The leucogranites of the Bhutan Himalaya (Crustal anatexis versus mantle melting)

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The Leucogranites of the Bhutan Himalaya
(Crustal anatexis versus mantle melting)

by *V. Dietrich*[1] and *A. Gansser*[1]

Abstract

Leucogranitic intrusions, crosscutting crystalline basement rocks as well as overlying Precambrian and Paleozoic and Mesozoic sediments in the High-Himalaya, are one of the most characteristic geological features in Bhutan.

The mainly uniform, fine-grained granites occur as sills or laccolithic to batholitic intrusions, often surrounded by an intricate halo of smaller stocks, lenses, dikes and apophyses. Normally the granites crosscut highly deformed metamorphic country rocks, which were subjected to the major Main-Himalayan metamorphism of ca. 30 m.y. Contact metamorphism is present in the surrounding sediments. The leucogranites themselves show only a weak cataclastic and probably postkinematic deformation. Only a minor variation in the modal proportions of quartz, plagioclase (An_{7-15}) and orthoclase is present in the leucogranites. Muscovite is the dominant mica and tourmaline (schorl) is a characteristic accessory mineral. A typical differentiation trend within the granites has not been found.

In order to evaluate the origin of the granitic melts, the leucogranites are discussed on the basis of their trace element chemistry and isotopic composition. In contrast to the mantle derived, calc-alkaline granodiorites and biotite-granites of the Cretaceous to Tertiary Trans-Himalayan batholith, the leucogranites clearly exhibit all of the geochemical features of the peraluminous S-type granites (the «sedimentary» derived granites of CHAPPELL and WHITE, 1974).

In addition, the high $^{87}Sr/^{86}Sr$ ratios (> 0.77) can be explained by melting of older sialic crust (sediments and granitic rocks). Available data from melting experiments in synthetic and natural granitic systems indicate that partial melting of water saturated sialic crust at temperatures of 750 to 800 °C and pressures of ca. 6 kbar could produce melts of leucogranitic composition. Due to insufficient isotopic homogenisation during melting, a whole-rock Rb-Sr isochron could not be established. On the basis of geological evidence the intrusive ages of the leucogranites can only be roughly estimated to lie between 30 and 12 m.y. The micas yielded cooling ages of ~ 12 m.y.

Tectonic shortening and intracrustal thrusting in Oligocene and Miocene time during the Indian-Eurasian continental collision is invoked as a mechanism for the Barrovian-type metamorphism and the partial melting of deeper parts of the crust followed by intrusion of the leucogranites into higher levels.

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Introduction

Leucogranites are known in the High-Himalaya within and at the northern edge of the crystalline basement units (Fig. 1). They appear frequently at the high elevations such as Nanga Parbat in the W, Badrinath and Kedernath in the Kumaon Himalaya, Api and Mustang in NW Nepal, Manaslu and its continuation into Sisha Pangma in northern Nepal and southern Tibet, Everest and Makalu region as well as Chomolhari and Kankar Pünzum areas in northern Bhutan. In five of these regions granites reach 8000 m and in the others they surpass the 7000 m elevation (GANSSER, 1964 and 1982; LE FORT, 1973).

The granites occur in the predominantly Precambrian crystalline rocks and also intrude the overlying Mesozoic sedimentary cover. Over a distance of nearly 2000 km the High-Himalaya units have been affected by syn-to postkinematic Barrovian-type metamorphism of Neogene age, which in several areas reached sillimanite grade (RAY, 1947; FRANK et al, 1973; KUMAR, 1978; HONEGGER et al, 1982).

LE FORT (1973 and 1975) and GHOSE and SINGH (1977) noted the intimate association of the highest grade metamorphic rocks, migmatites and granites in Nepal and in the Darjeeling area. From their experimental work, GHOSE and SINGH (1977) postulated that the leucogranites are derived from anatectic melting in the presence of excess water at pressures between 4 and 7 kbar and temperatures below 800°C. Further support for an anatectic origin of the leucogranites from old crystalline basement has been given by the high $^{87}Sr/^{86}Sr$ ratios > 0.74 and relatively low $^{143}Nd/^{144}Nd$ ratios around 0.5120 of the rocks (ALLÈGRE and BEN OTHMAN, 1980).

The aim of this article is to describe in detail the leucogranites on the example of the Bhutan Himalaya and to discuss trace-element and Sr-isotopic data as it pertains to the assumption of magma generation by melting of sialic crust.

For this reason it is interesting to note the profound contrast of the leucogranites with the granitic rocks of the ~ 2000 km long, Upper Cretaceous to Tertiary Trans-Himalayan batholith (Fig. 1). The latter granites yield low $^{87}Sr/^{86}Sr$ initial ratios < 0.706 and high $^{143}Nd/^{144}Nd$ ratios ≃ 0.5126 (ALLÈGRE and BEN OTHMAN, 1980) which are close to those of oceanic mantle and bulk earth composition (DE PAOLO and WASSERBURG, 1976; O'NIONS et al, 1979). Based on geological, petrological and geochemical evidence, HONEGGER et al, (1982) believed that the Trans-Himalayan granites have been crystallized from magmas derived by partial melting of mantle material due to large scale subduction processes during the early Himalayan orogenesis.

They also contrast from the cordierite bearing Lesser Himalayan biotite granites of ± 500 m.y. ages (JÄGER et al, 1971; LE FORT et al, 1980).

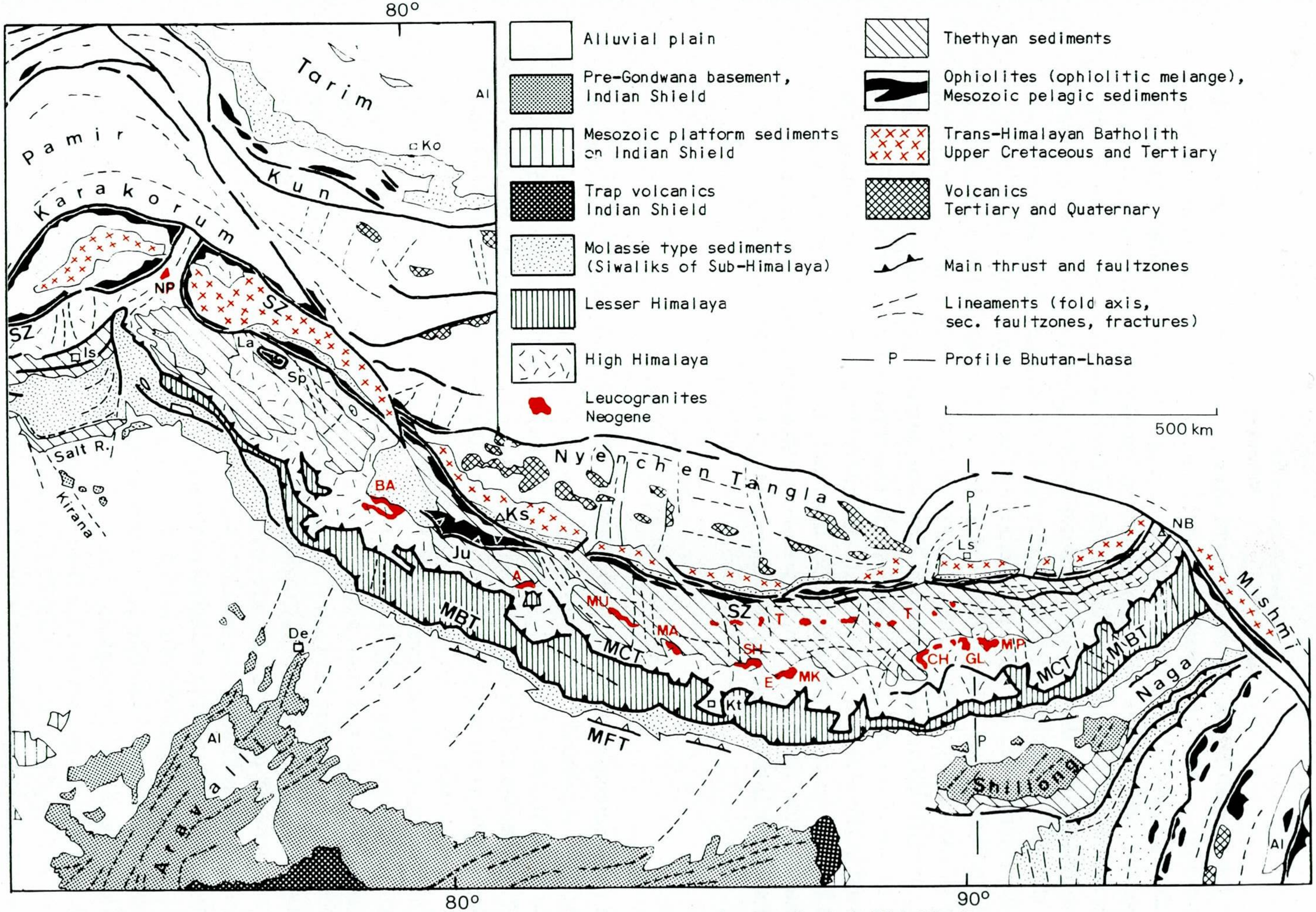

Fig. 1 Tectonic map of the Himalayas showing the major occurrences of Tertiary (Neogene) leucogranites in the High-Himalaya.
From NW to SE: NP = Nanga Parbat (8125 m), BA = Badrinath (7140 m), A = Api (7140 m), MU = Mustang (~ 6000 m), MA = Manaslu (8125 m), SH = Shisha Pangma (8012 m), T = South Tibet, E = Everest (8848 m), MK = Makalu (8475 m), CH = Chomolhari (7314 m) and Chung La, GL = Gohup La, MP = Mönlakarchung-Pasalum (Gang pünzum ~ 7500 m).
Abbreviations: De. Delhi, Is. Islamabad, Ju. Jungbwa nappe, Kb Kabul, Ks. Kailas Mt., Kt. Kathmandu, Ko. Khotan, La. Ladakh, Ls. Lhasa, NB. Namche Barwa Mt., Qt. Quetta, Sp. Spongtang Klippe, AI Alluvial plain.
Main structural units: SZ. Suture Zone (Indus/Tsangpo), MCT. Main Central Thrust, MBT. Main Boundary Thrust, MFT. Main Frontal Thrust.

Geologic setting

In the Bhutan Himalaya the leucogranites are restricted to the northern half of the main crystalline thrust sheets and increase in volume from South to North. The general distribution of the granites is shown in Fig. 2 (see also (GANSSER, 1982). Three main centres can be recognized, all following the northern border area: The Chung La granite in the NW with its extension into the Chomolhari range, the Gophu La granite in the eastern Lunana (northern area) and the Mönlakarchung-Pasalum granite E of Kankar Pünzum mountain (north-eastern area). All three granite bodies are surrounded by an intricate halo of smaller stocks, lenses, dikes and sills (Fig. 3), which can surpass the volume of the central bodies. Occasionally only the halo is exposed suggesting larger granite development at depth. However, some larger granites occur in the form of laccoliths and do not increase in size downwards. A good example is exposed in the southern range of Lunana where the higher summits consist of a thick layer of leucogranite which does not reach the valley bottom. The Manaslu leucogranite (N Nepal) and its eastern extension towards Sisha Pangma (S Tibet) have similar outcrop characteristics (LE FORT, 1973 and 1975).

THE CHUNG LA LEUCOGRANITE

In the headwaters of the Paro Chu in NW Bhutan, the Chung La leucogranite intrudes the mostly Precambrian Tremo La phyllites and calcschists. The contacts of the laccolithic body are generally parallel to the bedding of the meta-sediments, but in detail discordant features can be observed. At the contacts the leucogranites are more aplitic with a marked graphic texture. The predominant rock types of the internal parts are fine to medium grained tourmaline-muscovite granites.

Below Chekha the granite is locally fractured with cataclastic quartz exhibiting fine grained mortar rims. From there, sills up to 100 m thick, extend to the SW into the uppermost Ha valley. Apparently the same rocks reappear in the ranges of NE Sikkim where they form extensive sills within psammitic gneisses and calc-silicate layers which are well exposed in the south slopes of the Pauhunri-Chomoyummo mountains (AUDEN, 1935). The south slopes of the Chomolhari mountain range and its continuation towards Tremo La are classic examples of leucogranitic sills intruded into a sequence of well-bedded, more or less migmatitic sillimanite-garnet-biotite gneisses (base), biotite bearing psammitic gneisses, calc-silicate bands, calcschists and marbles (GANSSER, 1964). The sills are remarkable for their uniform granitic composition and fine-grained texture. The thickness varies from less than one metre to over one hundred metres and may extend for several kilometres.

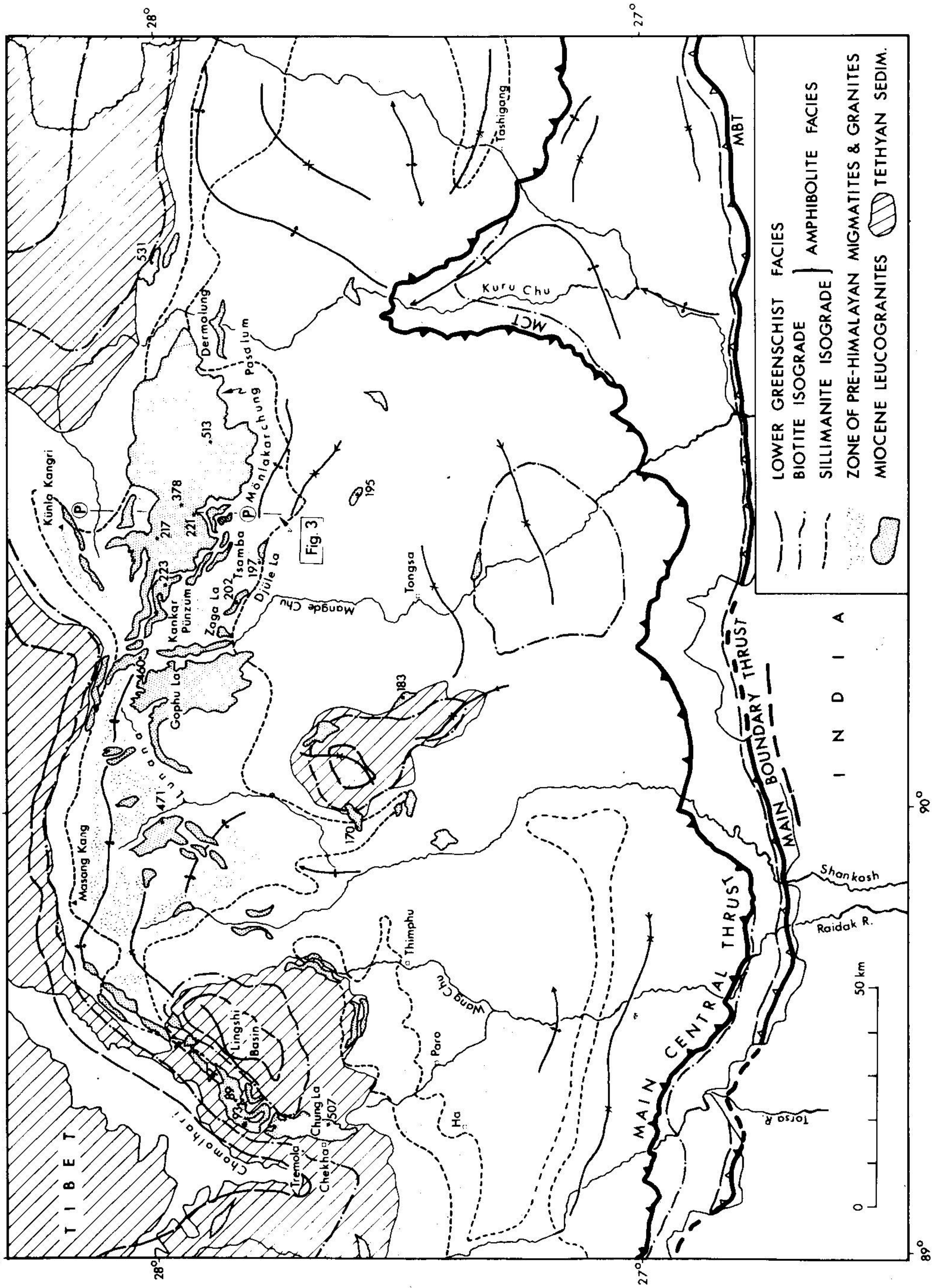

Fig. 2 Distribution of the Bhutan leucogranites (including sample numbers) and metamorphic isogrades.

Aplitic sills are also very frequent. However, instead of muscovite they contain more garnet. Locally black, skeletal tourmaline is very abundant and concentrated in up to several large radial aggregates (Fig. 4) surrounded by quartz rich rims.

THE GOPHU LA LEUCOGRANITES

Leucogranites are again widespread in the Lunana area, concentrated in the Gophu La region from where sills and dikes of varied dimensions spread out into the migmatitic gneisses and the carbonate zones. On the upper slopes of the northern border range, reaching 7000 m, parallel dike intrusions occur similar to those in the south slopes of the Chomolhari range. Large, and partly rootless sills occur in the southern ranges of Lunana. In the highly glaciated Gophu La region (~ 5400 m) they are probably more widespread than what is actually visible below the glacial cover. All these granites are consistently fine to medium grained with muscovite dominating biotite and are often rich in tourmaline. Garnet is occasionally present in the border zones. Towards the East and Southeast the leucogranites intrude the migmatites of the 7500 m high Kankar Pünzum (Fig. 2), forming a wild, net-like dike system rather than the parallel sill type intrusions of the Chomolhari area. They also intrude the carbonates of the Zaga La, which are the northwestern extension of the Djüle La metasedimentary belt (GANSSER, 1982).

THE MÖNLAKARCHUNG-PASALUM LEUCOGRANITES

The leucogranitic dikes and smaller stocks connect through the Kankar Pünzum range with the Mönlakarchung-Pasalum leucogranites, which form the largest leucogranite body in the Bhutan Himalaya with an approximate area of 800 km^2. To the South they terminate within the probably Precambrian metasediments of the Tsamba area and to the East in the migmatitic gneisses of the Dermalung region. The irregular dikes and stocks gradually increase in thickness and merge into the main granitic body. The peripheral zones are rich in biotite-psammite gneiss and biotite schist xenoliths.

To the North the Mönlakarchung-Palasum granite extends into Tibet. After an interruption by a zone of biotite schists, the dikes and granitic sills appear again in the southern walls of the 7600 m high Künla Kangri (southern Tibet), a surprising replica of the Kankar Pünzum range. Larger granitic masses are apparently not developed and it seems that the Künla Kangri forms the northern limit of the leucogranites and of the crystalline units as a whole. An extension to

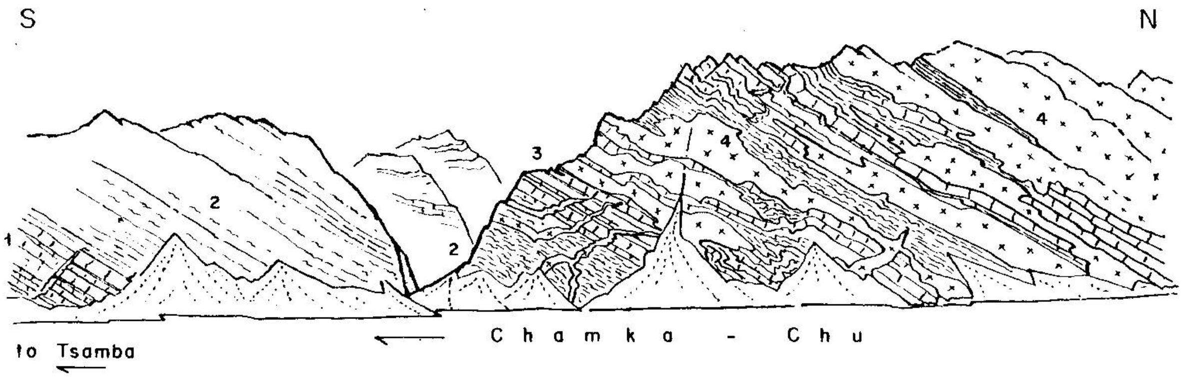

Fig. 3 Southern contact of the Pasalum leucogranites. Profile location indicated in Fig. 2. 1 = marbles, 2 = sillimanite schists, 3 = calcsilicate marbles, 4 = leucogranites..

the Northeast into the upper Kuru Chu region over a distance of approximately 15 km has been recognized.

Apart from these larger leucogranite intrusions in the northern part of Bhutan, several smaller occurrences are known further to the south (Fig. 2). There the leucogranite sills intruded the marbles at the southern edge of the Lingshi basin. They are well exposed in the Wong Chu valley and consist of medium grained tourmaline-muscovite granites. In some places the sills show an incipient schistosity parallel to the bedding of the surrounding migmatite gneisses. Other leucogranites outcrop as thick sills on the western and southwestern side of the Tang Chu basin. Near Chengana a large, finegrained sill is emplaced between biotite gneisses (base) and marbles. There too, the granite shows a weak schistosity. Further to the south, in the Tang Chu gorge, garnet bearing muscovite granites form discordant stocks. They intrude into quartzitic schists and impure marbles as well as into biotite gneisses. The granites are rather inhomogenous, rich in muscovite and contain irregular aplitic schlieren. Locally graphic textures are abundant.

Petrography

The most distinctive feature of the leucogranites is their relative homogeneous grain size and modal composition (Table 1): Quartz 30–34%, microcline 23–30%, albite 32–37%, muscovite 3–7%, biotite 1–3% and accessary amounts of ilmenite, apatite, tourmaline and garnet. In the Or-Qz-Ab triangle (Fig. 6) the Bhutan leucogranites fall into the field of other High-Himalayan leucogranites, such as from Rongbuk, Makalu, Api, Badrinath and Manaslu.

The grain size of the mainly non-equigranular irregular fabric (Fig. 4 and 5) varies from 1 mm to approximately 5 mm; subordinate are fine grained porphyritic and graphic textures. The texture is only partly massive (exceptions in aplitic varieties). A weak foliation is often present due to subparallel arrangement of muscovite and millimeter-sized wavy quartz-lenses and tourmaline streaks.

Quartz is intensively toothed and shows undulatory extinction. Microcline is very irregularly shaped and frequently penetrates plagioclase at intergranular boundaries. Plagioclase with K-feldspar inclusions often exhibits uniform optical orientation, but in most cases the extinction is strongly undulatory. Weakly zoned plagioclase (An_{7-15}) occur as subidiomorphic grains.

The entire intergrowth of quartz, microcline and albite indicates a eutectic crystallization, according to GHOSE and SINGH (1979) under 4 to 8 kbar pressures and 630–750 °C temperature. The cataclastic and weak mylonitic features of quartz and the feldspars as well as the planar fabrics of the rocks indicate that some leucogranites might have suffered a cold deformation after their latest recrystallisation.

Besides K-feldspar, xenomorphic mica flakes are included in plagioclase. Sporadic wedge-shaped kinkbands occur. Myrmekitic rims or lobes are widespread. Large muscovite flakes are sometimes shred-shaped to lenticular and in a few cases slightly bent. On some occasions the large crystals are overgrown by tiny «mica-palme» muscovite aggregates, probably due to a post-intrusive pegmatitic activity.

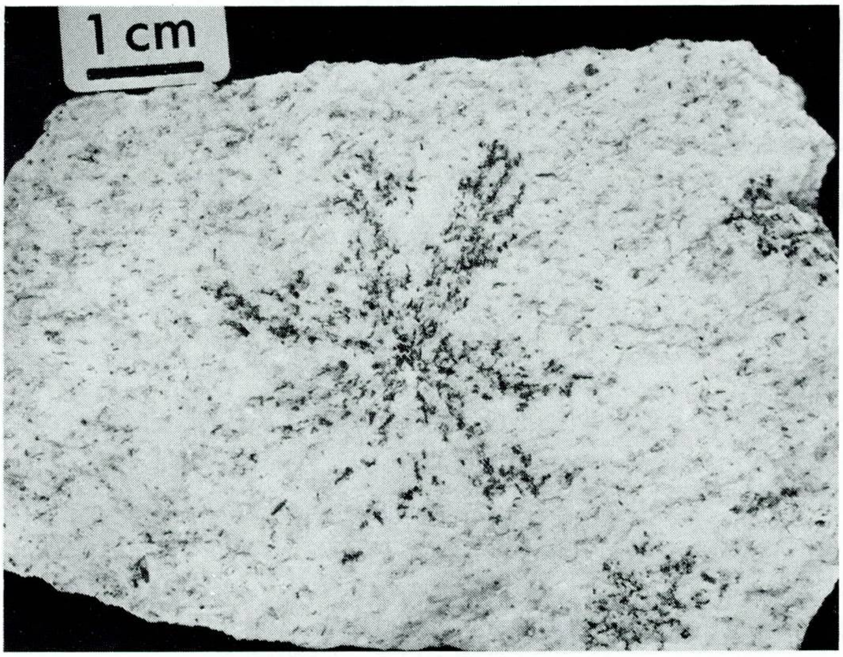

Fig. 4 Fine-grained, non-equigranular tourmaline (black) bearing leucogranite (GH 224) from the Mönlakarchung area (Fig. 2).

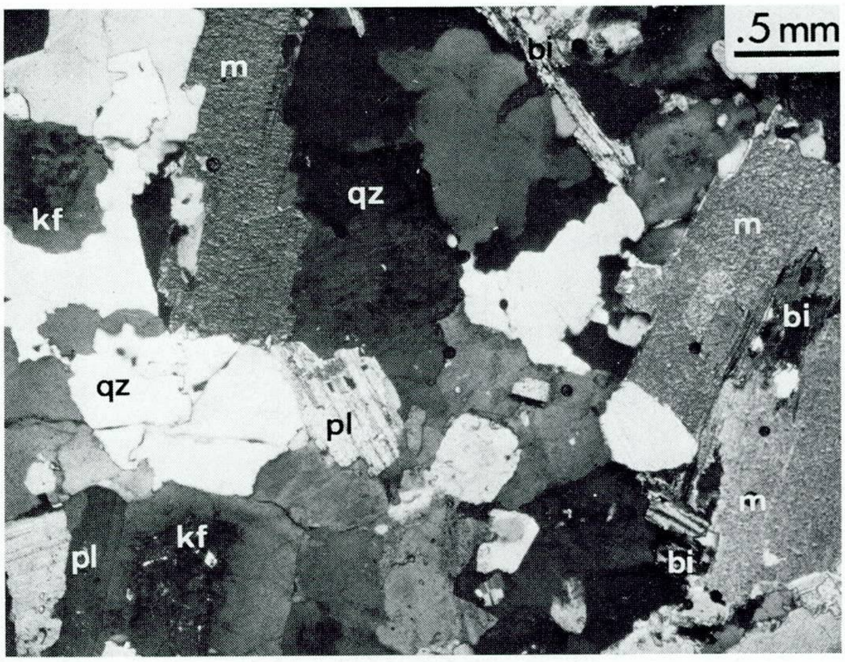

Fig. 5 Microphotograph of a typical leucogranite under crossed polars (GH 222, Mönlakarchung).
qz = quartz, kf = kalifeldspar, pl = plagioclase, m = muscovite, bi = biotite.

In several cases muscovite is penetrated by fine-grained quartz. Reddish-brown biotite, sporadically chloritized, often occurs as fine-grained shreds, partly intergrown with muscovite along (001) or enclosed in muscovite. Yellow-green and light-blue tourmaline is irregularly distributed. Fine to coarse grained angular and euhedral fragments occur as loose aggregates of a few mm or cm size (Fig. 4). According to their optical properties they can be grouped mainly as schorl. Drop-shaped quartz inclusions are frequent and give the tourmaline grains a skeletal habit.

Geochemistry of the leucogranites

Seventeen leucogranitic samples from Bhutan have been chosen for detailed bulk chemical and isotopic analysis (Tables 1 to 3). The leucogranites, although occurring in an area of ~ 2000 km², do not show significant chemical variation (Fig. 7 and 8). They are with few exceptions (GH 183, 195 and 197) potassium and aluminium rich granites: with SiO_2 between 71 and 75 wt.% - K_2O: 4.7 and 5.2 wt.%; Al_2O_3: 15 and 16.5 wt.% respectively. A differentiation trend cannot be recognized. This is in extreme contrast with the calc-alkaline granitoids from the Cretaceous and Tertiary Trans-Himalayan batholith (HONEGGER et al., 1982) which are composed of gabbros, diorites, quartz-diorites, tonalites, granodiorites and biotite granites.

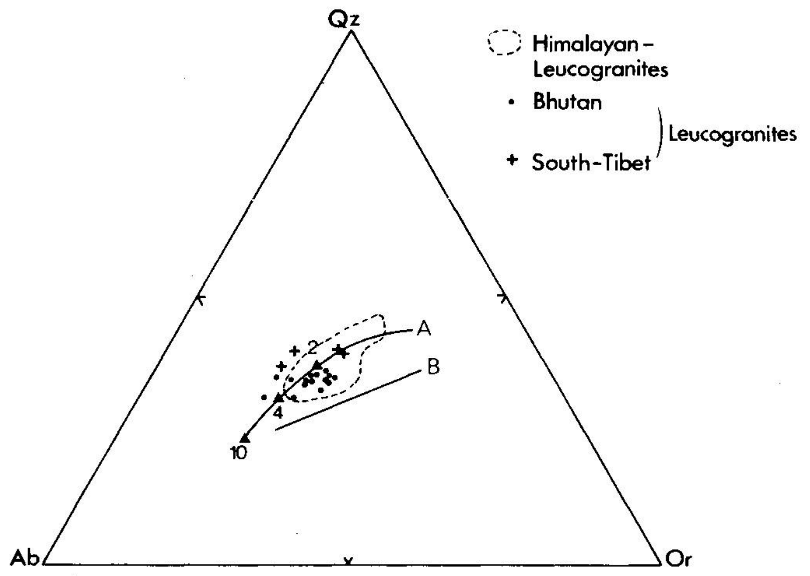

Fig. 6 Modal composition of the Bhutan-leucogranites within the Quartz-Albite-Orthoclase diagram indicating the close similarity with other Himalayan leucogranites. Line A is the cotectic line along which plagioclase, alkali feldspar, quartz, melt and gas coexist. The numbers correspond to the ternary eutectics at 2, 4 and 10 kbar pressures (TUTTLE and BOWEN, 1958). Line B ist the cotectic line at higher pressures (WINKLER and GHOSE, 1973).

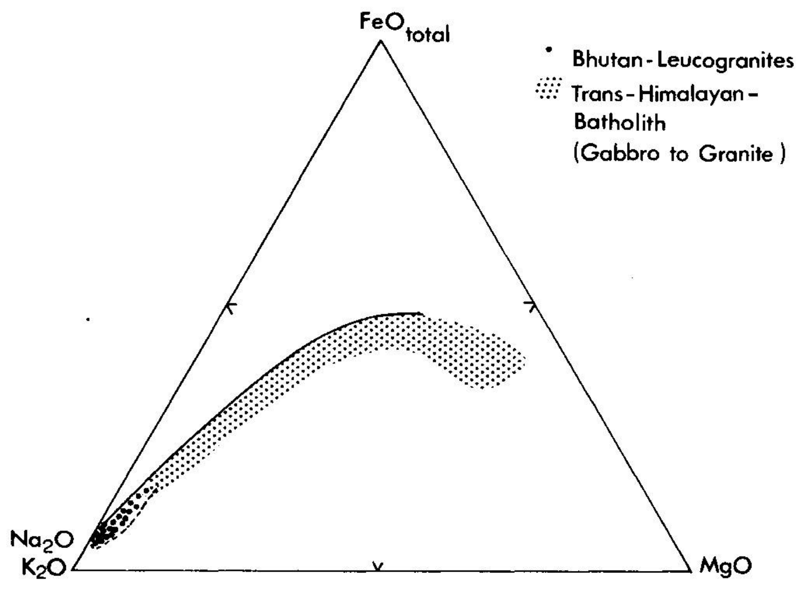

Fig. 7 A-F-M diagram illustrating the small chemical variation of the Bhutan-leucogranites compared to the typical calc-alkaline differentiation trend of granitoid rocks from the Trans-Himalayan Batholith.

Several characteristic and discriminative trace elements, such as Rb, Ba, Zr and Y have been chosen to underline the exceptional chemical composition and homogeneity of Bhutan leucogranites (Fig. 8). Although K_2O is only 20 to 30% higher than in the normal biotite granites, Rb is enriched up to 10%, reaching

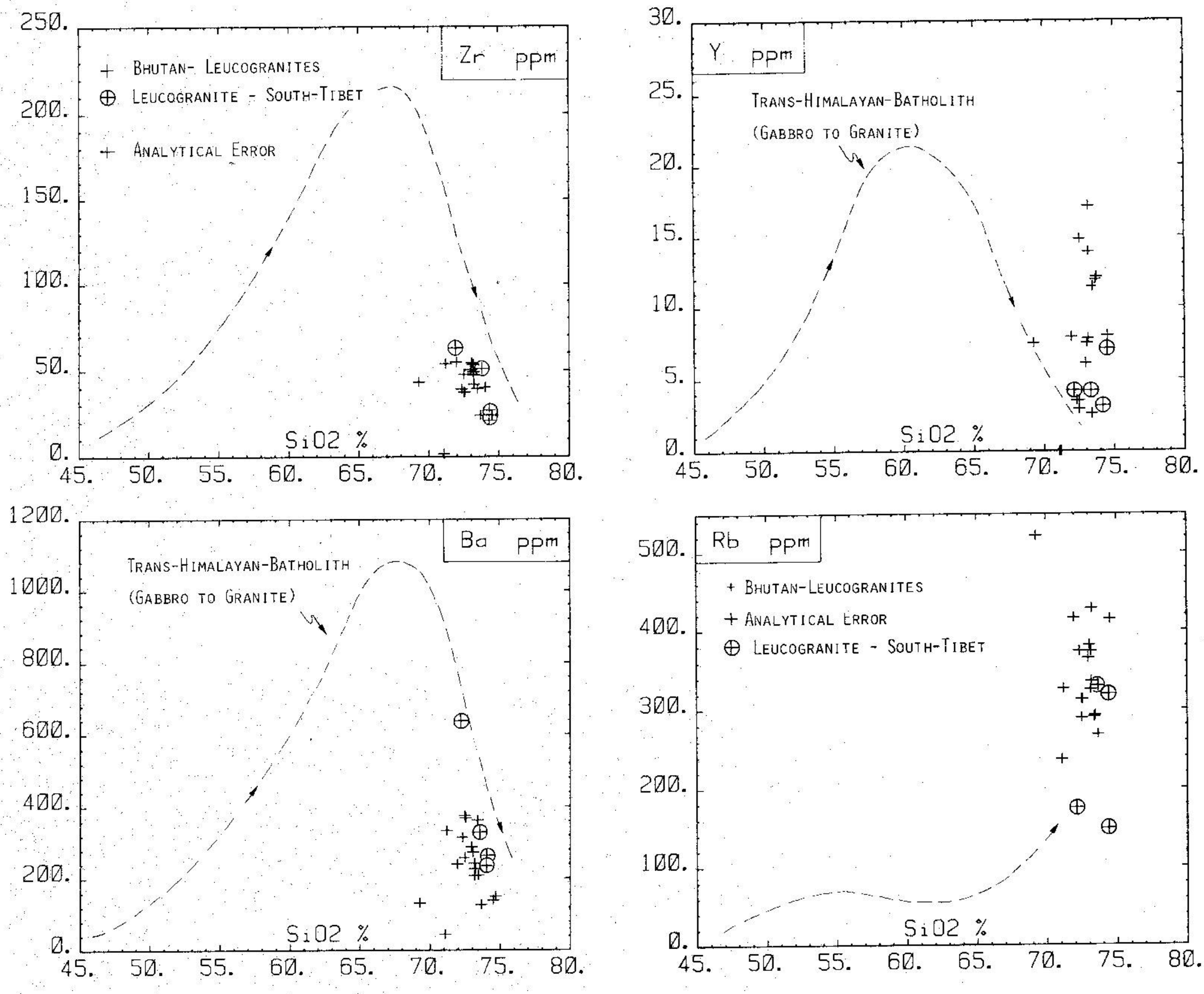

Fig. 8 Selected trace element distribution of leucogranites from Bhutan and South Tibet plotted in four different variation diagrams with increasing SiO_2. The leucogranites do not show a typical magmatic differentiation trend. This is in strong contrast to the calc-alkaline intrusives (gabbro to granite, stippled lines) of the Trans-Himalayan batholith (HONEGGER et al., 1982). The latter igneous series exhibit a nearly ideal possible correlation between Rb and SiO_2, Rb mainly concentrated in K-feldspar and biotite. The reason for the small maximum contents in the diorites is not yet known, but could be attributed to the relatively high biotite abundances. Ba, Zr and Y contents are highest in the granodiorites and decrease in amount from granodiorite to the granites. Crystallisation of plagioclase and K-feldspar in the granodiorites obviously sufficed to remove most to the Ba in form of the celsian-com ponent. Y seems to be bound in hornblende, apatite, sphene and to a certain extend in zircon (LAMBERT and HOLLAND, 1974). This is consistent with the high Y contents in quartzdiorite and tonalite, rocks rich in the above mentioned three Ca-bearing phases.

even 520 ppm in GH 183. Rb is probably fixed in the micas as well as in the K-feldspars. Muscovite may contain up to 1000 ppm, biotite ~ 2600 ppm (Table 3) and K-feldspar ~ 500 ppm (HAMET and ALLÈGRE, 1976). The latter mineral contributes the most to the bulk rock Rb concentrations. Y abundances are unusually high, but irregularly distributed. This element may be bound in apatite and to a smaller extend in tourmaline and garnet. The irregular distribution may reflect local differences of the granitic magmas. Ba and Zr as well as all of the other trace elements show significantly lower concentrations than nor-

Table 1 Bulk rock and modal compositions of leucogranites from Bhutan (GH) and South Tibet (T) (analysed by V. Dietrich with x-ray fluorescence; methods described in NISBET et al., 1978).
Cr < 10 ppm, Ni < 6 ppm, Cu < 6 ppm,
U < 5 ppm, Th < 8 ppm, S < 20 ppm,
F < 100 ppm.

Sample No.	GH 89	GH 93	GH 129	GH 170	GH 183	GH 195	GH 197
weight %							
SIO2	74.07	71.19	72.54	73.16	69.27	72.49	73.66
TIO2	0.04	0.13	0.11	0.11	0.23	0.10	0.07
AL2O3	14.50	15.51	15.37	15.45	16.54	15.64	15.03
FE2O3	0.53	0.35	0.36	0.32	0.44	0.29	0.14
FEO	0.10	0.45	0.50	0.50	1.40	0.40	0.50
MNO	0.05	0.01	0.02	0.02	0.04	0.03	0.02
MGO	0.04	0.12	0.13	0.09	0.37	0.08	0.07
CAO	0.44	0.92	0.77	1.04	0.52	0.69	0.83
NA2O	4.41	3.77	3.64	3.29	3.82	4.70	3.88
K2O	3.83	4.86	4.87	5.06	4.82	3.76	3.76
P2O5	0.18	0.17	0.17	0.15	0.19	0.16	0.08
H2O+	0.38	0.65	0.84	0.87	1.33	0.85	0.95
total	98.57	98.13	99.32	100.06	98.97	99.19	98.99
ppm :							
BA	45	334	369	208	132	258	128
RB	237	327	313	336	522	289	268
SR	8	108	100	69	34	128	34
PB	11	63	77	77	108	148	53
NB	<3	<3	3	9	19	3	<3
LA	<15	<15	<15	<15	19	<15	<15
CE	<10	20	11	13	26	<10	<10
ND	<10	<10	<10	<10	<10	<10	<10
Y	<3	<3	15	17	8	4	12
ZR	<3	54	37	47	43	37	24
V	<10	11	<10	<10	23	<10	<10
CO	15	13	19	11	14	18	18
ZN	7	40	38	32	116	43	28
GA	5	18	15	20	27	13	17
SC	<1	2	2	3	6	1	2
Modes							
Quartz	32	30	31	32	27	31	35
K-feldspar	23	27	27	29	26	22	19
Plagioclase	38	36	34	32	35	43	35
Muscovite	3	4	3.5	4	6.5	2	7
Biotite	2	1.5	2	1.5	1	0.5	2
Opaques (Ilmenite)	0.4	0.8	0.7	0.6	1.1	0.6	0.3
Apatite	0.4	0.4	0.4	0.4	0.5	0.4	0.2
Tourmaline (T) garnet (G)		T					G
Al/(Na+K+Ca/2)	1.12	1.15	1.16	1.17	1.25	1.21	1.26

Table 1 continued

Sample No.	GH 202	GH 217	GH 221	GH 223	GH 378	GH 460	GH 471
weight %							
SI02	73.43	73.20	72.48	73.04	71.94	72.96	73.16
TI02	0.09	0.11	0.14	0.12	0.11	0.13	0.11
AL203	14.97	15.07	14.82	14.95	14.82	14.80	14.52
FE203	0.28	0.05	0.07	0.11	0.54	0.16	0.19
FEO	0.60	0.85	0.90	0.85	0.52	0.82	0.90
MNO	0.02	0.03	0.02	0.03	0.04	0.03	0.04
MGO	0.09	0.12	0.17	0.16	0.26	0.16	0.14
CAO	1.19	0.76	0.94	0.84	0.63	0.86	0.74
NA20	3.30	3.57	3.40	3.61	3.87	3.30	3.04
K20	4.68	4.82	5.17	4.86	4.56	5.18	4.98
P205	0.10	0.16	0.12	0.14	0.19	0.18	0.16
H20+	0.91	0.98	0.53	0.73	1.60	0.49	0.75
total	99.66	99.72	98.76	99.44	99.08	99.07	98.73
ppm :							
BA	209	227	376	274	240	288	243
RB	293	428	313	381	416	365	373
SR	65	51	85	61	59	76	62
PB	86	69	90	72	73	64	45
NB	5	<3	<3	<3	14	<3	3
LA	<15	<15	<15	<15	<15	<15	<15
CE	17	<10	18	18	10	14	11
ND	<10	<10	<10	<10	<10	<10	<10
Y	11	4	3	8	8	6	14
ZR	39	42	48	54	55	50	49
V	<10	<10	<10	<10	<10	<10	<10
CO	16	15	16	16	22	18	17
ZN	38	46	46	44	62	39	31
GA	18	20	15	19	21	18	14
SC	3	2	3	1	2	2	3
Modes							
Quartz	34	32	30	32	30	32	34
K-feldspar	24	27	31	28	27	30	28
Plagioclase	33	33	34	33	34	31	28
Muscovite	6	5	2	3	4	1	6
Biotite	1	1	1.5	2.5	2	4	2
Opaques (Ilmenite)	0.6	0.3	0.4	0.5	1.0	0.5	0.5
Apatite	0.2	0.4	0.3	0.3	0.4	0.4	0.4
Tourmaline (T)			T	T		T	T
Al/(NA+K+Ca/2)	1.17	1.15	1.11	1.13	1.13	1.11	1.11

mal calc-alkaline biotite granites. In contrast to Y they cluster in a small area (Fig. 8). Ba and Sr correlate linearly (not shown in the figures), which indicates close geochemical relationships of these elements in the feldspars. Several interesting features emerge from the chondrite-normalized, rare earth element (REE) patterns (Fig. 9). The overall abundances in the leucogranites are half of those in the Trans-Himalayan batholiths (HONEGGER et al., 1982). The light- to

Table 1 continued

Sample No.	GH 513	GH 531	GH 507	T 11	T 16	T 27	T 37
weight %							
SIO2	73.13	72.32	74.52	74.62	74.24	73.49	72.10
TIO2	0.13	0.13	0.05	0.06	0.13	0.14	0.20
AL2O3	15.29	14.92	14.79	15.06	14.60	14.89	15.25
FE2O3	0.16	0.21	0.21	0.23	0.29	0.50	0.61
FEO	0.85	0.80	0.40	0.25	0.70	0.50	0.90
MNO	0.02	0.03	0.02	0.02	0.03	0.02	0.05
MGO	0.14	0.14	0.16	0.09	0.14	0.15	0.59
CAO	0.90	0.74	0.66	1.67	0.73	0.80	2.09
NA2O	3.55	3.64	4.28	3.36	3.07	3.00	3.04
K2O	5.14	4.74	4.22	3.58	4.41	4.87	3.65
P2O5	0.12	0.15	0.13	0.09	0.13	0.14	0.10
H2O+	0.61	0.77	1.27	0.60	0.75	0.65	0.80
total	100.04	98.59	100.71	99.63	99.22	99.15	99.40
ppm :							
BA	322	315	140	258	227	368	692
RB	326	374	414	147	326	331	168
SR	80	68	49	139	77	128	213
PB	101	102	59	21	33	42	46
NB	<3	<3	3	<3	<3	<3	<3
LA	<15	<15	<15	<15	<15	16	<15
CE	17	<10	<10	<10	<10	13	22
ND	<10	<10	<10	<10	<10	<10	<10
Y	8	4	8	7	3	4	4
ZR	53	39	24	23	27	52	63
V	<10	<10	<10	<10	<10	<10	36
CO	19	14	<8	19	21	<8	21
ZN	48	47	31	<3	47	44	46
GA	16	16	17	12	19	19	12
SC	1	2	<1	2	3	2	4
Modes							
Quartz	31	31	32	38	37	35	33
K-feldspar	30	28	25	19	23	24	17
Plagioclase	33	34	38	35	28	28	36
Muscovite	1	3	4	7	9	6	4.5
Biotite	5	2	< 1	< 1	< 1	4	7.5
Opaques (Ilmenite)	0.5	0.5	0.4	0.4	0.7	1	1.2
Apatite	0.3	0.4	0.3	0.2	0.3	0.3	0.3
Tourmaline	T	T	T		T		
AI/(Na+K+Ca/2)	1.13	1.14	1.13	1.31	1.25	1.20	1.34

heavy REE fractionation is less evident, except for the sample GH 197, which shows a strong heavy REE depletion probably due to the garnet free aliquot of the sample, which has been taken for analysis. The most remarkable feature is the strong negative Eu-anomaly suggesting that Eu was either already missing in the granitic melt or plagioclase has been extracted to a large extend from the melt. This is consistent with the low CaO-contents of the leucogranites between 0.5 and 1 wt.%.

Table 2 Rare earth element contents in ppm of 3 selected leucogranites and one biotite granite (GH 155) from Bhutan (analysed by S. Bajo and A. Wyttenbach with instrumental neutron activation technique, described by BAJO and WYTTENBACH (1980) and in HONEGGER et al., 1982).

	GH 89	GH 155	GH 197	GH 471
La	3.51	10.6	10.4	16.9
Ce	7.1	22.0	22.3	35.0
Nd	4.34	9.09	10.3	16.6
Sm	1.07	2.58	2.83	3.91
Eu	0.12	0.36	0.34	0.41
Tb	0.25	0.48	0.53	0.59
Yb	1.47	1.80	0.68	1.59
Lu	0.23	0.27	0.09	0.24

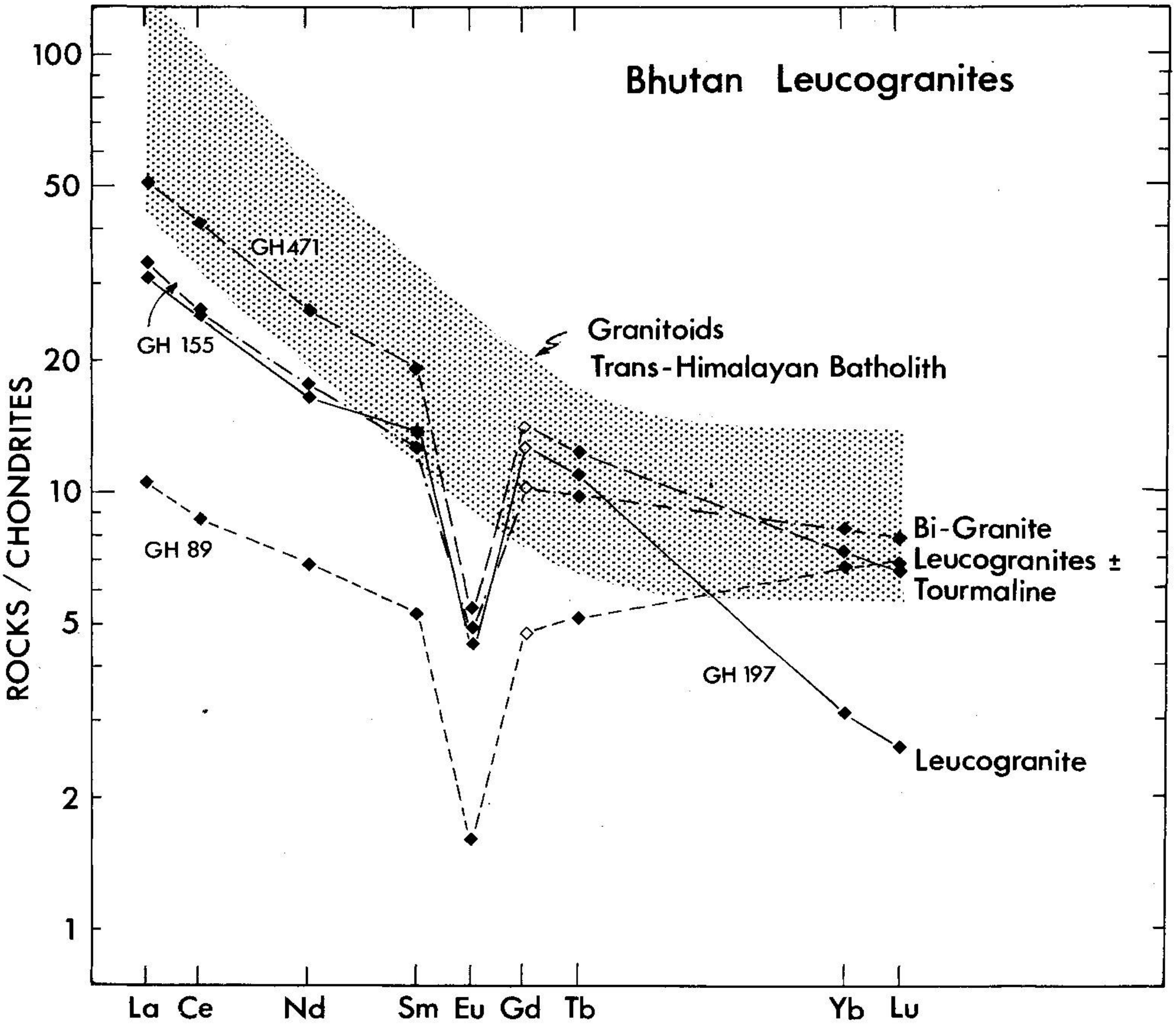

Fig. 9 Rare earth element contents from three selected Bhutan leucogranites and one biotite granite. The most characteristic feature of the leucogranites is the strong negative Eu-anomaly. For comparison field of granitic rocks from the Trans-Himalayan batholith. REE values (Table 2) normalized to average chondrites of NAKAMURA, 1974. The REE patterns of the dioritic to granitic rocks from the Trans-Himalayan batholith (HONEGGER et al., 1982) are very similar to those of the Mesozoic Peruvian batholith (ATHERTON et al., 1979). These patterns show negative slopes with strong LREE enrichment and HREE depletion. A weak negative Eu-anomaly is sometimes present in the more felsic rocks.

Isotope chemistry and ages of the Bhutan leucogranites

The Rb-Sr and K-Ar data (sample weights ~ 1 kg each) are shown in Table 3. All leucogranites yield medium to high Rb/Sr ratio > 2 and present $^{87}Sr/^{86}Sr$ ratios around 0.77. Due to the limited number and size of samples as well as to their irregular regional distribution (Fig. 2) a whole rock Rb-Sr isochron (Fig. 10) cannot be drawn. Thus, it is difficult to give an initial $^{87}Sr/^{86}Sr$ ratio. Assuming an age of about 20 m.y.(hypothetical two point isochron of the Pasalum-leucogranites, Fig. 10), the initial ratio would be fairly high, in the order of 0.77. Similar high $^{87}Sr/^{86}Sr$ ratios have been obtained from other High-Himalayan leucogranites: Manaslu 0.7433 to 0.7874 (HAMET and ALLÈGRE, 1976 and 1978; VIDAL, 1978) and Everest 0.7630 to 0.773 (KAI, 1981 b). These high ratios can only be achieved by melting at least Paleozoic and older Himalayan crystalline rocks (Fig. 11). Good protolith candidates are the granitic rocks which yield a 500 m.y. intrusive and metamorphic event (JÄGER et al., 1971; Frank et al., 1977; BHANOT et al., 1979; LE FORT et al., 1980). On the basis of low $^{143}Nd/^{144}Nd$ ratios of 0.51183 ± 7 (Manaslu leucogranite) ALLÈGRE and BEN OTMAN (1980) postulate a remelting of 1,100–2,300 m.y. old Himalayan basement. The Bhutan leucogranites crosscut Paleozoic sediments, whereas equivalent granites in the western continuation in Nepal intrude Mesozoic sediments (HAGEN, 1968 p. 130). In addition the Bhutan leucogranites intrude highly metamorphosed rocks, which reached their last metamorphic climax approximately 30 m.y. ago (GANSSER, 1964; FRANK et al., 1973 and 1977; METHA, 1980 and KAI, 1981 a and c).

Table 3 Isotopic data from the Bhutan leucogranites and pegmatites, Rb-Sr contents determined by x-ray fluorescence (Table 1), isotopes determined by isotopic dilution technique (W. Frank and R. Hänny).

Whole rock

Sample No.	Locality	Rock Type	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
GH 221	Mönlakar-chung	Leuco-granites	313	85	10.65	0.78060±0.0002
GH 223	Mönlakar-chung	Leuco-granites	381	61	18.05	0.78004 "
GH 471	W Lunana	Leuco-granites	373	62	17.39	0.77260 "
GH 507	S Chekha	Leuco-granites	414	49	24.43	0.78220 "
GH 513	SE Lunana	Leuco-granites	326	80	11.78	0.78250 "

MINERAL AGES

Sample No.	Locality	Mineral	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Rb-Sr age	K-Ar age
GH 507	S Chekha	Biotite	2666	4.20	1904.0	1.0764	11 my	
		Muscovite	1048	4.93	630.3	0.9455		
GH 186	W Tongsa	Muscovite (Pegmatite)	-	-	-	-	-	12 my
GH 188	W Tongsa	Biotite (Pegmatite)	-	-	-	-	-	11 my

However, the real ages of intrusions of the different leucogranitic sills, stocks and dikes can only be roughly estimated. A whole rock Rb-Sr isochron of the Manaslu granite gave an intrusive age of 29 ± 1 m.y. (Fig. 11) with a $^{87}Sr/^{86}Sr$ initial ratio of 0.742 (HAMET and ALLÈGRE, 1976 and 1978). VIDAL (1978) questioned this age, obtaining slightly different isotopic results from parts of the same examples. For the Makalu leucogranite (including some two mica granitic gneisses) KAI (1981 b) derived a whole rock isochron of 92.7 ± 9.4 m.y. with an initial ratio of 0.743. This Upper Cretaceous age seems to be very unrealistic on the basis of the structural position of the Makalu granite. A Cretaceous metamorphic event in the High-Himalaya, which could produce granitic melts is absolutely unknown. Therefore further investigations should be made to clarify, if such ages can also be explained by partial homogenisation of Sr-isotopes in older granitic rocks.

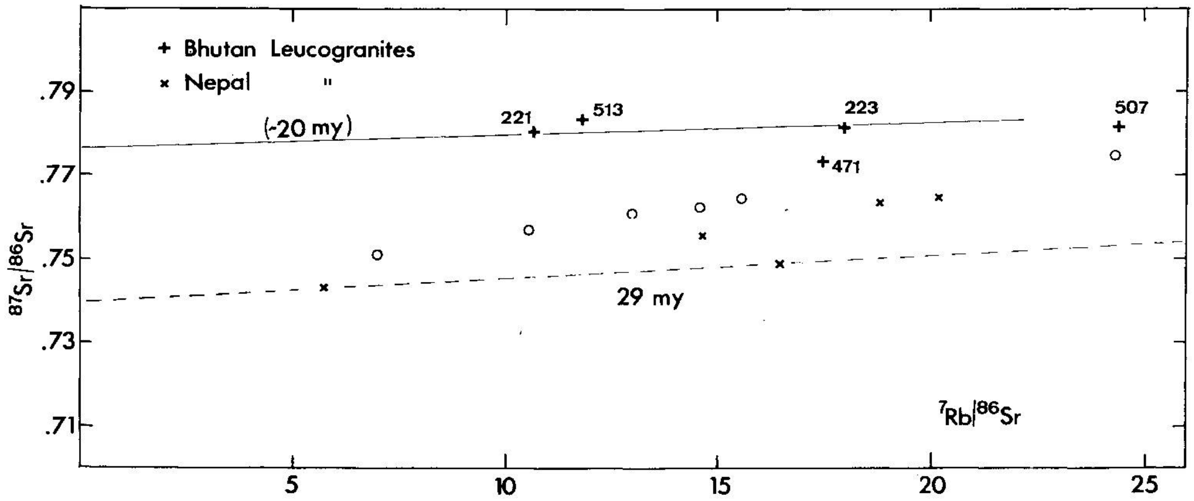

Fig. 10 Rb-Sr diagram for whole rocks from several Bhutan leucogranites. The localites of the samples are shown in Fig. 2.
Due to heterogeneity of the $^{87}Sr/^{86}Sr$ ratio no real isochron can be drawn. The "~ 20 m.y." line is only a hypothetical isochron for the Mönlakarchung-Pasalum leucogranites. For comparison data from the Makalu- (circles, (KAI, 1981 b) and Manaslu-leucogranites (small crosses, (HAMET and ALLÈGRE, 1978 and VIDAL, 1978) are given; 29 ± 1 m.y. isochron by HAMET and ALLÈGRE (1978).

Muscovites and biotites from the leucogranites and pegmatites yielded K-Ar ages between 17 and 11 m.y. (15 m.y. for the Mustang granite and ~ 17 m.y. for the Makalu granite in Nepal - KRUMMENACHER, 1971; ~ 23 m.y. for the Manas-

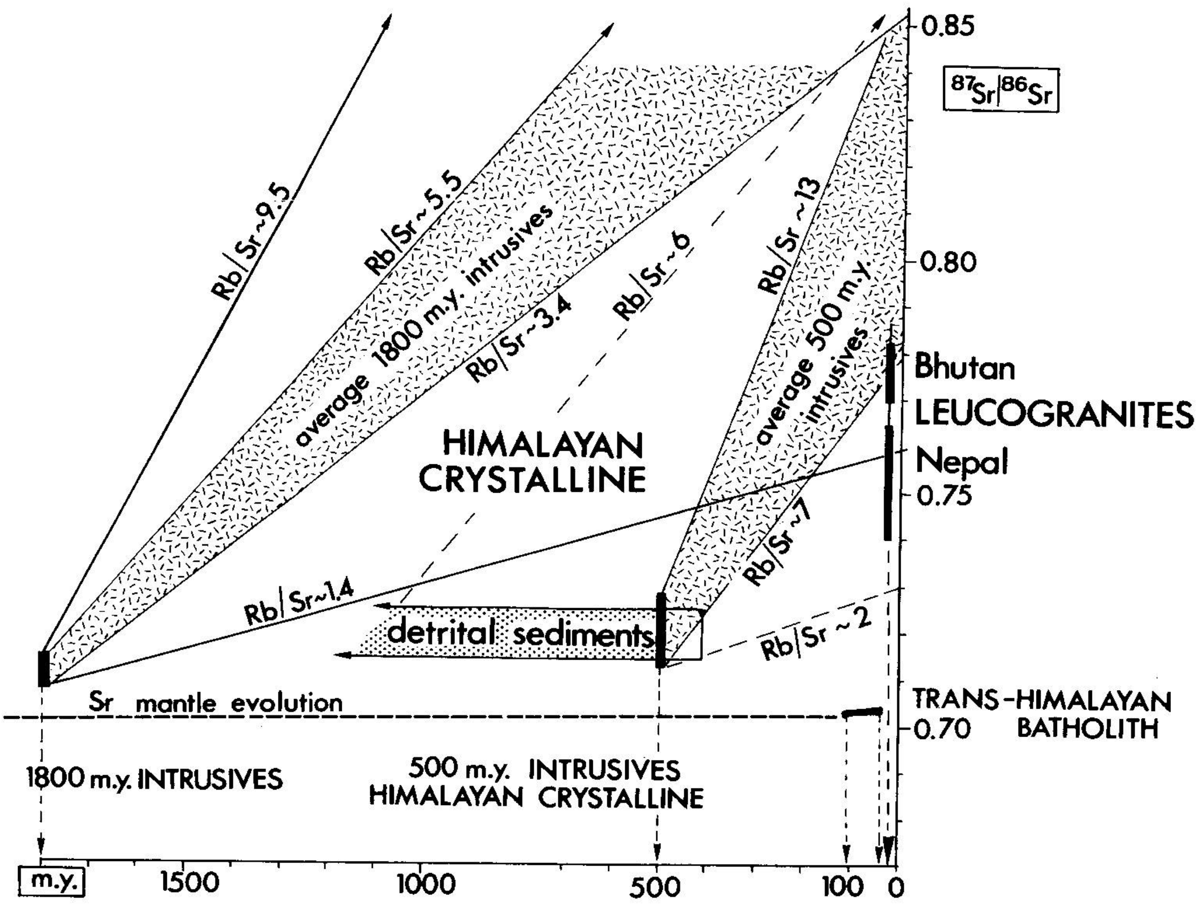

Fig. 11 $^{87}Sr/^{86}Sr$ evolutionary diagram in time reflecting the fundamental difference of source material between the Neogene High-Himalayan leucogranites and the Cretaceous to Tertiary intrusives of the Trans-Himalayan batholith north of the Indus-Tsangpo suture zone. Data from FRANK et al. (1973 and 1977) and HONEGGER et al., (1982).

lu granite in Nepal - HAMET and ALLÈGRE, 1978; 14 to 16 m.y. for the Rongbuk granite in Tibet - WAGER, 1965; 11 and 12 m.y. for pegmatites west of Tongsa in Bhutan - Table 3). Similar ages have been obtained using Rb-Sr dating on muscovites and biotites (i. e. 14 m.y. biotite age from the Everest granite). The latter age has been interpreted as a cooling age due to rapid uplift (KAI, 1981 c). Although locally cataclastic features and a weak foliation are present in the Bhutan leucogranites, it appears, petrographically, that the young Cenozoic regional metamorphism did not affect the granites. The contact aureoles do not exhibit a metamorphic overprint. Except for the latest fracturing event, the deformational structures of the surrounding country rocks are discordantly cut by the leucogranites. The structures and metamorphic overprint within marginally enclosed xenoliths correlate with those observed in the country rocks. Therefore, the real ages of intrusions of the leucogranites must be considered to lie between 30 and 12 m.y.

The origin of the leucogranites

Field observations in Bhutan do not clarify the origin of the leucogranites, since only their roof has been exposed by the present erosion level. This is in contrast to the much older, often cordierite - bearing, biotite and two-mica granites (~ 370 m.y.), which show all gradual changes from migmatites to granites (GANSSER, 1982). In some places the leucogranites intrude «lit par lit» metasedimentary units, in particular the carbonate rocks. Transitional zones between migmatites and clear leucogranites were not observed. Petrological and geochemical observations, however, do shed some light on the problem of origin.

The Bhutan leucogranites plot in a very narrow field near the eutectic minimum in the ternary Qz-Ab-Or diagram (Fig. 6). They do not differ significantly from the compositions of other High-Himalayan leucogranites (GHOSE and SINGH, 1977). The compositions lie between two cotectic lines, the upper curve marking melting of granitic rocks at lower pressures around 2 kbar (TUTTLE and BOWEN, 1958), the lower line melting at higher pressures between 2 and 7 kbar and temperatures between 730 and 686 °C respectively (WINKLER and GHOSE, 1973, WINKLER, 1974).

In contrast to other granitic rocks, the leucogranites are enriched in albite, which suggests melting at higher pressures (Fig. 6 and LUTH et al, 1964). Melting experiments at 4 kbar water pressure of two-mica, high-grade sillimanite gneisses from the Darjeeling area yielded a liquidus temperature of 796 °C (GHOSE and SINGH, 1977). At 7 kbar quartz and biotite were still stable up to 764 °C, while 80% of the rock had been molten. Thus it seems very reasonable to assume that melting of high-grade metamorphic basement rocks at reasonable crustal depth could have produced leucogranitic melts.

Distinction between I- and S-type granitic magmas

CHAPPELL and WHITE (1974), PITCHER and others in ATHERTON and TARNEY (1979) provided geochemical tools for discrimination of two major granitic magma types reflecting the difference of source material: I-type granitoids, derived from mantle material and S-type granitoids, derived from remelted continental crust.

For comparision Table 4 contains characteristic petrological and geochemical features of the two major types of young granitic rocks in the Himalaya: the leucogranites of the High-Himalaya in Bhutan and the biotite granites from the Trans-Himalayan batholith. In contrast to the leucogranites, the biotite-granites constitute only 10% of the total volume of the calc-alkaline intrusive suite.

The leucogranites from Bhutan are without exception an extremly clear example of S-type granites. Typical calc-alkaline granitoids have not been recog-

Table 4 Geological, mineralogical and geochemical dissimilarities between the Bhutan leucogranites and granites from the plutonic suite of the Trans-Himalayan batholith.

LEUCOGRANITES of the HIGH-HIMALAYA	PLUTONIC SUITE of the TRANS-HIMALAYAN BATHOLITH
Structural setting	
Sill and laccolithe like intrusions of m to km thickness within high-grade metamorphic basement rocks; small sized contact-aureoles No volcanism associated	Multiple intrusions forming plutons of several kilometers in diameter. Contact-aureoles in low grade-metamorphic country rocks (island arc volcanics; ocean floor rocks; continental margin-type sediments). Plutonic suite accompanied, but not nessecarily consanguineous with basic to acidic volcanism (i.e. ignimbrites and pyroclastics).
Age of igneous activity	
Single phase activity general age spread in the whole High-Himalaya from 28 to 14 my	Time-integrated accumulation of intrusive activity of approx. 75 million years from 110 to 35 my
Plutonic rocks	
	Ultramafic to mafic cumulates: Olivine-gabbro, two-pyroxene gabbro, norite, anorthosite, hornblende-gabbro, hornblendites, amphibolites
Mainly muscovite-granite or two-mica granite	Differentiation series: Diorites, quartzdiorite, tonalite, granodiorite, biotite-granite, aplite granites
Tourmaline, garnet and ilmenite present	Hornblende, sphene and magnetite as abundant phases present. Porphyry copper deposits.
Chemistry	
No differentiation series	Normal calc-alkaline differentiation series
Discriminat chemical criteria for granitic rocks (SiO_2 : 71 - 75 wt.%)	
K_2O : 4.7 - 5.2 wt.% Na_2O : 3.8 - 3.3 " Al_2O_3 : 15 - 16.5 " Al/(Na+K+Ca/2) > 1.11 - 1.26 Corundum normative: 2 - 3 wt.% TiO_2 : 0.15 - 0.05 wt.% Fe_2O_3/FeO < 0.5 Zr 60 - 20 ppm Y 3 - 25 ppm Ba 400 - 200 ppm Rb 250 - 500 ppm REE: relatively low, LREE less enriched, strong Eu anomaly present Rb/Sr > 2	K_2O : 2.0 - 4.5 wt.% Na_2O : 4.3 - 2.9 " Al_2O_3: 15 - 13 " Al/(Na+K+Ca/2) < 1.1 (Chappel & White, 1974) TiO_2 : 0.3 - 0.08 wt.% Fe_2O_3/FeO $\geq$ 1 Zr 150 - 50 ppm Y < 5 ppm Ba 800 - 200 ppm Rb 150 - 250 ppm REE: relatively high, LREE enriched, weak negative Eu anomaly present Rb/Sr 0.5 - 1.5
Isotope chemistry	
$^{87}Sr/^{86}Sr$ > 0.74 $^{143}Nd/^{144}Nd$ $\sim$ 0.5119 *	Sr initial ratios: $^{87}Sr/^{86}Sr$ < 0.706 $^{143}Nd/^{144}Nd$ $\sim$ 0.5126 - 0.5127 *

* ALLÈGRE and BEN OTHMAN (1980)

nized and volcanics are completely missing. The rather restricted acidic leucogranites are surrounded by older migmatitic gneisses and locally contain xenoliths of the host material. Muscovite is the dominating mica, in addition ilmenite, tourmaline and garnet occur. The bulk chemistry discussed above indicates typical high potassic granites ($K_2O \sim 4.7 - 5.2$ wt.%) with low Na_2O contents ($\sim 3.8 - 3.3$ wt.%). The Fe_2O_3/FeO ratios and TiO_2 contents (0.05 to 0.15) are very low. As indicated by low CaO and Eu abundances, plagioclase must have been almost completely removed from the melt prior to crystallisation. Thus the residual rocks must be characterized by the presence of refractory minerals such as plagioclase, hornblende or pyroxene.

The S-type leucogranites are peraluminous in the sense of Shand (1950). Using CHAPPELL and WHITE's (1974) ratio of $Al/(Na+K+Ca/2)$, the leucogranites yield ratios between 1.11 and 1.26. I-type granites in contrast have ratios < 1.1. The reason for the smaller ratio originates from higher Na_2O contents.

However, this ratio alone does not favour another source region. At least Sr-isotopes are necessary to confirm the origin. All of the granitic rocks from Bhutan have extremely high $^{87}Sr/^{86}Sr$ ratios (> 0.77). On the basis on these values, together with the other petrologic and geochemical evidence, the interpretation of the young granites as anatectic melts derived from sialic crust appears to be valid.

Conclusion

The general crossection through Bhutan and Tibet (Fig. 12) shows clearly the two major contrasting young granitic environments of the Himalaya.

Along the «southern» Tibetan continental margin granitic crust, «the Trans-Himalayan batholith» accreted over a time span of approximately 70 million years from Late Cretaceous to Tertiary. According to petrologic and isotopic evidence the calc-alkaline magmas may have been formed by partial melting from oceanic and subcontinental mantle, probably generated by the effect of subduction of the Mesozoic Tethyan oceanic lithosphere (HONEGGER et al, 1982). There are good geological and geochemical reasons to believe that the primary magma was similar to that of the most primitive, low-Ti, water-bearing island arc tholeiites (e. g. Dras basalts in the Ladakh-Himalaya, DIETRICH et al, 1982). Accumulation of olivine, spinel, pyroxene, calcic plagioclase and hornblende formed ultramafic to mafic cumulates giving rise to residual dioritic to quartzdioritic melts. Fractionation of plagioclase, hornblende and magnetite lead to tonalites, granodiorites and finally to granitic melts.

The plutonic sequence seemed to be accompanied consanguineously by calc-alkaline volcanism, although, in the field a direct connection between the plutonic and volcanic rocks is rare.

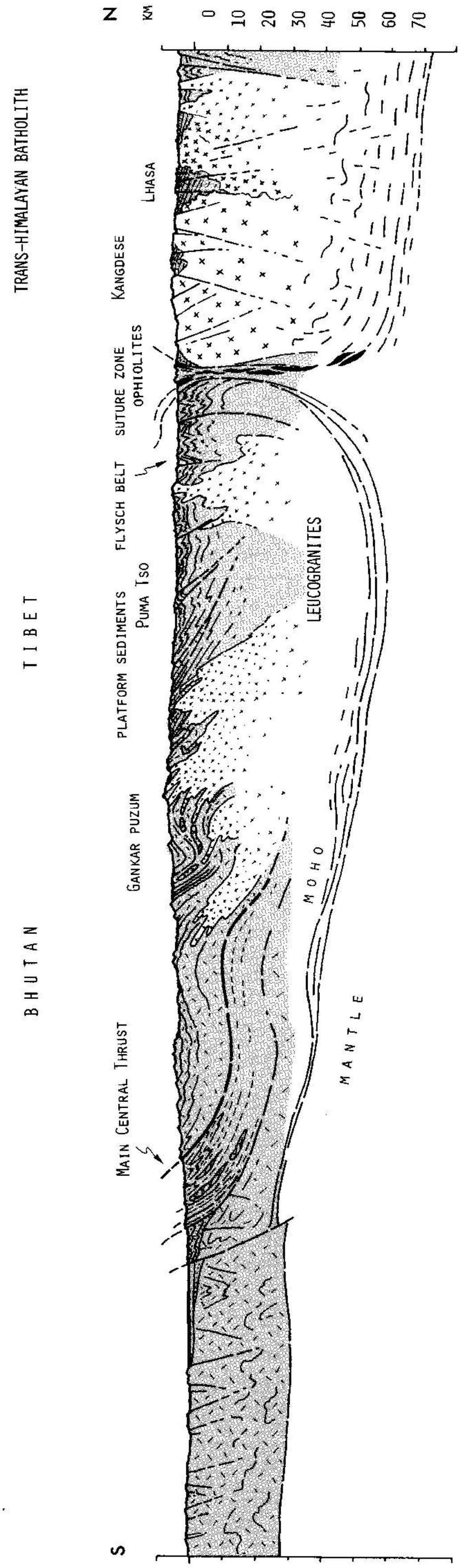

Fig. 12 Schematic crossection through the Himalaya at 90°E.

South of the major structural divide within the Himalaya, the Indus-Tsango suture zone (Fig. 1), the Tertiary leucogranites occur within the High-Himalayan crystalline basement and overlying Paleozoic and Tethyan Mesozoic platform-type sediments. The leucogranites (and partly two-mica granites) in southern Tibet north of eastern Nepal and north of Bhutan (Fig. 12) appear as plugs aligned along a zone, where the Tethyan platform-type facies changes into a flysch facies. In general the leucogranites are much less voluminous than the Trans-Himalayan batholith. Most of the leucogranites may have been generated only over a small time span of approximately 15 million years during the Late Tertiary. Typical differentiation series as well as associated volcanism are unknown.

Petrologic evidence points to anatectic melting of high-grade metamorphic crystalline basement at a depth between 15 and 30 km, thus near the «root» of the «Main Central Thrust». No refractory rocks, such as pyroxyene-granulites and hornblende-biotite gneisses have been found together with the leucogranites in the higher parts of the High-Himalaya. The hypothesis of melting metamorphic crystalline basement of probably sedimentary origin is supported by geochemical and isotopic evidence. With the exception of Rb, the leucogranites are highly depleted in their trace element contents. The strong negative Eu-a nomaly indicates a preexisting negative anomaly. From a Sr-evolution diagram (Fig. 11) it can be concluded that basement rocks, which have been subjected to a 500 m.y. intrusive and metamorphic event at least, could produce the high $^{87}Sr/^{86}Sr$ ratio > 0.77. The observed heterogeneity of the high $^{87}Sr/^{86}Sr$ ratios can be explained by insufficient isotopic homogenisation during or after the melting process.

The reason for the melting of deeper parts of the crust and contemporaneous to subsequent Barrovian-type metamorphism in the higher parts of the High-Himalaya is probably due to strong crustal thickening and shortening after the collision between India and Eurasia during the Uppermost Eocene and Oligocene. A continuous «northwards» drift of India in Oligocene and Miocene time resulted in intracrustal thrusting (Main Central Thrust) producing a drastic increase of heat within the lower and middle parts of the up to 70 km thick sialic crust and generation of fluids along faults and thrusts. The abnormal high production of heat and circulation of fluids may have caused partial melting of the deeper parts of the crust to form the leucogranitic melts. The mostly subsequent uplift of the High-Himalaya may have been partly due to the isostatic rebound of the total volume of the Himalaya with the upper mantle.

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