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Late Pan-African magmatism in the Himalaya: new geochronological and geochemical data from the Ordovician Tso Morari metagranites (Ladakh, NW India)

by *Matthieu Girard*[1] and *François Bussy*[1,2]

Abstract

Two granitic plutons, the Tso Morari gneiss and the Rupshu metagranite, crop out in the Tso Morari area. The Polokongka La granite, classically interpreted as a young intrusion in the Tso Morari gneiss, has been recognized as the undeformed facies of the latter. Conventional isotope dilution U–Pb zircon dating on single-grain and small multi-grain fractions yielded magmatic ages of 479 ± 2 Ma for the Tso Morari gneiss and the Polokongka La granite, and 482.5 ± 1 Ma for the Rupshu granite. There is a great difference in zircon morphology between the Tso Morari gneiss (peraluminous type) and the Rupshu granite (alkaline type). This difference is confirmed by whole-rock chemistry. The Tso Morari gneiss is a typical deformed S-type granite, resulting from crustal anatexis. On the other hand, the Rupshu granite is an essentially metaluminous alkali-calcic intrusion derived from a different source material. Data compilation from other Himalayan Cambro-Ordovician granites reveals huge and widespread magmatic activity all along and beyond the northern Indian plate between 570 and 450 Ma, with a peak at 500–480 Ma. A major, continental-scale tectonic event is required to generate such a large magmatic belt; it has been tentatively compared to the Variscan post-orogenic extensional regime of Western Europe, as a late evolution stage of a Pan-African orogenic event.

Keywords: Himalaya, Cambro-Ordovician, zircon dating, granite, Pan-African.

Introduction

The Himalaya (including Karakorum) is the youngest orogenic belt in the world. It resulted from the closure of the Neotethys ocean, and the subsequent Eocene continent-continent collision between India and Asia (GANSSER, 1964). In a broad sketch, a geotraverse from the Indian plain up to the Tibetan plateau will first show the Siwaliks molassic hills that are overthrust by the Lesser Himalaya, itself overthrust by the High Himalayan Crystalline Sequence (HHCS). This metamorphic unit passes gradually into the less metamorphosed Tethyan Zone, which is composed of Precambrian to Early Eocene sediments. In the area studied, a crystalline dome (the Tso Morari dome) occurs north of the Tethyan Zone. This unit represents the Northern Himalayan Crystalline. Further north the Indus Molasse and the ophiolitic Indus-Tsangpo Suture Zone crop out. On the other side of this oceanic suture lies the Early Cretaceous to Early Oligocene Transhimalayan batholith, generated during the subduction of the Tethyan ocean (SHARMA, 1991). These plutons consist mainly of calc-alkaline diorites, tonalites and granodiorites. In addition to this magmatic episode, two others generating granitic rocks can be distinguished in the Himalaya: the well known Tertiary leucogranites and the Cambro-Ordovician metagranites. The leucogranites are clearly of collisional type and result from the anatexis of metasediments during the Himalayan

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orogeny (DIETRICH and GANSSER, 1981; LE FORT et al., 1981). The origin of the widespread Cambro-Ordovician metagranites is much more debated, but they have often been connected with the Pan-African orogenic events (FRANK et al., 1977; LE FORT et al., 1986).

The area studied is situated in the Rupshu region of NW India, near the western border of the Tibetan plateau (Fig. 1). This paper deals with the Cambro-Ordovician metagranites outcropping in this area, more specifically the Tso Morari gneiss, the Polokongka La granite and the Rupshu granite. Several open questions about these metagranites were addressed:

(1) Is the Polokongka La granite a different intrusion than the Tso Morari gneiss, or is there some evidence of a genetic relationship?

(2) Similarly, is the Rupshu granite linked to the Nyimaling granite, a pluton located in its western prolongation?

(3) What is the significance of the Cambro-Ordovician magmatism in the Himalaya?

This paper provides a new framework for these questions on the basis of field observations, and the mineralogy, geochronology and geochemistry of the metagranites.

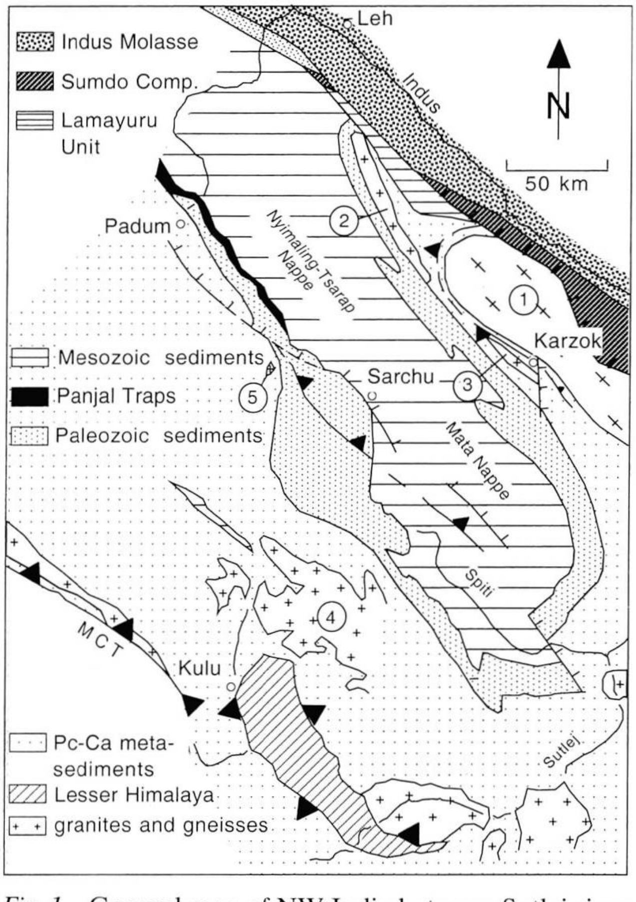

Fig. 1 General map of NW India between Sutlej river and Leh (after STECK et al., 1998). 1 = Tso Morari gneiss; 2 = Nyimaling granite; 3 = Rupshu granite; 4 = Hanuman Tibba granite; 5 = Ogi Bihal granite; MCT = Main Central Thrust.

Geological setting

In the Rupshu area, exhumation of the northern end of the Indian plate and late doming allow direct observation of deep parts of the Indian crust. A sedimentary series starting from Precambrian and going up to Triassic (and even Lower Tertiary further south or west) with several gaps hosts the granites in the Precambrian and Cambrian sediments (Fig. 2). The metamorphism generated by the Himalayan orogeny in the Rupshu area varies between greenschist in the south to amphibolite facies in the north. This gradient is well documented by metapelites (DE SIGOYER et al., 1997; Girard, in prep.).

Just south of the Indus Suture Zone, the Tso Morari gneiss (HAYDEN, 1904) forms the core of a vast antiform (Fig. 1). This massif has often been correlated with the Gurla Mandhata dome in Tibet (BERTHELSEN, 1953; HEIM and GANSSER, 1939). Similar gneiss complexes in a comparable tectonic position exist at several places in the Himalayan chain (e.g. Kaghan, SPENCER, 1993); Kangmar (DEBON et al., 1984); Gurla Mandhata (HEIM and GANSSER, 1939). The Kaghan gneiss, situated in the western Himalaya (Pakistan), and the Tso Morari gneiss presumably experienced a similar metamorphic history, as both contain eclogite lenses. Such high pressure–low temperature rocks are restricted to the NW Himalaya. The only occurrences are in the Kaghan (POGNANTE and SPENCER, 1991), Neelum (Fontan, in prep.) and the Stak valleys (LE FORT et al., 1997) in Pakistan and in the Tso Morari area in India (BERTHELSEN, 1953). P-T conditions for this metamorphism are estimated at 13–18 kbar, 650 ± 50 °C for the Kaghan gneiss (POGNANTE and SPENCER, 1991) and 20 ± 3 kbar, 580 ± 60 °C for the Tso Morari gneiss (DE SIGOYER et al., 1997; GUILLOT et al., 1997). The age of eclogitisation in the Tso Morari area is 55 ± 17 Ma (U/Pb, DE SIGOYER et al., 1999). In the Kaghan Valley the eclogites preserved a Sm/Nd age on a garnet-clinopyroxene pair of 49 ± 6 Ma (TONARINI et al., 1993).

The metagranite that crops out near the Polokongka La has been investigated separately from the Tso Morari gneiss, as many authors consider it as intrusive in the latter (FUCHS and LINNER, 1996; GUILLOT et al., 1997; SHARMA and KUMAR, 1978; THAKUR and VIRDI, 1979). But we will show that this hypothesis is no longer valid, and the term "Polokongka La granite", largely used in the literature, should be deleted. We will use this name in the following chapters in a purely descriptive sense as a link with previous work.

A smaller pluton (35 km long, maximum 5 km thick), called the Rupshu granite (HAYDEN, 1904), forms the 6000 m high range of the Mata mountain, west of the Morari lake (Fig. 2). Detailed mapping suggests that the Rupshu granite is an eastern equivalent of the Nyimaling granite dated at 460 ± 8 Ma (Rb–Sr on whole-rock, STUTZ and THÖNI, 1987). It will be shown that these two granites have different characteristics.

Several hypotheses have been proposed concerning the age and origin of the Tso Morari and Rupshu metagranites. BERTHELSEN (1953) suggested that both granites belong to the same basement, which crops out in the Tso Morari dome (the Tso Morari gneiss) and in the Mata range as

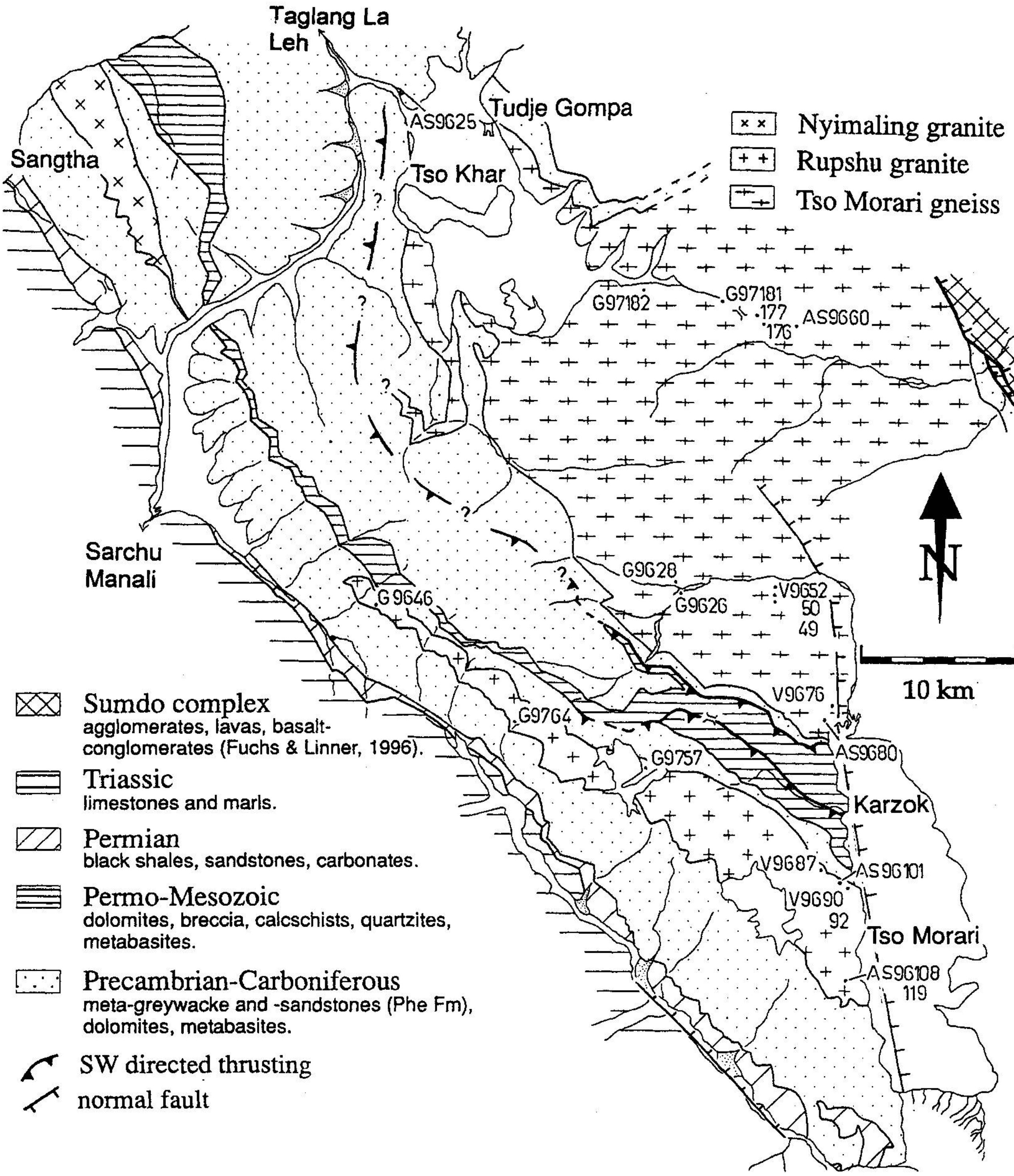

Fig. 2 Geological map of the Rupshu district, NW India and location of the samples.

a tectonic wedge (the Rupshu granite). The formation of the Rupshu granite was supposed to be pre-Upper Carboniferous and caused by a Variscan, Caledonian or Pre-Cambrian event. VIRDI et al. (1978) regarded the Tso Morari gneiss as high grade metamorphic rocks derived from Carboniferous to Lower Permian sediments, and the Rupshu granite as a Late Triassic to Jurassic intrusion, contemporaneous with the Polokongka La granite. None of these hypotheses is based on a detailed study, with the notable exception of the excellent petrographic description of BERTHELSEN (1953). Unpublished Rb–Sr ages of TRIVEDI (1990) for the Polokongka La (487 ± 25 Ma) and Rupshu (487 ± 14 Ma) granites are mentioned in VALDIYA (1995). Similar Rb–Sr ages of 458 ± 14 Ma have recently been obtained for the Polokongka La granite by DE SIGOYER et al. (1998).

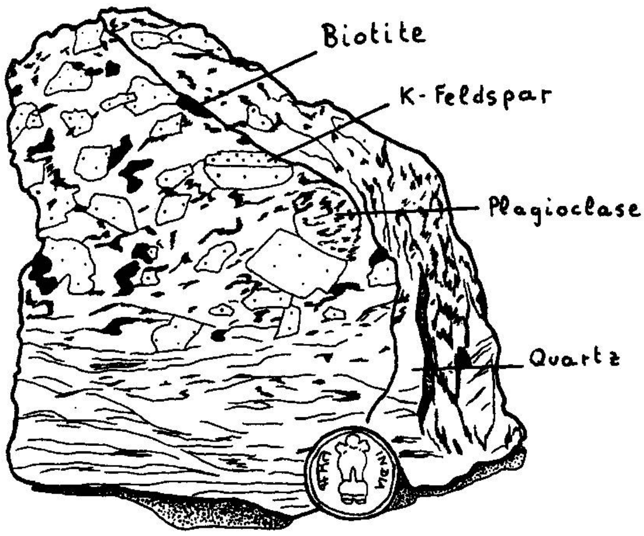

Fig. 3 Gradual change between gneissic and granitic facies of the Tso Morari gneiss. Sample from Polokongka La area.

Field observations

THE TSO MORARI GNEISS

The Tso Morari gneiss forms a vast NW–SE dome, which covers an area of at least 1000 km^2. In the west, the massif plunges under metasediments in the Tso Kar area. The eastern extension is still unknown since it is part of the military restricted area.

The Tso Morari gneiss complex is mainly composed of quartzo-feldspathic metamorphic rocks derived from granitoids. The most frequent facies is a coarse grained augengneiss with cm-long feldspar clasts. Eclogitic or retrogressed eclogitic lenses are scattered throughout the complex, aligned parallel to the gneiss fabric. Metasedimentary quartz-biotite schists or gneisses, in which relict parageneses from the eclogite facies have also been found (GUILLOT et al., 1997), occur as thin discontinuous levels concordant with the banding of the orthogneiss. These eclogitic relics are found only within the Tso Morari gneiss and in the first few hundred meters of metasediments above it. This leads us to define a new tectonic unit (STECK et al., 1998), the Tso Morari nappe, which experienced high-pressure metamorphism. The next two overlying nappes (Tetraogal and Mata nappes, STECK et al., 1998) lack any evidence of eclogitic metamorphism.

Deformation within the Tso Morari gneiss complex is highly heterogeneous and textures vary from magmatic to mylonitic. Nevertheless a main schistosity can be followed throughout the gneiss; it is domed by the NW–SE Tso Kar anticline (BERTHELSEN, 1953; STECK et al., 1998; THAKUR and VIRDI, 1979). More details on the structural framework and evolution of the area are given in STECK et al. (1998).

The Tso Morari complex is overlain by garnet-bearing metapelites of the Phe (or Haimantas) Formation of Precambrian to Cambrian age. The main schistosity transposes this sediment-granite contact to a parallel structure. In Nuruchan, few meter thick levels of mylonitic granite are found in the Phe Formation just above the main gneissic body. They could represent either paralleled apophyses of the intrusive granite or isoclinal folds, which affect the contact. No aplitic or pegmatitic dikes related to the Tso Morari gneiss have been found.

In the Polokongka La area, the original, undeformed facies of the granite is preserved in several places, mostly as a coarse-grained mesocratic rock with large biotite flakes. The transition between the granite and the gneiss is gradual (Fig. 3) and features which could be interpreted as intrusive contacts have never been observed. The undeformed facies occurs as patches dispersed within the gneiss, with diffuse limits parallel to the regional schistosity. Several other undeformed granite bodies of variable size have been found at various places within the Tso Morari gneiss (Gyanbarma, Nuruchan...), reflecting the heterogeneity of deformation at all scales.

THE RUPSHU GRANITE

The Rupshu granite is quite different from the Tso Morari gneiss. It is a smaller elongated body situated in a higher tectonic level, in the core of the

Tab. 1 Electron microprobe mineral analyses of coexisting Bt, Phe, Grt and feldspar in three different samples (V9676, AS9660 and G9646). Data are in weight percent and in molecular proportions for the last five lines. Analyses conditions: Cameca SX50 electron microprobe, 15 kV, scanning mode (4 X 5 μm) for Bt (15 nA), feldspar (10 nA), Phe (15 nA), spot mode for Grt (30 nA).

	Biotite					**Garnet**			
	Tso Morari		**Polo. La**	**Rupshu**		**Tso Morari**		**Polo. La**	**Rupshu**
Sample	V9676	V9676	AS9660	G9646		V9676	V9676	AS9660	G9646
SiO_2	37.45	33.66	33.96	36.23		36.25	36.82	37.35	38.13
TiO_2	1.67	1.80	2.49	1.21		0.07	0.09	0.07	0.12
Al_2O_3	17.15	17.84	16.84	17.30		20.12	20.55	20.30	20.50
Cr_2O_3	–	–	–	–		0.01	0.02	0.07	0.00
Fe_2O_3	1.11	0.03	0.11	1.96		–	–	–	–
FeO	13.88	28.26	28.30	20.32		28.21	28.81	27.22	17.51
MnO	0.09	0.15	0.24	0.43		5.45	0.19	1.89	2.75
MgO	13.59	4.46	3.88	8.18		0.36	1.24	0.20	0.16
CaO	0.00	0.00	0.00	0.00		8.55	11.43	12.87	20.74
Na_2O	0.00	0.00	0.00	0.00		–	–	–	–
K_2O	10.04	9.47	9.54	9.70		–	–	–	–
F	0.54	0.08	0.41	0.47		–	–	–	–
Sum	95.50	95.76	95.78	95.80		99.02	99.13	99.96	99.90
Xann	0.33	0.65	0.67	0.51	Prp	1.48	4.94	0.79	0.61
Xphl	0.53	0.18	0.16	0.33	Alm	61.00	61.81	58.11	35.09
Fe/Fe+Mg	0.38	0.78	0.80	0.60	Sps	12.57	0.43	4.27	6.10
					Adr	4.84	4.19	4.04	4.88
					Grs	20.07	28.59	32.56	53.31

	Phengite				**Feldspar**						
	T. Morari	Polo. La	Rupshu		Tso Morari		Polokongka La		Rupshu granite		
Sample	V9676	AS9660	G9646		V9676	V9676	AS9660	AS9660	G9646	G9646	V9692
SiO_2	47.44	45.88	49.36		68.51	63.13	65.56	68.57	69.41	65.54	59.26
TiO_2	0.58	0.01	0.17		–	–	–	–	–	–	–
Al_2O_3	31.36	32.68	28.36		19.89	23.22	18.52	19.35	19.68	18.38	26.17
Fe_2O_3	2.25	3.57	3.18		–	–	–	–	–	–	–
FeO	0.56	0.27	0.50		0.01	0.05	0.06	0.00	0.08	0.07	0.14
MnO	0.00	0.00	0.00		–	–	–	–	–	–	–
MgO	1.61	0.93	2.39		–	–	–	–	–	–	–
CaO	0.00	0.00	0.08		0.66	4.68	0.04	0.25	0.15	0.01	7.71
Na_2O	0.66	0.35	0.11		11.25	8.95	0.62	9.19	11.60	0.65	7.22
K_2O	10.42	11.10	10.66		0.06	0.08	15.74	3.65	0.09	15.84	0.17
F	0.01	0.02	0.01		–	–	–	–	–	–	–
Sum	94.89	94.81	94.82		100.40	100.10	100.54	101.02	101.02	100.48	100.66
Si p.f.u.	3.18	3.10	3.32	An	3.10	22.30	0.21	1.20	0.71	0.04	36.74
				Ab	96.50	77.20	5.63	78.32	98.78	5.85	62.28
				Or	0.40	0.40	94.15	20.48	0.51	94.11	0.97

Mata nappe. Its magmatic texture is better preserved, although intense deformation occurs near the borders of the intrusion and along shear zones. It hosts a younger, but undated, acid-basic composite dike, which might be an equivalent of the Permian bimodal Yunam intrusions (SPRING et al., 1994). The Rupshu granite is over- and underlain by metasediments of the Phe formation. The contacts are sharp and parallel to the main schistosity, without apophyses, except for a 1 m thick rhyolitic dike, 2 m above the upper contact in the Mata range. A fine grained porphyritic facies is locally developed along the lower contact (Fig. 5b in STECK et al., 1998). Metasediments at the upper contact are thermally metamorphosed locally, over a distance of max. 40 meters. These dark brown hornfelses consist of recristallized quartz with Chl + Ms + Bt ± Grt.

Petrography

Mineral abbreviations used in this chapter are: Ab = albite, Ap = apatite, Alm = almandine, Aln = allanite, Ann = annite, Bt = biotite, Cc = calcite, Chl = chlorite, Czo = clinozoisite, Ep = epidote, Grs = grossular, Grt = garnet, Ilm = ilmenite, Kfs = K feldspar, Oli = oligoclase, Phe = phengite, Phl = phlogopite, Prp = pyrope, Qtz = quartz, Rt = rutile, Sps = spessartine, To = tourmaline, Ttn = titanite, Ur = uraninite, Zr = zircon (SPEAR, 1993).

THE TSO MORARI GNEISS

This rock is composed of Qtz, Phe (Si = 3.1–3.28 p.f.u.), Kfs, Ab-Oli, Bt, Zr, ± Ap, To, Ilm, Chl, Czo, Grt, Ttn. The biotite is chemically homogeneous and totally re-equilibrated with metamorphism. It has a high F content in coarse-grained facies close to the contact with the host metasediments. K-feldspar is present as coarse magmatic relict crystals (Or95/Or25 perthites), or as finely recrystallized grains. Plagioclase is much less abundant. Albite and oligoclase coexist as individual grains. Albite has a slight reversed chemical zonation.

There are three garnet types. The most frequent one forms coarse ante-kinematic grains surrounded by a retromorphic schistosity associated with a top-to-the-NW shearing. This garnet is almandine-rich with about 25 mol% of Grs and less than 5 mol% of Prp (Tab. 1 and Fig. 4). The Sps content and the Fe/Fe + Mg ratio show a bell-shaped zonation ranging from 0.83 to 8.79 mol% and from 0.95 to 0.99 wt%, respectively. The second ante-kinematic type consists of coarser almandine-rich grains slightly depleted in Grs compared to the others, but which may have a Prp component as high as 14.8 mol% at its rim. We interpret these ante-kinematic garnets as relics of the eclogitic phase (see discussion below). The third type has been found in a unique mylonitic sample (G97175), and consists of syn-kinematic crystals with relatively high Sps and Grs contents (15.8 and 36.9 mol% in average). These garnets are zoned with respect to Alm and Grs molecules, which increase and decrease, respectively, from core to rim.

THE "POLOKONGKA LA GRANITE"

This granitic facies consists of Kfs, Qtz, Ab, Bt, Phe, ± Ilm, Ttn, Ep, To, Zr, Ap, Grt. There is no schistosity but the albite sericitization is slightly banded. K-feldspar forms coarse perthitic grains. Coarse-grained biotite is always rimmed by smaller crystals of the same composition, which points to chemical re-equilibration of magmatic biotite during metamorphism. The white mica has a low Si content (Tab. 1); it occurs either as relatively coarse and subidiomorphic grains, or as very small secondary grains. Albite is ubiquitous, always interstitial and highly sericitized. Garnet, if present, forms small unaltered or strongly chloritized grains. It is always linked either to the plagioclase sericitization or to the alteration of the magmatic biotite into Phe + Grt + Qtz (Fig. 5). Its composi-

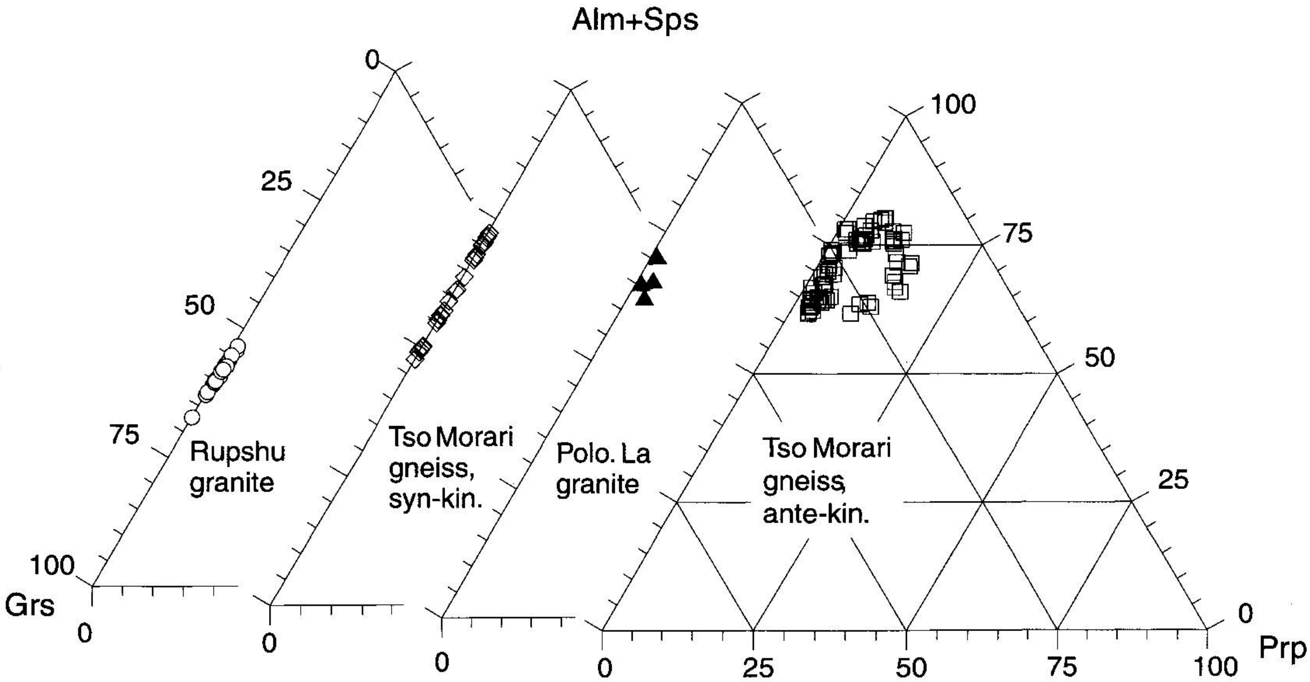

Fig. 4 Ternary diagram showing the garnet compositions. The highest Sps content is 25% and occurs in a syn-kinematic grain of the Tso Morari gneiss. Otherwise Sps is generally less than 10 %mol.

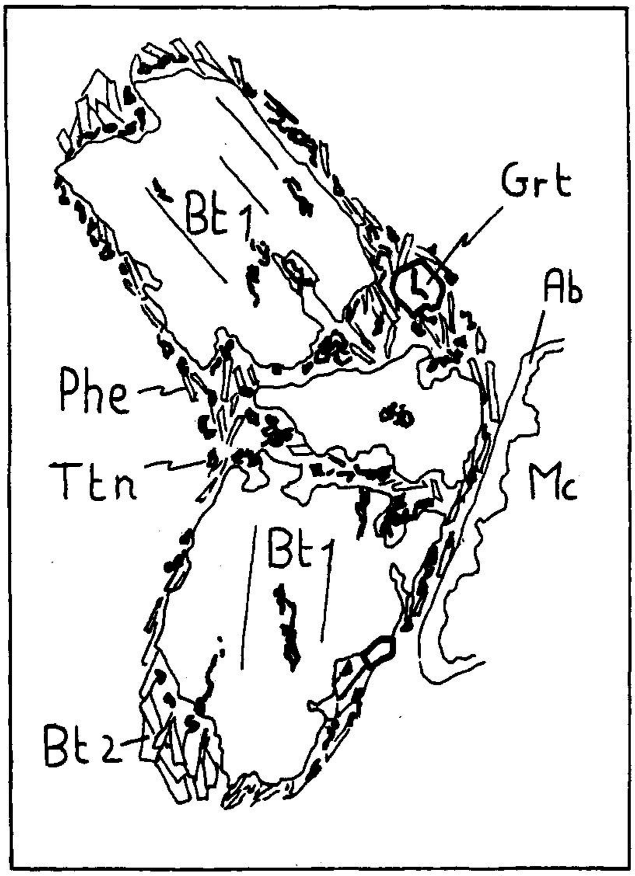

Fig. 5 Reaction rims of the Polokongka La coarse biotite 1, showing the metamorphic growth of garnet and biotite 2 at its expense. See chapter "mineralogy" for abbreviations.

tion is homogeneous and identical to that of the ante-kinematic Alm-rich, Prp-poor garnet of the Tso Morari gneiss.

THE RUPSHU GRANITE

It differs from the Tso Morari gneiss essentially by its greater amount of biotite relative to phengite. The mineralogy consists of Qtz, Pl, Bt, Kfs, Ep, Zr, ± Aln, Chl, Ttn, Phe, Cc, Rt, Ap, Grt, Ur. K-feldspar perthitic phenocrysts (Or 94-70) are partially replaced by albite ± minor oligoclase. A complexly zoned magmatic plagioclase (Ab-And) is recognizable in the less deformed facies; otherwise it is purely albitic. Coarse biotite coexists with the magmatic plagioclase. It is rimmed by finer grained metamorphic biotite (Xphl = 32%) associated with Phe + Ttn. Secondary epidote is particularly abundant. Small garnets with a high Grs content (up to 64 mol%) (Fig. 4) have been found in one sample (G9646).

Zircon characteristics and U–Pb dating

As a refractory and resistant mineral, zircon has proven to be a valuable tool for the identification and dating of highly (poly-)metamorphosed granitic rocks. Its morphology, which is dependent on the magma composition (Pupin, 1980), easily survives metamorphic overprints as long as partial melting does not occur. This allows testing of consanguinity between orthogneisses outcropping in the same area and, more generally, a comparison with reference granite types. Carefully selected zircons also yield primary magmatic ages using the U–Pb isotopic system, even if the rocks experienced several metamorphic overprints (e.g. Bussy and Cadoppi, 1996; Bussy et al., 1998).

A 20 to 30 kg sample of each granite type was crushed and zircons were isolated using conventional heavy liquid and magnetic separation techniques. Bulk fractions between 50 and 160 microns were used for electron microprobe analysis and morphological identification according to the typological method of Pupin (1980). Gem-quality non-magnetic crystals were selected under a binocular microscope for U–Pb dating according to optical criteria described in Bussy and Cadoppi (1996). Age determinations were done using the conventional isotope dilution method, following the standard procedure developed at the Royal Ontario Museum (Krogh, 1973) and described in detail e.g. in Bussy et al. (1995). Air abrasion was performed systematically to reduce or eliminate surface-correlated lead loss and younger overgrowths if present (Krogh, 1982). Regression lines were computed using the ISOPLOT program of Ludwig (1988). Errors are quoted at the 95% confidence level.

THE "POLOKONGKA LA GRANITE" (AS9660)

Most zircons are clear, inclusion free, colorless to slightly pink. They are euhedral and sharp faceted, without any trace of resorption, which is in line with the almost undeformed character of the rock. Crystals are essentially short and stubby, except for a few that form acicular prisms. {110} and {211} crystallographic forms are largely dominant (Fig. 6b). According to Pupin (1980; 1988), this kind of zircon is typical for granites of crustal anatectic origin (i.e. S-type granites). Back-scattered electron (BSE) imaging revealed frequent inherited rounded cores, as well as delicate oscillatory zoning characteristic of magmatic crystal growth. Chemical profiles across selected grains using the electron microprobe show variable contents in trace elements in the range of 500–5000 ppm U,

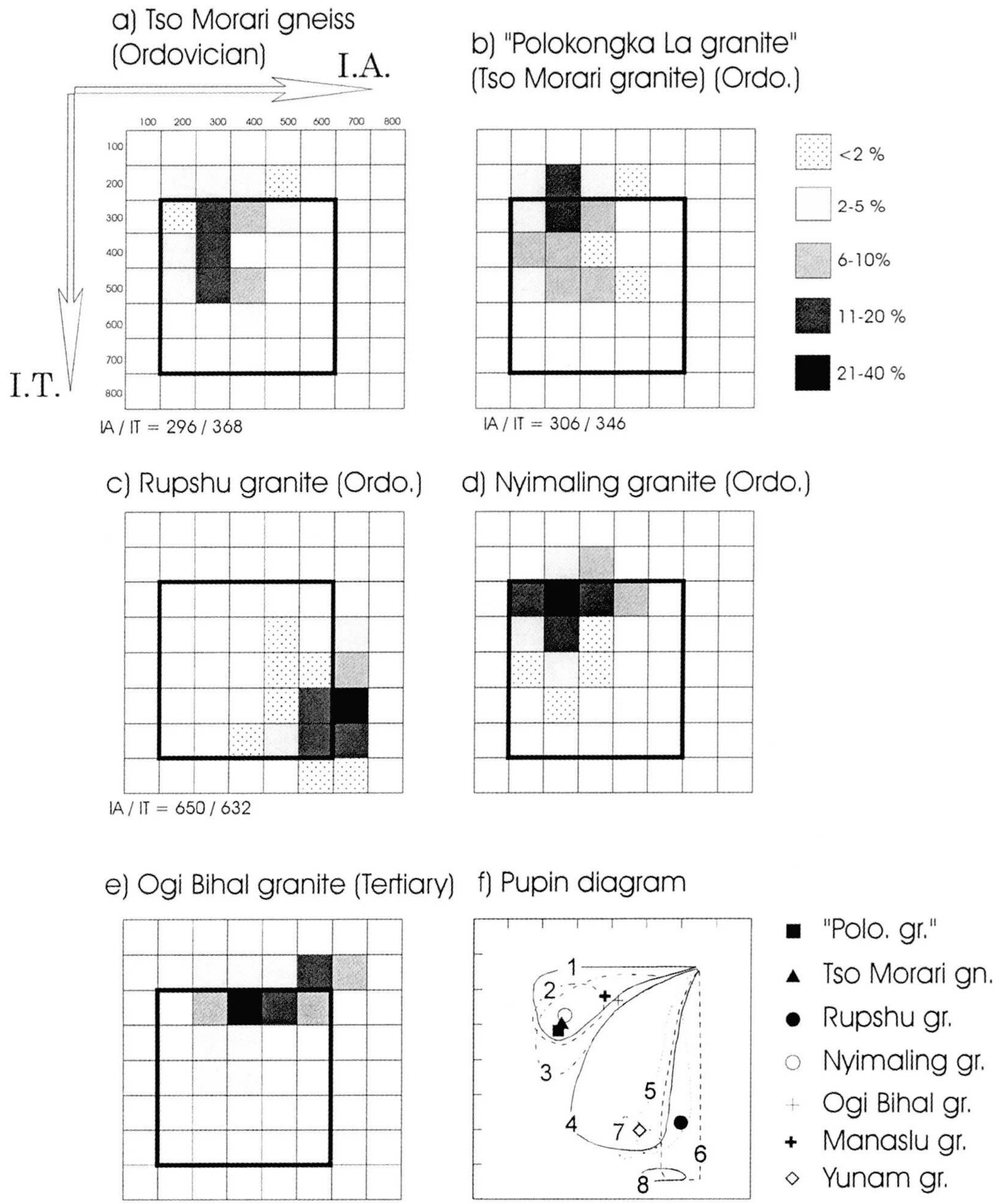

Fig. 6 Zircon typology grids after PUPIN (1980). (a), (b) and (c): this study. (d) Nyimaling granite: (STUTZ and THÖNI, 1987). (e) Ogi Bihal granite: (VANNAY, unpublished data). (f) Mean IA / IT points in the classification diagram of PUPIN (1988); Manaslu granite (BROUAND et al., 1990); Yunam granite (SPRING et al., 1994). 1 = aluminous granites; 2 = (sub)autochthonous monzogranites-granodiorites; 3 = intrusive aluminous monzogranites-granodiorites; 4 = calc-alkaline and K calc-alkaline series granites; 5 = subalkaline series granites; 6 = alkaline series granites; 7 = continental tholeiitic granites; 8 = oceanic tholeiitic series granites.

Tab. 2 U/Pb analytical data. *: radiogenic; **a:** in mole% relative to total radiogenic Pb; **b:** corrected for spike Pb and for fractionation; **c:** corrected for fractionation, spike, U and Pb blanks, and initial common Pb when present; error estimates (95% confidence level) refer to the last significant digits of the isotopic ratios and reflect reproducibility of standards, measurement errors and uncertainties in the common Pb correction.

#	Mass	Concentrations			Atomic ratios				Apparent ages (Ma)		
		U	Pb*	^{208}Pb*	206/204	206/238	207/235	207/206	6/38	7/35	7/6
	mg		ppm	a	b	c	c	c			
Polokongka La metagranite – AS9660											
[1]	0.003	383	28	5	2763	0.07705 ± 22	0.6021 ± 38	0.05667 ± 32	478.5	478.6	478.8
[2]	0.003	544	42	8	4294	0.07786 ± 24	0.6136 ± 30	0.05715 ± 22	483.4	485.8	497.3
[3]	0.002	528	39	6	3146	0.07667 ± 18	0.5993 ± 34	0.05669 ± 28	476.2	476.8	479.6
Tso Morari orthogneiss – G9628											
[4]	0.013	300	22	4	3211	0.07655 ± 18	0.5981 ± 20	0.05667 ± 12	475.5	476.0	478.7
[5]	0.003	364	27	7	2583	0.07607 ± 18	0.5944 ± 40	0.05668 ± 34	472.6	473.7	479.0
[6]	0.005	378	28	4	4945	0.07718 ± 18	0.6033 ± 26	0.05669 ± 18	479.2	479.3	479.7
Rupshu metagranite – V9692											
[7]	0.003	264	24	14	2717	0.08454 ± 40	0.6888 ± 42	0.05909 ± 10	523.1	532.1	570.5
[8]	0.004	848	66	9	13712	0.07767 ± 38	0.6084 ± 32	0.05682 ± 10	482.2	482.6	484.5
[9]	0.004	336	33	14	5025	0.09110 ± 42	0.8205 ± 44	0.06532 ± 14	562.0	608.3	784.8
[10]	0.002	321	26	14	1642	0.07773 ± 38	0.6085 ± 42	0.05678 ± 26	482.5	482.6	483.1
[11]	0.002	254	21	13	2375	0.07773 ± 36	0.6081 ± 46	0.05674 ± 30	482.6	482.4	481.6

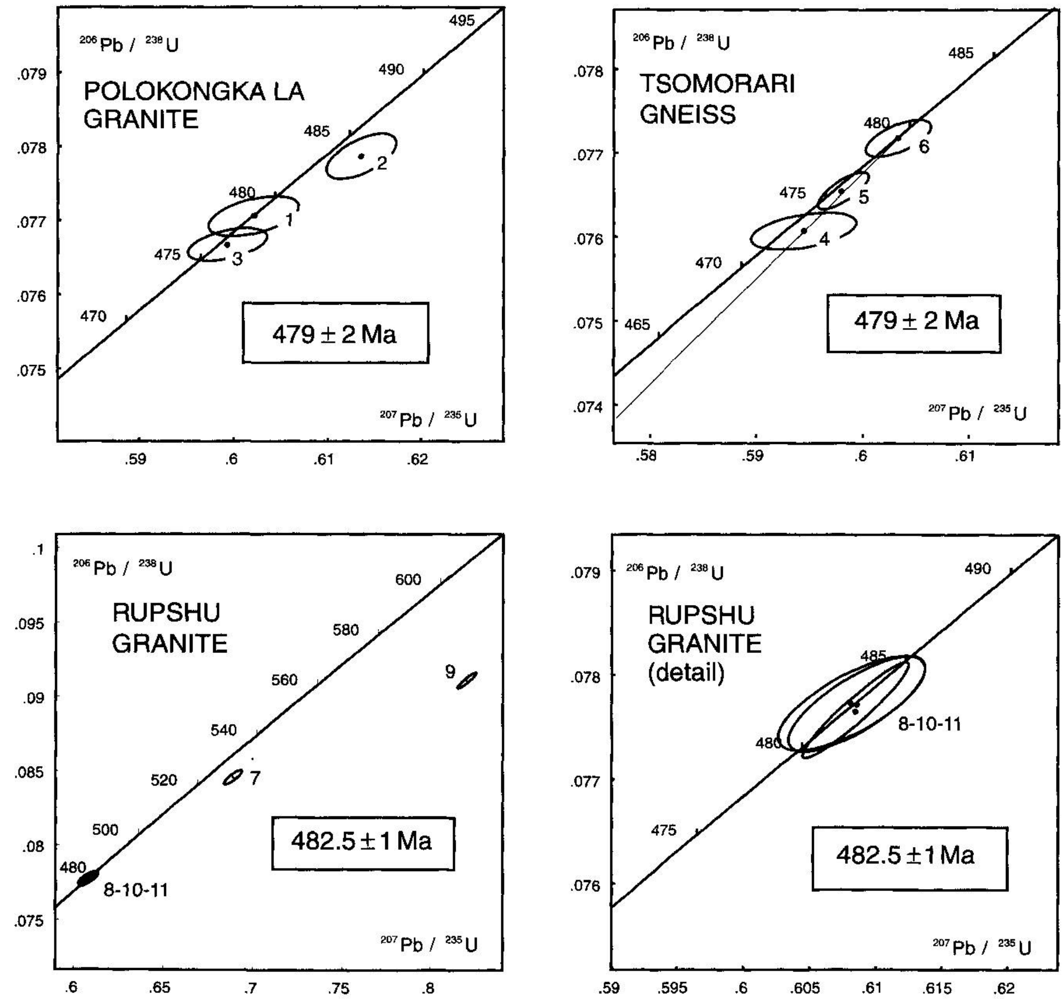

Fig. 7 U/Pb concordia diagrams for the analysed granitic samples; fraction numbers refer to text, ellipses are 2 sigma errors and the preferred ages are framed, see text for discussion.

350–7000 ppm Y, 2700–18,000 ppm Hf and < 150 ppm Th. Data points plot in the field of anatectic granites in the HfO_2–Y_2O_3 and UO_2–ThO_2 discriminant diagrams of PUPIN (1992) (not shown).

Three zircon fractions have been selected for U–Pb isotopic dating (Tab. 2 and Fig. 7). Fraction [1] consisted of a single pink flat prism with a central tubular melt inclusion, which is the best indication of the absence of an inherited core. This single grain yielded a perfectly concordant age of 479 ± 2 Ma. Fraction [2] consisted of 6 colorless acicular prisms and yielded an older $^{207}Pb/^{206}Pb$ age of 497 Ma, which is ascribed to the presence of an inherited component. Three moderately abraded flat prisms with central melt inclusions were analyzed together as fraction [3] and gave a mean U–Pb age of 477 ± 2 Ma. A residual lead loss due to incomplete abrasion might be responsible for the slight downward shift of [3] relative to [1] on the concordia diagram. Relying preferentially on the single grain analysis, 479 ± 2 Ma is proposed as the intrusion age of the Polokongka La granite.

THE TSO MORARI GNEISS (G9628)

Zircons from the Tso Morari gneiss have the same morphology as those from the "Polokongka La granite" (Fig. 6 a and b), but they show resorption features (smoothed outline and edges) ascribed to the strong deformation experienced by the rock. Inclusions, inherited cores, trace element concentrations, and growth zoning patterns are also similar in the two zircon populations. Again, three zircon fractions have been selected for U–Pb dating (Tab. 2 and Fig. 7). Fraction [4] was a single big yellowish prism with a central tubular melt inclusion, [5] a group of three small and flat colorless prisms, and [6] a single flat prism with a central trail of small bubbles. All three data points are analytically concordant within errors, but clearly define a linear array, interpreted as resulting from a slight lead loss related to the deformation event. As none of the analysed grains seems to record inheritance; preference is given to the oldest and best concordant data point [6], i.e. 479 ± 2 Ma. This age is identical to that of the Polokongka La metagranite, which, together with the zircon morphological data, definitely confirm field-based conclusions that the Tso Morari gneiss is the deformed equivalent of the Polokongka La granite.

THE RUPSHU GRANITE (V9692)

Zircons abound in the Rupshu granite and are very different from those of the Tso Morari intrusion. They are euhedral, mostly elongated, sharp faceted pink prisms with frequent central tubular melt inclusions or occasional rounded inherited cores. {101} and {100} crystallographic forms are largely dominant, {211} pyramid is often absent (Fig. 6c). This morphology is characteristic of zircons from alkali-calcic and alkaline granites (Fig. 6f) (PUPIN, 1988). BSE imaging is mostly the same as for Tso Morari zircons, but with more contrasted growth zones corresponding to higher trace element contents (up to 23,000 ppm Hf, 8000 ppm U, 12,000 ppm Y, 4000 ppm Th). Microprobe data points with highest concentrations plot in the alkaline subsolvus field of Pupin's discriminant diagrams (PUPIN, 1992). Five zircon fractions ([7]–[11]) have been analyzed for age determination (Tab. 2, Fig. 7). [7] to [9] were small multigrain fractions of 3, 4, respectively 8 crystals, whereas [10] and [11] were single prisms. Zircons [8] have a mean U content of 850 ppm, which is distinctly higher than in Tso Morari zircons, in accordance with microprobe data. Three data points ([8], [10] and [11]) plot together on the Concordia at a mean U–Pb age of 482.5 ± 1 Ma. Conversely, fractions [7] and [9] are clearly discordant with older apparent ages and presumably contain inherited cores. 482.5 ± 1 Ma is interpreted as the intrusion age of the Rupshu granite.

ZIRCON MORPHOLOGY IN NEIGHBOURING HIMALAYAN GRANITES

The 460 ± 8 Ma old (whole-rock Rb–Sr, STUTZ and THÖNI, 1987) Nyimaling metagranite is a large peraluminous intrusion in the same structural position as the Rupshu granite, and located in the western prolongation of the latter (Fig. 2). Because of these tectonic relationships, the Rupshu granite was expected to be very similar to the Nyimaling granite, if not part of it. Nevertheless, their respective zircon morphologic distributions are strikingly different (Fig. 6f), which precludes any consanguinity between these two granitic intrusions. On the other hand, zircons from the Nyimaling granite, characterised by low A and T indices, are similar to those of the peraluminous Tso Morari gneiss.

The Tertiary Ogi Bihal and Manaslu granites (VANNAY, unpublished data; BROUAND et al., 1990, respectively) are pure anatectic leucogranites resulting from decompression melting of the underlying basement (GUILLOT et al., 1993; VIDAL et al., 1982). According to Pupin's typological grid, their zircons are representative of more evolved peraluminous granites than the Ordovician intrusions.

Finally the Permian acid-basic dike of the Yunam valley in Lahul (SPRING et al., 1994) is characterized by alkaline chemical affinities, interpreted as an early evidence of the Permo-Mesozoic rifting. The granitic facies hosts zircons very similar to those of the Ordovician Rupshu granite.

In summary, isotopic dating and zircon morphology confirm that the Tso Morari orthogneiss and the Polokongka La metagranite are two structural varieties of one and the same Ordovician intrusion. The Rupshu granite, on the other hand, intruded more or less at the same time, but has contrasting zircon characteristics of alkaline affinity, which also distinguishes it from the Nyimaling metagranite.

Geochemistry

Eighteen samples of metagranites have been analysed for major and trace elements (Tab. 3). One sample of each type has also been analysed for REE by ICPMS. Considering the metamorphic and deformation events experienced by the rocks, chemical remobilization cannot be ruled out at the sample scale and only general trends should be considered. Results will be compared with some other granites and gneisses from the Himalaya.

MAJOR ELEMENTS

The Tso Morari gneiss and its undeformed facies "the Polokongka La granite" are peraluminous (A/CNK between 1.14 and 1.38) S-type granodiorites to syenogranites (DE LA ROCHE et al., 1980), in perfect agreement with the zircon typology. Despite its size, the Tso Morari intrusion is chemically rather homogeneous. It consists of differentiated, silica-rich, alumino-potassic rocks with 72–75.5 weight-% SiO_2, 5.8–8.5% Na_2O + K_2O, and K_2O/Na_2O and FeO/FeO + MgO ratios between 1.25–3.3, and 0.6–0.9, respectively.

The Rupshu metagranite is somewhat different from the Tso Morari gneiss. It has a wider compositional range with 68.8 to 77% SiO_2. It is slightly peraluminous (A/CNK around 1.05), except, as often observed, for the most differentiated facies (1.18–1.24). It is somehow less potassic than the Tso Morari intrusion with 5.7 to 7.7% Na_2O + K_2O and a K_2O/Na_2O ratio of 1.3 to 1.8. The most differentiated facies deviates from the mean with very high Na_2O contents of 5%, yielding K_2O/Na_2O ratios of 0.3 to 0.45. The Rupshu pluton is an essentially I-type intrusion, not A-type, as would be expected from zircon typology. Indeed, data points plot neither in the "within-plate granite" (WPG) field of the Y versus Nb diagram of PEARCE et al. (1984), nor in the A-field of the Ga/Al versus Zr diagram of WHALEN et al. (1987).

Tab. 3 Whole-rock geochemistry of the three dated samples.

Whole rock analyses			
	Tso Morari	Polo. La	Rupshu
Sample	G9628	AS9660	V9692
Major elements (wt%			
SiO_2	73.56	74.46	68.76
TiO_2	0.27	0.19	0.63
Al_2O_3	13.66	13.19	13.76
Fe_2O_3	0.94	1.00	1.94
FeO	1.44	0.83	2.37
MnO	0.05	0.02	0.06
MgO	0.54	0.30	1.42
CaO	1.03	0.59	2.98
Na_2O	2.37	2.36	2.50
K_2O	4.31	5.66	3.19
P_2O_5	0.18	0.17	0.13
H_2O	1.07	0.57	1.45
Sum	99.41	99.33	99.20
Trace elements (ppm):			
Ba	220	162	502
Rb	331	321	172
Sr	45	28	157
Pb	34	43	25
Th	13.7	15.7	32.2
U	3.4	2.5	3.9
Nb	11	10	12
Y	22	46	39
Zr	83	65	162
V	22	18	85
Cr	114	66	73
Ni	4	3	9
Co	6	4	19
Zn	58	52	59
Ga	21	17	19
Cu	10	9	15
REE (ppm):			
La	21.5	21.0	40.1
Ce	49.2	46.5	88.0
Pr	5.5	5.4	10.4
Nd	21.5	21.2	40.8
Sm	6.1	6.5	9.8
Eu	0.5	0.4	0.9
Gd	5.2	7.0	8.4
Tb	0.8	1.4	1.2
Dy	5.1	9.9	7.9
Ho	0.9	1.6	1.5
Er	2.4	3.9	4.5
Tm	0.3	0.4	0.6
Yb	2.0	2.4	4.1
Lu	0.3	0.3	0.6

TRACE ELEMENTS

The Tso Morari gneiss and its Polokongka La undeformed facies have trace element distributions in line with the differentiated and alumino-potassic character of the rock. Moderate to low Sr, Zr, Ba contents and a marked Eu anomaly point to mineral fractionation processes, whereas a rather high mean Rb content of 280 ppm reflects the abundance of white mica. They have almost identical and moderate LREE contents (21 ppm La) (Tab. 3) with a $(La/Sm)_N$ fractionation ratio of 2. Conversely, their HREE contents are surprisingly different, with significantly higher values for the Polokongka La metagranite (Fig. 9). These discrepancies might be related to a local concentration of HREE-rich accessory minerals in the analyzed Polokongka La sample, e.g. to the presence of a small restitic clots.

Trace element contents in the Rupshu granite are partly, although not dramatically, different from those of the Tso Morari gneiss (Tab. 3 and Fig. 8). For a given SiO_2 value, concentrations in Rb are lower, in line with the K content, but higher in Sr, Ba, V, Zr, Y and REE, which confirms essentially an I-type affinity. REE spectra (Fig. 9) are similar to those of the Tso Morari pluton, with a marked Eu anomaly, but with slightly smaller HREE fractionation ratios. The indisputable alkaline-type morphology of the Rupshu zircons is weakly reflected in the trace element chemistry. Typical features of A-type granites (e.g. WHALEN et al., 1987) are definitely absent. Nevertheless, the relatively high contents of Zr, Y and REE are very similar to those found in alkali-calcic granites (e.g. BUSSY and CADOPPI, 1996), which also host high-A indice zircons, and are interpreted as the early products of post-orogenic alkaline magmatism (BONIN et al., 1998).

COMPARISON WITH OTHER HIMALAYAN GRANITES

Data from the following intrusions have been considered: the Nyimaling granite from the upper Marka valley in Ladakh (STUTZ and THÖNI, 1987), the Jispa and Kade gneisses from Lahul (two samples of the same intrusion, N of Keylong, SEARLE and FRYER (1986), the Koksar gneiss from Lahul (VANNAY, unpublished data) and the Kaghan gneiss from Pakistan (SPENCER, 1993). These intrusions are all dated and belong to the Cambro-Ordovician event (FRANK et al., 1977; POGNANTE et al., 1990; STUTZ and THÖNI, 1987; TRIVEDI, 1990). Granite analyses from Ogi Bihal in Zanskar (22 Ma, DÈZES et al., 1999), from the Gangotri granite in Garwhal (SCAILLET et al., 1990) and from Manaslu in Nepal (VIDAL et al., 1982) are also used as representatives of the Tertiary granites.

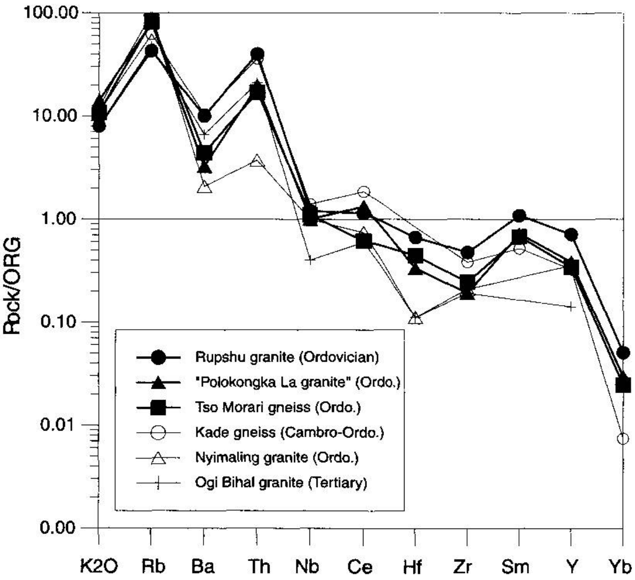

Fig. 8 Normalised multi-element diagram for some NW Himalayan metagranites. Values are normalised to the ocean ridge granite of PEARCE et al. (1984). Kade gneiss: (L107 in SEARLE and FRYER, 1986). Ogi Bihal granite (V106) and Nyimaling granite (48931): (VANNAY, unpublished data).

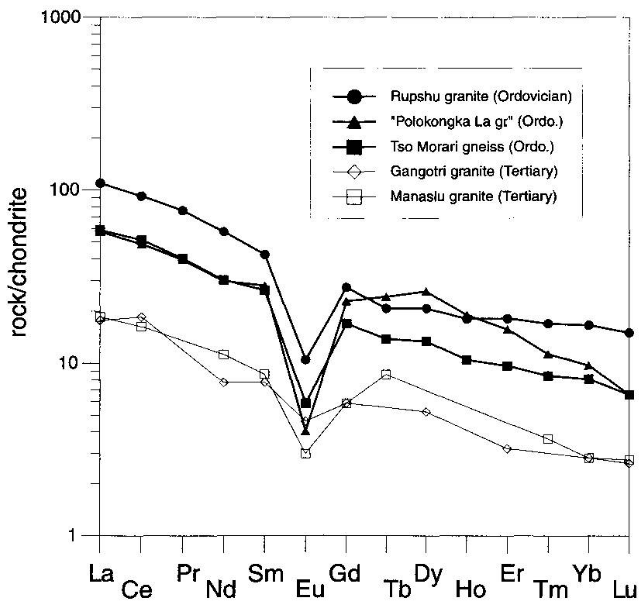

Fig. 9 Chondrite normalised (TAYLOR, 1985) REE diagram for the studied metagranites compared with two High Himalayan leucogranites: Gangotri granite (SCAILLET et al., 1990) and Manaslu granite (U average in VIDAL et al., 1982).

Tab. 4 Compilation of the Himalayan Cambro-Ordovician magmatism. Intrusions are listed from the younger to the older. The suggested characteristics are taken from the literature.

Intrusion name	Age	$Sr^{87/86}$ initial ratio	Suggested characteristics	Datation references
Dalhousie, India :	456 ± 50 Rb–Sr	–		(BHANOT et al., 1974)
Nyimaling, India :	460 ± 8 Rb–Sr	0.7365 ± 0.0002	S–type	(STUTZ and THÖNY, 1987)
Zanskar, India :	463 ± 13 U–Pb	–		(NOBLE and SEARLE, 1995)
Simchar, Nepal :	466 ± 40 Rb–Sr	0.7205 ± 0.0046		(LE FORT et al., 1981)
	509 ± 56 Rb–Sr	0.7087 ± 0.0049		(LE FORT et al., 1983)
Manikaran, India :	467 ± 45 Rb–Sr	0.719		(BHANOT et al., 1979)
Dadeldhura, India :	470 ± 4.6 Rb–Sr	0.7266 ± 0.0012		(EINFALT et al., 1993)
Kaghan, Pak :	470 ± 11 Rb–Sr	0.7216 ± 0.0023	S–type / A–type?	in (TRIVEDI et al., 1986)
Palung, Nepal :	470 ± 4 U–Pb	–	S–type	(SCHÄRER and ALLÈGRE, 1983)
	486 ± 10 Rb–Sr	0.720		(MITCHELL, 1981)
Temasa, India :	472 ± 9 U–Pb	–		(POGNANTE et al., 1990)
Tso Morari, India :	479 ± 2 U–Pb	–	S-type	This study
Rupshu, India :	482 ± 1 U–Pb	–	I-type	This study
Tamen, India :	486 ± 65 Rb–Sr	0.7142 ± 0.0053	Peral, I-type	(BHALLA et al., 1994)
Hante, India :	489 ± 20 Rb–Sr	0.7170 ± 0.0012	S-type, syn-COLG	(RAO et al., 1990)
Jespa, India :	495 ± 16 Rb–Sr	0.720 ± 0.002	S-type	(FRANK et al., 1977)
Karcham, India :	495 ± 50 Rb–Sr	–		in (TRIVEDI et al., 1986)
Deed, India :	500 ± 19 Rb–Sr	0.7201 ± 0.0013	S-type	(BHALLA et al., 1994)
Kulu, India :	500 ± 8 Rb–Sr	0.7190 ± 0.0007	Syn.COLG	(MEHTA, 1977)
Manshera, Pak :	516 ± 16 Rb–Sr	0.7189 ± 0.0006	S-type	(LE FORT et al., 1980)
Tibetan slab, Nepal :	517 ± 62 Rb–Sr	0.710		(LE FORT and VIDAL, 1982)
Anduo, Tibet :	531 ± 14 U–Pb	–		(XU et al., 1985)
Kade, India :	549 ± 70 Rb–Sr	0.7175 ± 0.0073		(POGNANTE et al., 1990)
Dudh Kosi, Nepal :	550 ±16 Rb–Sr	–		(FERRARA et al., 1983)
Champawat, India :	560 ± 20 Rb–Sr	0.7109 ± 0.0013	crustal	(TRIVEDI et al., 1984)
Kangmar, Tibet :	562 ± 4 U–Pb	–	Peraluminous	(SCHÄRER et al., 1986)
	485 ± 6 Rb–Sr	0.7186 ± 0.0018		(DEBON et al., 1981)
	484 ± 14 Rb–Sr	0.714		(WANG et al., 1981)
	435 ± 37 Rb–Sr	0.721		(JIN and XU, 1984)
Mandi, India :	545 ± 12 Rb–Sr	0.7019 ± 0.0015	Syn-COLG	(MEHTA, 1977)
	507 ± 100 Rb–Sr	0.718 ± 0.025		(JAEGER et al., 1971)
Rhotang, India :	581 ± 9 Rb–Sr	0.7113 ± 0.0007	Syn-COLG	(MEHTA, 1977)

Cambro-Ordovician metagranites from Ladakh and Lahul are mostly peraluminous S-type granites with typical high initial $^{87}Sr/^{86}Sr$ ratios (Tab. 4). The Tso Morari gneiss and its undeformed Polokongka La facies clearly belong to this category. All have similar major and trace element contents. On the other hand, Tertiary peraluminous granites seem to have contrasting trace element contents, especially REE (Fig. 9), which might reflect contrasting source materials and/or partial melting conditions. No equivalent of the Rupshu granite has yet been identified. This is not surprising, since this granite type is characterized more by its zircon typology than by its chemical composition. Similar intrusions probably exist and will be recognized through detailed studies. In accordance with zircon typological data, chemistry confirms that the Rupshu granite is definitely not linked to the peraluminous Nyimaling intrusion, which is situated in its western continuation.

Finally, the Kaghan gneiss from High-Himalaya deserves special attention. This 470 ± 11 Ma old evolved granite (whole-rock Rb–Sr, TRIVEDI et al., 1986) has been described by SPENCER (1993) as a within-plate S-type granite on the basis of high A/CNK values and high SiO_2, F, Zr, Nb, Y and REE. Such trace element contents are actually typical for A-type granites (EBY, 1992; WHALEN et al., 1987), and more specifically post-orogenic alkaline granites (as their Sr and Ba contents are still rather high, BONIN (1990). Considering the abnormaly low Al and Na concentrations in the available analyses, it is thought that the high A/CNK ratio has been acquired secondarily through pervasive alteration during ductile deformation and, consequently, that this granite does not belong to the dominant S-type group, but represents the first record of Ordovician alkaline magmatism in the Himalaya.

Post-emplacement evolution of the granites

THE TSO MORARI GNEISS

The Polokongka La metagranite is clearly the undeformed facies of the Tso Morari gneiss, as demonstrated by field relationships, as well as mineral and whole-rock chemistry, zircon typology and U–Pb ages. The use of the name "Polokongka La granite" is thus no longer justified.

Thin discontinuous metasedimentary levels within the orthogneiss suggest a multiple granite intrusion within sedimentary country rocks, the original intrusive contacts being subsequently transposed parallel to the schistosity during the main deformation. After emplacement, the Tso Morari granite experienced a complex polymetamorphic history. As shown by the eclogite lenses, an early high-pressure metamorphism affected the granite (DE SIGOYER et al., 1997; GUILLOT et al., 1995). An almandine garnet older than the amphibolitic schistosity grew at the expense of magmatic biotite. Its morphology and composition are similar to those of the garnet of the Monte Mucrone high-pressure peraluminous metagranite in northern Italy (OBERHÄNSLI et al., 1985), which suggests that the Tso Morari garnet grew during the eclogitic event, rather than during a late-magmatic stage.

The origin of the basic lenses within the Tso Morari gneiss is not yet clear. They could possibly be linked to the Permian volcanism of the Panjal Traps, as postulated by SPENCER (1993) on the basis of geochemical arguments for a similar occurrence in the Pakistani Kaghan gneiss.

The HP-LT metamorphism in the Tso Morari area has been dated at 55 ± 17 and 55 ± 12 Ma (U/Pb on Aln and Lu/Hf on Grt-Cpx-Rt respectively, DE SIGOYER et al., 1998). Eclogitization thus occurred during subduction of the Indian plate below Asia. This age is comparable to that of 49 Ma (Sm/Nd on a Grt-Cpx pair, TONARINI et al. (1993) obtained for the Kaghan eclogites. A pressure drop followed the eclogitic phase and brought the Tso Morari gneiss to lower amphibolite facies conditions, as documented by small Ca-bearing (ca. 38 mol% Grs) syn-kinematic garnets growing in mylonitic samples, with concomitant crystallization of albite and oligoclase (STECK and BURRI, 1971). The main schistosity and the mylonitic textures overprint a pre-existing (eclogitic?) gneiss structure. Metapelitic xenoliths hosted by the Tso Morari gneiss point to similar metamorphic conditions (GUILLOT et al., 1997; STECK et al., 1998). Phengites from the gneiss (Si = 3.1–3.28 p.f.u.) indicate a pressure of 9 kbar at 610 °C, according to the MASSONNE and SCHREYER (1987) geobarometer. But these values do probably not reflect peak conditions, as DE SIGOYER (1995) obtained higher Si contents of 3.47 p.f.u. in the same occurrence.

A hydrothermal alteration occurred locally, probably at the time of amphibolite facies metamorphism, as suggested by the high F content of some syn-kinematic biotites and the growth of tourmaline in the main schistosity.

THE RUPSHU GRANITE

The Rupshu granite is clearly distinct from the Tso Morari intrusion. Field observations demonstrate that these two plutons are not spatially linked and belong to two different tectonic units (the Tso Morari and Mata nappes), whereas analytical data, especially zircon typology, point to contrasting magma types. The Rupshu granite is intrusive in the Phe metasediments, as evidenced by its porphyritic marginal facies and the contact metamorphism it induced. The increased deformation near the contacts is attributed to heterogeneous Himalayan tectonics rather than to emplacement mechanisms.

The subsequent tectono-metamorphic history is different from that of the Tso Morari gneiss. No trace of high-pressure metamorphism has been found in the Rupshu granite. Doleritic dikes within the granite show a fairly well preserved magmatic mineralogy with andesine + hornblende + pigeonite as the main constituents.

The deformation stage associated with the SW-verging movements might have occurred in a lower metamorphic facies (upper greenschist) in the Rupshu granite than in the Tso Morari gneiss. Although both plutons contain syn-kinematic garnet, the latter is much more calcic in the Rupshu granite (Fig. 4), which is an expected difference between the greenschist and amphibolite facies (STECK and BURRI, 1971). The presence of albite + epidote with minor amounts of oligoclase in the metamorphic parageneses is consistent with this interpretation.

Significance of the Cambro-Ordovician magmatism in the Himalaya – the orogenic-anorogenic controversy

The Cambro-Ordovician granites in Himalaya are part of a huge magmatic belt extending all along southern Asia (LE FORT et al., 1986). Most plutons intruded between 520 and 460 Ma (Tab. 4) and have very similar characteristics such as a peraluminous granite composition, Al-rich minerals (muscovite, cordierite, andalusite, garnet), high to very high $^{87}Sr/^{86}Sr$ initial ratios, and frequent mafic microgranular inclusions. The Tso Morari gneiss is a typical example of this granite belt. On the other hand, the Rupshu alkali-calcic granite or the Kaghan alkaline granite, which both probably derived from a different source, also intruded during this period.

Basic rocks are very scarce and are mostly represented by microgranular enclaves in the granites, the Mandi gabbro (Kulu valley, NW India), and some Cambrian(?) dolerite sills intruded in the Phe Formation (Wyss and Hermann, in prep.). Volcanic or volcanoclastic deposits are volumetrically very subordinate; a few basaltic tuffitic layers were found in mid-Cambrian sediments of the Kurgiakh Formation (Zanskar) and interpreted as derived from a nearby immature volcanic arc (Garzanti et al., 1986).

Such a huge and widespread crustal-derived granitic magmatism could only be generated by a major thermal anomaly linked to a large-scale geologic event. Many authors invoked an orogenic cycle at 500–550 Ma (e.g. Frank et al., 1977; Garzanti et al., 1986). However the existence of a pre-Himalayan orogeny is not clearly documented. The calm, monotonous and long-lasting shallow-level sedimentation of the late Precambrian to Cambrian series has been interpreted as evidence for a slowly subsiding passive margin (e.g. Bond et al., 1984). Ordovician sedimentary rocks in Lahul also record an extensional rather than a compressional tectonic setting (Spring, 1993; Steck et al., 1993; Vannay, 1993). Several tectono-metamorphic studies also showed that only the Himalayan orogeny is recorded (Epard et al., 1995; Le Fort, 1974; Powell and Conaghan, 1978; Steck et al., 1998; Vannay and Steck, 1995).

Nevertheless, several authors have reported some signs of pre-Himalayan orogeny. Ferrara et al. (1983) obtained a 449 ± 56 Ma whole rock Rb/Sr age on Precambrian to Cambrian garnet-bearing paragneisses in the Mt Everest area, interpreted as an upper age limit for a pre-Himalayan metamorphism. Garzanti et al. (1986) interpreted the discordant Ordovician Thaple formation as a molassic sedimentation deposited in front of a Cambro-Ordovician orogenic mountain belt. In Zanskar Pognante and Lombardo (1989) have found some metabasites with high-pressure granulite assemblages, intruded by Paleozoic granitoids. Valdiya (1995) relates the hiatus between Late Cambrian and Ordovician sedimentation to a tectonic uplift due to the Pan-African event. The strongest argument for a pre-Himalayan orogeny is the discovery by Marquer et al. (submitted) of xenoliths of kyanite sillimanite bearing paragneisses in the Lower Palaeozoic Kinnar Kailas granite (Sutlej valley, Himachal Pradesh, India).

Such contrasting lines of evidence are difficult to reconcile, but the understanding of the Cambro-Ordovician granite magmatism should help to better define the Himalayan geotectonic evolution at that time. A syn-collisional granitic magmatism is clearly incompatible with the sedimentary record and can be ruled out. On the other hand, at least three extensional geotectonic settings might potentially generate a large-scale magmatic activity: (1) anorogenic extension, (2) back-arc extension and (3) post-orogenic extension.

Anorogenic extension (1) relates to rifting within a cold continental crust of normal thickness. This tectonic setting is illustrated by the Permian extension of the northern Indian plate. It is characterized by shallow-level, often bimodal alkaline magmatism (e.g. Spring et al., 1994), without substantial volumes of anatectic S-type granites.

A good example of back-arc extension (2) is the Late Miocene anatectic province of Tuscany (Western Italy), characterized by a widespread plutonic and volcanic peraluminous acidic magmatism (e.g. Barberi et al., 1971; Bussy, 1990; Taylor and Turi, 1976). Anatexis of the Tuscan continental crust resulted from the high heat flow associated with the back-arc extension of the Tyrrhenian sea, which occurred in response to the subduction of Adria under the European margin (e.g. Di Girolamo, 1988; Malinverno and Ryan, 1986).

The Himalayan context has characteristics incompatible with both settings (1) and (2). It lacks true anorogenic alkaline rocks and substantial volcanic deposits. Conversely, it is reminiscent of a post-orogenic extensional regime (3), such as that found at the end of the Variscan orogeny in Western Europe (e.g. Schaltegger and Corfu, 1995). About 60 to 80 Ma after continental collision, the thickened Variscan continental crust underwent a transtensional to extensional tectonic regime in response to gravitational reequilibration. Large volumes of felsic magmatic rocks emplaced along crustal-scale transcurrent faults and thick detrital sediments of molassic type were deposited in foreland basins. Both S- and I-type granites intruded, with a general evolution towards alkali-calcic, then post-orogenic alkaline, and finally anorogenic alkaline granites (Bonin et al., 1998). In the Dora-Maira massif (Northern Italy), late-Variscan peraluminous and alkali-calcic granites are contemporaneous (Bussy and Cadoppi, 1996), in the same way as the Himalayan

Tso Morari and Rupshu plutons are. The post-orogenic alkaline Kaghan metagranite from the High Himalaya, which seems to be younger than most of the surrounding peraluminous intrusions (470 Ma, Tab. 4) is in line with this evolutionary trend. In conclusion, the Cambro-Ordovician granite magmatism in the Himalaya definitely has more common features with post-orogenic than with anorogenic extensional settings. This would imply that about 540 to 560 Ma ago, 60 to 80 Ma before the intrusion of the Tso Morari and Rupshu granites (in comparison with the timing of the Variscan orogeny), an orogenic event occurred in the future Himalayan area. This timing corresponds to the end of the so-called Pan-African orogeny.

Link with the Pan-African orogeny

The Pan-African term was introduced by KENNEDY (1964), who referred to a "thermo-tectonic episode". For UNRUG (1996) the Pan-African-Brasiliano orogeny represents a megacycle, which ended with the formation of the Gondwana supercontinent (720 to 550 Ma). Evidence of these events is found almost everywhere in Gondwanian terrains. 480 Ma ago, the Indian plate was part of Gondwana, its western border being attached to the present-day Somalia and Kenya, with Madagascar in-between them (DALZIEL, 1991; 1992; UNRUG, 1996; SACKS et al., 1997; SMITH et al., 1981). But geotectonic reconstructions traditionally consider that only the extreme south of the Indian plate was affected by the Pan-African events (e.g. STERN, 1994).

Most of the Pan-African mobile belts host granites of various types. In several cases (e.g. in Hoggar, Mali or southern Brazil; BONIN et al., 1998), a general magmatic evolutionary trend is observable, with early basic ophiolitic rocks, then Cordilleran-type low-K calc-alkaline plutons linked to slab subduction, anatectic crustal melts, late-orogenic ± high-K calc-alkaline to alkali-calcic granites, post-orogenic alkaline, and finally anorogenic alkaline granites. Closer to India, syn- and late- to post-orogenic Pan-African granites have intruded the Arabian-Nubian shield (WINDLEY et al., 1996). The youngest intrusions are about 500 Ma old A-type granites in Saudi Arabia (ALEINIKOFF and STOESER, 1989), Egypt (HASSANEN, 1997), or southern Somalia (LENOIR et al., 1994). In Kerala (SW India), some A-type granites have been dated between 750 and 550 Ma (NAIR et al., 1985; SANTOSH et al., 1989).

According to the available data (Tab. 4), the Himalayan granite magmatism occurred between 580 and 450 Ma (the lower limit being subject to caution considering the poor precision of the Rb–Sr age), mostly around 500–480 Ma, with a late A-type activity recorded at 470 Ma (Kaghan granite). This is slightly younger than the closest Pan-African belt of the Arabian-Nubian shield, which suggests that there has been an eastward shift with time of the orogenic activity in eastern Gondwana. The exact nature of the inferred orogenic activity in northern India is difficult to assess. Typical subduction-related rocks are lacking, but if the analogy with the late-Variscan extensional setting is valid, then crustal thickening must have occurred in some way around 560–540 Ma, followed by isostatic readjustment, exhumation and extension. A closer look at other Cambro-Ordovician granites in Himalaya should allow to further test this hypothesis.

Conclusions

Field relationships, geochemistry, zircon typology, and U–Pb dating clearly establish that the Polokongka La metagranite is the undeformed facies of the 479 ± 2 Ma Tso Morari gneiss. It is a typical S-type, peraluminous granite intrusion, very similar to many other plutons in the area. The 482 ±1 Ma Rupshu alkali-calcic granite is quite different from the Tso Morari intrusion in terms of zircon typology. It is not the eastern prolongation of the nearby Nyimaling peraluminous pluton. Together with the post-orogenic alkaline Kaghan metagranite of Pakistan, these granite types are reminiscent of a post-orogenic extensional setting, which may be the manifestation of an orogenic event in the northern Indian plate (eastern Gondwanaland) some 580 to 540 Ma ago, at the end of the so-called Pan-African episode.

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