$ ratios between 0.51189 and 0.51204. This group includes all but one Gumburanjun samples and five samples from Gophu La.

3) In view of the close isotopic similarity between our low-Sr_i group and the Manaslu leucogranite we suggest that an origin from partial melting of an isotopically heterogeneous metasedimentary protolith like Formation 1 of the Tibetan Slab in Central Nepal is also likely for the low-Sr_i leucogranite magma in Gumburanjun and Gophu La.

4) The origin of the higher Sr_i group seems to be better explained by partial melting of an igneous protholith susceptible of yielding large amounts of melts close to "minimum" compositions with a small range of Nd isotope ratios and $^{87}Sr/^{86}Sr > 0.77$. This last feature could reflect

variations in Rb/Sr ratios of source rocks, hence different contents of inherited radiogenic ^{87}Sr.

The best candidates as parents of the high-Sr_i magma appear to be represented by the "500 Ma intrusives", i.e. the lower Palaeozoic metagranites and orthogneisses, which comprise large tracts of the High Himalayan Crystallines and also occur in the Lesser Himalaya.

5) The common occurrence of magmas with both low and high Sr_i in a single pluton (e.g. Gophu La and Gumburanjun), points to a close association of the two parent materials in a single source region, as is actually the case in areas of the High Himalaya Crystallines so far apart as Bhutan, the Mount Everest region and Zanskar.

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Appendix 1

Major-element composition of the Gumburanjun leucogranite

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
SiO_2	74.16	73.96	75.04	73.15	73.91	73.81	74.51	74.10	75.36	73.50
TiO_2	0.09	0.05	0.05	0.06	0.09	0.05	0.03	0.07	0.03	0.06
Al_2O_3	15.03	15.52	14.61	15.63	14.63	15.31	14.80	15.21	14.48	15.53
Fe_2O_3	0.59	0.54	0.37	0.44	0.81	0.41	0.62	0.57	0.39	0.50
FeO	0.37	0.14	0.29	0.28	0.63	0.24	0.10	0.42	0.10	0.23
MnO	0.03	0.02	0.02	0.02	0.04	0.02	0.05	0.03	0.01	0.03
MgO	0.18	0.13	0.13	0.15	0.24	0.13	0.07	0.16	0.09	0.13
CaO	0.57	0.58	0.56	0.58	0.73	0.58	0.43	0.58	0.48	0.71
Na_2O	4.38	4.25	4.29	3.86	3.37	4.48	4.64	4.59	4.81	4.27
K_2O	3.99	4.03	3.96	4.95	4.39	4.26	4.09	3.53	3.83	4.14
P_2O_5	0.14	0.16	0.14	0.22	0.42	0.14	0.16	0.19	0.12	0.28
L.O.I.	0.48	0.61	0.54	0.67	0.73	0.52	0.45	0.56	0.31	0.63

G1, G3, G6 and G9: medium-grained, tourmaline-rich leucogranite
G2, G4, G5 and G10: ditto, with star-shaped tourmaline clusters
G7: aplitic tourmaline granite with accessory garnet
G8: banded tourmaline granite, with large biotite crystals and accessory garnet
All the samples were collected along a 150 meters high section in the central couloir of the western face.

	G11	G12	G13	G14	G15	G16	Z597
SiO_2	71.39	74.28	75.03	73.09	73.19	72.76	75.24
TiO_2	0.09	0.01	0.05	0.07	0.07	0.09	0.04
Al_2O_3	16.99	15.34	14.56	15.65	16.16	15.60	14.20
Fe_2O_3	0.75	0.36	0.49	0.35	0.39	0.44	0.62
FeO	0.34	0.10	0.10	0.49	0.40	0.82	0.10
MnO	0.01	0.07	0.01	0.02	0.02	0.02	0.01
MgO	0.29	0.13	0.11	0.26	0.21	0.28	0.12
CaO	0.53	0.59	0.57	0.58	0.63	0.75	0.53
Na_2O	2.96	4.26	4.74	3.20	3.88	4.06	4.57
K_2O	5.77	4.39	3.84	5.40	4.38	4.18	3.96
P_2O_5	0.17	0.07	0.09	0.20	0.12	0.20	0.12
L.O.I.	0.70	0.39	0.40	0.69	0.56	0.83	0.27

G11, G14 and G16: medium-grained, muscovite-tourmaline leucogranite, with rare biotite
G15: coarse-grained, muscovite-tourmaline-garnet-biotite leucogranite
G12 and G13: fine-grained, muscovite-tourmaline-garnet leucogranite
Z597: medium-grained, tourmaline-rich leucogranite
All the samples, with the exception of Z597 (from the couloir in the western face, M. Gaetani leg.) were collected at the base of N ridge, close to the lower margin of the pluton.

Appendix 2 Analytical procedures

Strontium, Neodymium and Oxygen isotope data were obtained by conventional mass spectrometric techniques described in standard references. The $\delta^{18}O$ values are reported in permil and are relative to the SMOW standard with a precision of ± 0.1%. NBS 28 has a $\delta^{18}O = +9.6$ on this scale.

The Sr isotopic composition was determined using both Varian MAT TH5 and 54E mass spectrometers. $^{87}Sr/^{86}Sr$ ratios were normalized to a $^{86}Sr/^{88}Sr$ value of 0.1194.

Determinations of NBS 987 standard gave $^{87}Sr/^{86}Sr = 0.71033 \pm 0.00002$ (2 σ). Rb and Sr concentrations were determined by isotope dilution.

The Nd isotopic composition was determined using a VG 54E mass-spectrometer and $^{143}Nd/^{144}Nd$ ratios were normalized to a $^{146}Nd/^{144}Nd$ value of 0.7219. Determinations of La Jolla standard gave $^{143}Nd/^{144}Nd = 0.51188 \pm 0.00001$ (2 σ).