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Tourmaline chemistry in the metamorphic rocks of the central Nepal Himalaya

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ABSTRACT

Tourmaline occurs in various tectonic units of the Himalaya. It is found in almost all formations, from the Lesser Himalaya to the Tibetan-Tethys Sedimentary Series. They are also found in the Cambro-Ordovician granite of the Kathmandu nappe and Miocene leucogranites of the Higher Himalaya.

The chemical composition of tourmalines from the central Nepal Himalaya is presented in schorlite (Fe)-dravite (Mg)-elbaite (Al) diagram. The variation in chemistry of tourmaline in different types of rock is found to depend on the composition of the host rocks, the grade of metamorphism and the position in the structural edifice. The chemical results show that the Mg-rich tourmaline (dravite) is found to be concentrated in marble, calcic gneiss, whereas schorlite-elbaite end members are found in the pelitic gneiss, mica schist, migmatite, and quartzite, with little increase of elbaite content.

The Lesser Himalayan tourmalines show a correlation between their chemistry and the grade of metamorphism of the host rocks. The Mg content of the tourmaline increases whereas Fe and Al contents decrease from chlorite to kyanite isograd. In the chlorite isograd rocks, the tourmalines are detritic in origin and are affected very little by the low-grade metamorphism. With increasing grade of metamorphism, the fluids rich in boron are mobilized in the schist and quartzite, and reacted with aluminium silicate associated elements resulting in the crystallization of the tourmalines. In the Higher Himalayan Crystallines, where the temperature remains constant and the pressures decreases upward in the hanging wall of the MCT, the composition of the tourmaline is found to be evolved with an increase of Fe content and decrease of Mg and Al contents in the higher structural level.

INTRODUCTION

The rocks of the Himalayan range are known for the wide occurrence of tourmaline, sometimes in large quantities. It is found in almost all the formations of central Nepal, from the Lesser Himalayan units to the Tibetan-Tethys Sedimentary Series, and granites and their aplo-pegmatitic veins. The fluids have played an important role during the movement along the Main Central Thrust (MCT) in the evolution of the Miocene leucogranite. The common occurrence of tourmaline in the central Nepal Himalaya is the indicator of a wider circulation of the fluids and show distinct sensitiveness to the physico-chemical constraints of the Himalayan orogeny. The study of circulation of the fluids in the central Nepal has been undertaken only by a few workers (Pêcher 1979; Le Fort 1981; France-Lanord 1987; Brouand 1989; Rai 1993; Rai and Le Fort 1993). From the same pluton of the Higher Himalayan granite, the tourmaline granites have higher Na_2O content than the two mica granites. The higher content of Na_2O can be related to the B_2O_3 content in the metapelitic source zone. In case of the Manaslu granite, the boron content was probably higher in the metapelitic layers before melting. It could have influenced the Na_2O/K_2O ratio in the granitic melt (Guillot and Le Fort 1995).

The investigated area of the central Nepal Himalaya is located between the longitude 83°30' to 85°30'E and latitudes 27°50' to 29°00'N (Fig. 1a). The main objectives of this study were to discuss the distribution and chemistry of tourmalines in the metamorphic rocks of the area and the role of circulating fluids during the Himalayan orogeny.

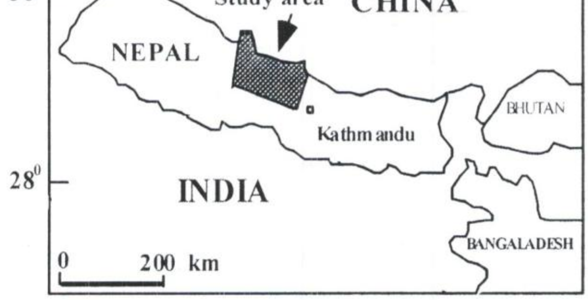

Fig. 1a: Location map of the study area.

GEOLOGICAL SETTING

The study area tectonically belongs to the Lesser Himalaya, Higher Himalayan Crystallines (Tibetan Slab) and Tibetan-Tethys Sedimentary Series (Fig. 1b). A brief geology of the area is presented below.

Lesser Himalaya

The Lesser Himalaya is bordered by the Main Boundary Thrust (MBT) in the south and the Main Central Thrust (MCT) in the north. It can be divided into the lower (Kuncha Formation of Bordet 1961, consisting of homogeneous and thick sequence of phyllite and metasandstone) and the upper Lesser Himalayan units (mainly slate, phyllite, schist, metasandstone, carbonate rocks and Ulleri-type augen gneiss and minor amount of pelitic gneiss in the vicinity of MCT). The upper stratigraphic unit in the vicinity of the MCT has undergone strong deformation and metamorphism, producing garnet, staurolite and kyanite (Le Fort 1975; Pêcher 1978, 1989).

Higher Himalayan Crystallines

Tectonically, the Higher Himalayan Crystalline unit includes the rocks lying above the MCT and below the fossiliferous Tibetan-Tethys Sedimentary Series. The upper limit of this unit is generally marked by the South Tibetan Detachment Fault System (STDFS). This unit consists of 10-12 km thick succession of amphibolite to granulite facies metamorphic rocks. From bottom to top, it is divided into three formations: Formation I, Formation II and Formation III (Le Fort 1975). The Formation I consists of mainly pelitic gneiss, probably indicating sedimentary origin. This formation is partially migmatised. The Formation II consists of calcic gneiss, banded gneiss and amphibole-pyroxene bearing marble which is also partially migmatised. The Formation III consists of essentially augen gneiss of granitic origin and minor amount of mica schist.

Tibetan-Tethys Sedimentary Series

The metasediments of this unit are originally the epicontinental marine deposits of ante-Llanvirnian to upper Cretaceous age. These metasediments are rich in fossils. The grade of the metamorphism decreases from the base to the top of the section. This unit consists of shale, limestone, metasandstone, marble, schist and quartzite. The metasediments of the unit are affected by the contact metamorphism that occurred during the emplacement of Miocene Manaslu leucogranite.

P-T conditions

The Lesser Himalayan and the Higher Himalayan Crystallines consist of greenschist to granulite facies metamorophic rocks.

The appearance of the chlorite, biotite, garnet, staurolite in the Lesser Himalaya is directly related to a temperature increase from about 450^0 C to 550^0 C towards the MCT

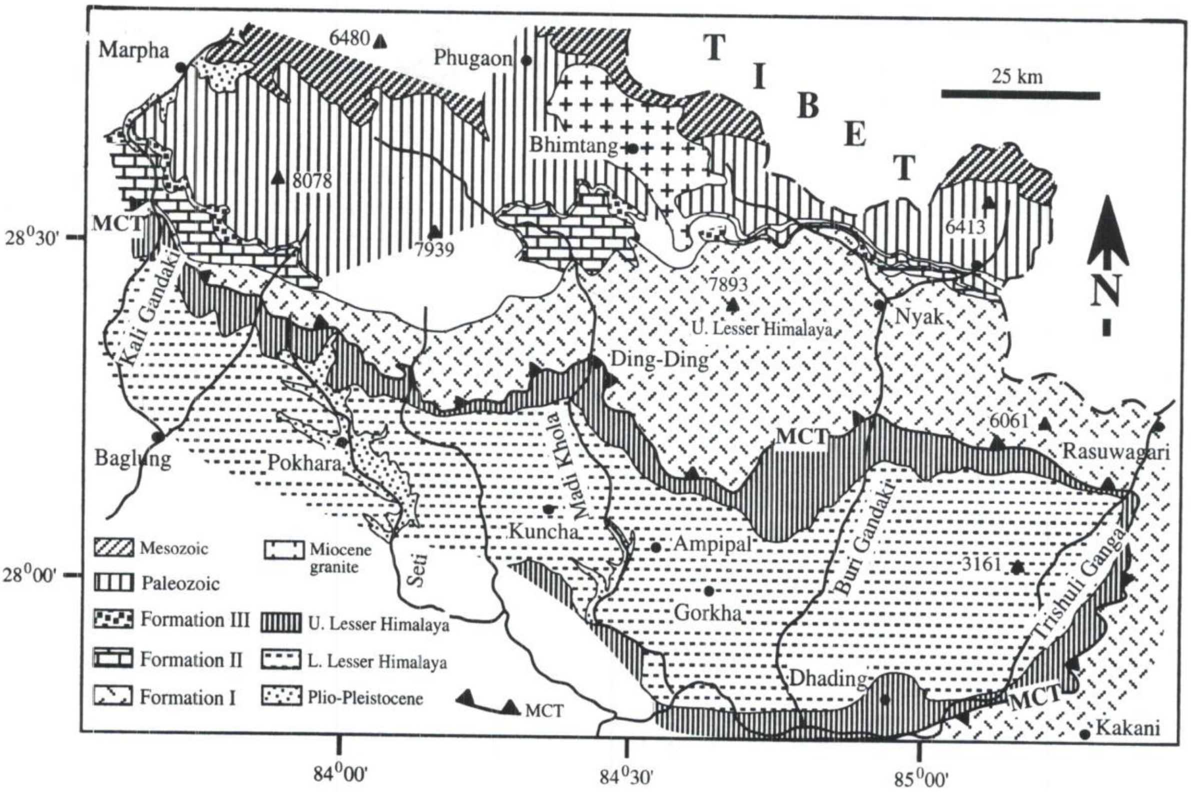

Fig. 1b: Geological map of the central Nepal Himalaya (after Colchen et al. 1980, 1986; Rai 2001, Stocklin 1980). Paleozoic-Mesozoic: Tibetan-Tethys Sedimentary Series, Formation I-III : Higher Himalayan Crystallines, MCT : Main Central Thrust.

within the central Nepal (Pêcher 1978, 1989; Caby et al. 1983; Macfarlane 1995; Rai et al. 1998) while pressure is estimated from 500 MPa in the Annapurna section (Caby et al. 1983), intermediate pressure (800 MPa) in the Manaslu section (Pêcher 1989) and 950 MPa in the Gosainkund section (Macfarlane 1995). The presence of such index minerals records the inverted metamorphic evolution during the MCT movement (Le Fort 1975; Hodges et al. 1996). In the Higher Himalayan Crytallines the metamorphic condition associated with the MCT movement shows a pressure range between 650 MPa to 865 MPa and a temperature range between 540^{0}C to 605^{0}C. The P-T conditions recorded in the Tibetan-Tethys Sedimentary Series are 300 MPa-100 MPa and 510^{0}C to 370^{0}C, respectively (Garzanti et al. 1994; Schneider and Masch 1993). The pressure estimated in the metamorphic aureole of the Manaslu granite is 540 MPa at the base of the series and 330 MPa in the Triassic unit (Guillot et al. 1995). The temperature of 550^{0}C along the contact of the granite reflects the local thermal reequilibration during the emplacement of the granite (Guillot et al. 1995).

TOURMALINE PETROGRAPHY

The tourmalines from the Lesser Himalayan mica schist are fine - to medium-grained, sub-automorphs, and prismatic in shape. The crystals are more or less aligned along the foliation plane of the host rocks. Some crystals show irregular zoning, with the development of secondary outgrowth around the detrital grains formed during the progressive metamorphism.

The tourmalines in the mica schist and pelitic gneiss from the Higher Himalayan Crystallines are fine- to medium-grained, automorph in shape. Both zoned and unzoned tourmalines are found. They show fractures perpendicular to the length of the crystals. Some crystals show traces of the development of secondary outgrowths. The tourmalines could be pre- to syn-metamorphic in origin.

The tourmalines in mica schist and marble from the Tibetan-Tethys Sedimentary Series are fine- to coarse-grained, automorph in shape, poorly to well zoned. The fractures in the tourmaline are perpendicular to the length of the crystals. Some crystals show inclusions of quartz and mica.

TOURMALINE CHEMISTRY

The microprobe analyses of tourmalines collected from different metamorphic rocks from the Lesser Himalaya, Higher Himalayan Crystallines and the Tibetan-Tethys Sedimentary Series were carried out in the Institut Polytechnique de Grenoble and CRPG-CNRS, Nancy, France, using CAMEBAX SX-50 microprobe. The accelerating voltage was 15 kV for a sample current of 15.1 nA and counting time of 5 s. Standards were natural silicates and oxides. Representative chemical analyses are presented in Table 1. The results obtained from the microprobe analyses are recalculated as the three major end members of tourmaline: schorlite (%), dravite (%) and elbaite (%). The amount of Li could not be obtained from the microprobe, so the proportion of the elbaite is indirectly calculated on the basis of amount of dravite and schorlite. The structural formula of the tourmaline is based on the 24.5 oxygen. For the present study, the general structural formula used is Na (Mg, Fe, Mn, Li, Al)$_3$ Al$_6$ (Si$_6$ O$_{18}$) (BO$_3$)$_3$ (OH, F)$_4$. For each end member, the structural formulae used are: schorlite: Na (Fe, Mn)$_3$ Al$_6$ B$_3$ Si$_6$ O$_{27}$ (OH, F)$_4$; dravite: Na (Mg)$_3$ Al$_6$ B$_3$ Si$_6$ O$_{27}$ (OH, F)$_4$ and elbaite: Na (Al, Li)$_3$ Al$_6$ B$_3$ Si$_6$ O$_{27}$ (OH, F)$_4$.

The average chemical analyses of individual end members obtained from the tourmalines in different metamorphic rocks are presented in Fig. 2 and Table 2. The chemistry of tourmalines found in different lithologies of the tectonic units is described below.

Quartzite

The average composition of tourmalines in the quartzite collected from the Upper Lesser Himalaya is: 51% schorlite, 41% dravite and 8% elbaite (Fig. 2 and Table 2). The Mg content increases from the core to the margin of the tourmaline crystals in biotite isograd quartzite (Fig. 3a). The increasing Mg content with systematic decrease in Al and Fe contents from the core to margin has been interpreted to be related to the increase of grade of metamorphism (Henry and Guidotti 1985). The development of secondary growth around few detrital tourmaline grains from the quartzite of the study area is a good evidence of the increase of grade of metamorphism.

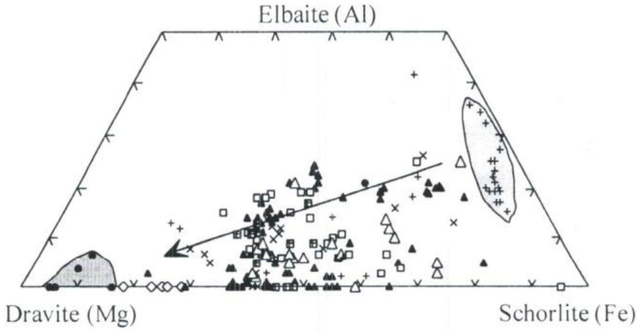

Fig. 2: Composition of tourmalines in different rock types from the central Nepal in the schorlite-dravite-elbaite diagram.

Table 1: Representative chemical compositions of the tourmalines in the different rock types from the central Nepal. The microprobe analyses were carried out in the Institut Polytechnique de Grenoble and CRPG-CNRS, Nancy, France, using CAMEBAX SX-50 microprobe. FI, Gneiss-Kakani (FI), FIIa-b, FIII: Higher Himalayan Crystallines, C: Contact metamorphism, R: Regional metamorphism.

Formation	Rock	Sample No.	SiO_2	Al_2O_3	FeO tot	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	Total
Lower Lesser Himalaya	Mica schist (R)	L82	35.61	30.44	7.84	0.07	5.44	0.67	1.62	0.03	0.69	82.39
"	Mica schist (R)	NL3	35.30	33.10	8.12	0.00	4.07	0.43	1.79	0.04	0.75	83.70
Upper Lesser Himalaya	Pelitic gneiss	MB430	36.15	32.03	6.04	0.00	7.60	0.38	2.46	0.05	0.57	85.28
"	Quartzite	NA406	35.00	30.23	8.68	0.02	5.27	0.53	1.55	0.02	0.57	81.86
"	Mica schist (R)	NA407	35.92	29.92	7.41	0.00	6.83	0.65	2.15	0.04	0.70	83.61
"	Mica schist (R)	NA387	36.20	29.48	12.43	0.00	1.81	0.42	1.59	0.03	0.39	83.85
Tibetan Slab (FI)	Pelitic gneiss	L54	35.54	31.01	9.37	0.04	4.54	0.51	2.04	0.00	0.63	83.66
"	Mica schist (R)	NL43	35.50	31.98	7.13	0.00	5.73	0.62	1.80	0.00	0.82	83.56
Tibetan Slab (FIIa)	Migmatite	MB301	35.35	32.10	9.21	0.06	5.74	0.55	2.07	0.09	0.91	86.08
"	Migmatite	MB363	35.83	32.92	7.17	0.03	6.96	1.12	2.06	0.07	0.58	86.74
"	Migmatite	MB370	35.44	27.78	12.01	0.02	7.42	2.55	1.54	0.05	0.74	87.55
Tibetan Slab (FIIb)	Mica schist (R)	NA361	34.54	31.65	8.68	0.00	6.47	2.07	1.21	0.16	0.82	85.51
Tibetan Slab (FIII)	Mica schist (R)	NA348	34.87	29.17	13.63	0.31	4.23	0.94	2.15	0.06	1.18	86.50
Annapurna Formation	Mica schist (C)	D60	36.37	31.07	10.04	0.00	4.32	0.11	1.91	0.06	0.53	84.41
"	Marble	XP103	37.02	27.91	5.21	0.00	9.53	2.06	1.64	0.06	1.30	84.72
"	Calcic gneiss	XP115	36.80	29.56	7.61	0.00	6.93	1.39	1.79	0.07	0.02	84.17
Upper Paleozoic	Calcic gneiss	XP109	34.54	32.90	10.74	0.00	3.52	0.00	1.26	0.01	0.30	83.26
"	Calcic gneiss	XP110	35.26	28.18	9.40	0.04	7.03	2.74	1.28	0.03	0.62	84.58
"	Mica schist (C)	XP281	35.42	33.34	8.05	0.00	4.74	0.94	1.56	0.04	0.88	84.97
"	Mica schist (C)	XP285	35.26	30.80	11.81	0.04	3.47	0.38	2.06	0.03	0.88	84.73
Triassic unit	Calcic gneiss	U381b	36.49	32.49	1.89	0.00	9.90	2.13	1.46	0.07	0.73	85.16
"	Mica schist (C)	U453	36.41	33.81	6.11	0.02	6.83	1.05	1.78	0.00	0.78	86.79
"	Mica schist (C)	U456	34.85	34.21	12.78	0.00	2.18	0.04	1.26	0.00	0.43	85.75
"	Mica schist (C)	U468	35.63	31.36	8.61	0.08	5.75	0.57	2.01	0.04	0.86	84.91
"	Mica schist (C)	XG04a	35.71	32.67	8.88	0.03	4.78	0.38	1.91	0.00	0.73	85.09
"	Mica schist (C)	XG18	35.38	33.28	7.13	0.07	5.44	0.67	1.61	0.00	0.67	84.24
Contact-Manaslu	Tourmalinite	U447	34.46	32.95	13.62	0.07	0.50	0.16	1.67	0.01	0.71	84.13
"	Tourmalinite	X56	34.31	32.61	13.17	0.11	0.51	0.17	2.21	0.00	1.35	84.44
Gneiss-Kakani	Tourmalinite	74120	34.98	30.32	11.26	0.00	4.87	0.70	2.00	0.02	0.88	85.04

Table 2: Average composition of tourmalines in different rock types from the central Nepal. C: Contact metamorphism, R: Regional metamorphism.

Sample no.	Metamorphic rock	No. of analyse	Elbaite (%)	Dravite (%)	Schorlite (%)
U 381b, XG109, XG110, XP115	Calcic gneiss	8	4	74	22
L54, MB430	Pelitic gneiss	21	10	48	42
XP103	Marble	5	0	76	24
D60, U453, U456, U468, U468, XG04a, XG18, XP281, XP285	Mica schist (C)	24	11	42	47
L82, NA348, NA361, NA387, NA407, NL43, NL3	Mica schist (R)	70	10	44	46
MB301, MB363, MB370	Migmatite	14	8	50	42
NA406	Quartzite	19	8	41	51
74120, U447, X56	Tourmalinite	36	15	25	60

Mica schist

The tourmalines in the mica schist from the Lesser Himalaya and Higher Himalayan Crystallines which have developed as a result of regional metamorphism show an average composition of 46% schorlite, 44% dravite and 10% elbaite (Fig. 2 and Table 2). In some tourmalines of the garnet isograd mica schist, the content of Mg increases from the core to the margin (Fig. 3b). However, the content of Al is negligible. The development of secondary growth around few detrital tourmaline grains from the mica schist of the study area is a good evidence of the increase of grade of metamorphism.

The tourmalines from the low-grade mica schist (chlorite isograd) show relatively homogeneous composition from one crystal to another. This homogeneous composition could indicate the crystallization of the tourmalines in a very low P-T condition.

The sediments of the Tibetan-Tethys Sedimentary Series (Upper Paleozoic and Triassic) are intruded by the Miocene Manaslu granite. Near the granite body, the rocks have been changed into schists due to contact metamorphism. The tourmalines from these mica schists show an average composition of 42% dravite, 47% schorlite and 11% elbaite (Fig. 2 and Table 2).

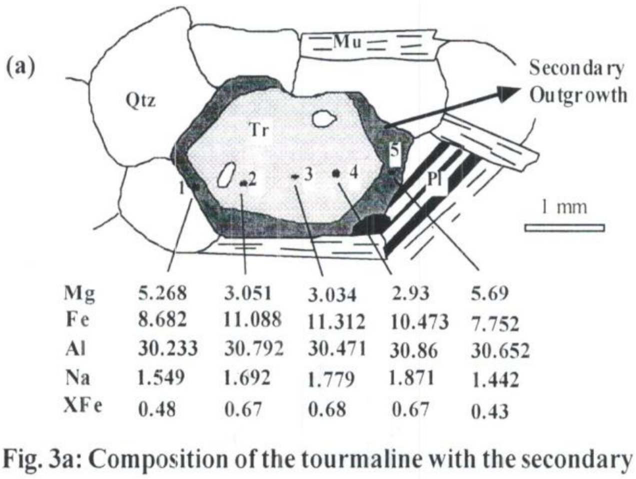

Fig. 3a: Composition of the tourmaline with the secondary outgrowth in biotite isograd quartzite (sample No. 406) from the Lesser Himalaya. Mu: Muscovite, Pl: Plagioclase, Qtz: Quartz, Tr: Tourmaline, 1-5: Point of microprobe analyse.

Pelitic gneiss

The tourmalines in the pelitic gneiss from the Upper Lesser Himalaya and Higher Himalayan Crystallines show an average composition of 42% schorlite, 48% dravite and 10% elbaite (Fig. 2 and Table 2). The Fe content in the tourmalines decreases from the core to the margin, while the contents of Al and Mg do not show any systematic variation.

The chemical composition of the tourmalines from the pelitic gneiss and mica schist plotted in the elbaite-schrol-dravite diagram of Henry and Guidotti (1985) shows that they fall in the fields of the metapelites and pssamites. Globally, their composition is variable and largely dispersed near the poles of dravite and schorlite end members.

Calcic gneiss

The tourmalines from the calcic gneiss of the Tibetan-Tethys Sedimentary Series show an average composition of 74% dravite, 22% schorlite and 4% elbaite (Fig. 2 and Table 2). The Mg content decreases from the core to the rim of the

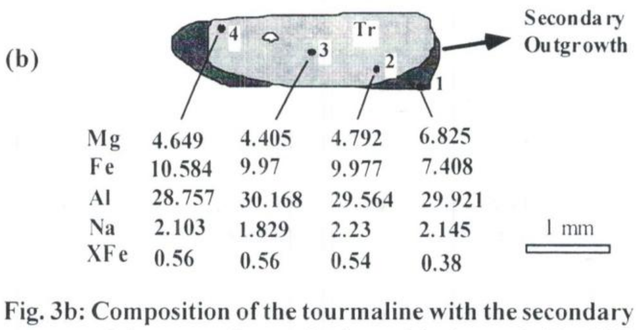

Fig. 3b: Composition of the tourmaline with the secondary outgrowth in garnet isograd mica schist (sample No. 407) from the Lesser Himalaya.

crystals in the Formation III, can be related to the activity of the South Tibetan Detachment System (STDS) that produced a drop in pressure.

Marble

The tourmalines in the marble from the Annapurna Formation of the Tibetan-Tethys Sedimentary Series show an average composition of 76% dravite, 24% schorlite and 0% elbaite (Fig. 2 and Table 2). No systematic variation in chemical composition between the margin and the core of the crystals is noted. Tourmalines from marble are rich in Mg.

The origin of the dravitic tourmaline could be controlled by the composition of the host rocks (Deer et al. 1962). Reynolds (1965) proposed the liberation of the boron from the marine limestone and illites with the crystallization of the dravitic tourmaline during the metamorphism. The dravitic tourmalines in the marble from the Tibetan-Tethys Sedimentary Series may have evolved during the metamorphism of the evaporite. Their composition could be also controlled by the crystallization of the pyroxene and amphibole within the marble.

Migmatite

The tourmalines in the migmatite of the Higher Himalayan Crystallines show an average composition of 50% dravite, 42% schorlite, and 8% elbaite (Fig. 2 and Table 2).

Tourmalinite

The tourmalines in the tourmalinite found at the contact of Manaslu granite and at the contact of the orthogneiss in Kakani area, north of Kathmandu, show an average composition of 60% schorlite, 25% dravite and 15% elbaite (Fig. 2 and Table 2). However, the composition is variable from one sample to another. The circulation of fluids rich in boron during the magmatism was responsible for the crystallization of the abundant tourmaline by the replacement of biotite and feldspar (Deer et al. 1962). The transmission of the fluids from the magmatic body to the country rocks was responsible for the crystallization of the tourmaline. The majority of the tourmalines formed in these conditions are schorl type (Henry and Guidotti 1985). The granitic magma concentrates the fluids and boron during melting process and then transported the fluids and boron throughout the Himalayan crust from the melting source to the locality of emplacement in where the degassing of the granite, liberates the boron in the surrounding rocks. The formation of the abundant tourmalines in the country rocks of the Manaslu granite could have resulted due to the circulation of the fluids and boron during the establishment of the local equilibrium.

COMPOSITION OF TOURMALINES IN DIFFERENT TECTONIC UNITS

The tourmalines found in the central Nepal Himalaya fall in the intermediate composition between the schorl and dravite end members with only minor proportion of elbaite (Fig. 4 and Table 3).

Lesser Himalayan tourmalines

The tourmalines in mica schist from the Lower units of the Lesser Himalaya show their average composition of 49% schorlite, 35% dravite and 16% elbaite (Fig. 4 and Table 3). The tourmalines in pelitic gneiss, mica schist and quartzite from the Upper units, on the other hand, show dispersion. This dispersosn could be related to the variation in mineral assemblages within different rocks. The content of Al in the tourmalines of mica schist is negligible as compared to the tourmalines of other rocks. The Mg content in the tourmalines of the pelitic gneiss is very high. The contents of Mg and Fe in the tourmalines from mica schist of the quartzite are similar. Globally, the tourmalines from the Lesser Himalaya fall in the field of metapelite and metapsammite of Henry and Guidotti (1985).

Higher Himalayan tourmalines

The composition of tourmalines in pelitic gneiss and mica schist from Formation I of the Higher Himalayan Crystallines fall in between the the poles of dravite and schorl end members (Fig. 4). The tourmalines from the mica schist are more dravitic than the tourmalines from the pelitic gneiss (Table 3). The tourmalines in the migmatite and mica schist from the Formation II show relatively similar composition. Their composition falls in between the poles of schorl and dravite. The tourmalines in the mica schist from the Formation III are more schorlitic. In mica schist, the content of Mg increases from the core to the margin. The tourmalines in the tourmalinite from the Kakani area, north of Kathmandu show high Fe content (schorlitic).

In general, the tourmalines from the mica schist of the Formation III are more schorlitic and less dravitic and elbaitic

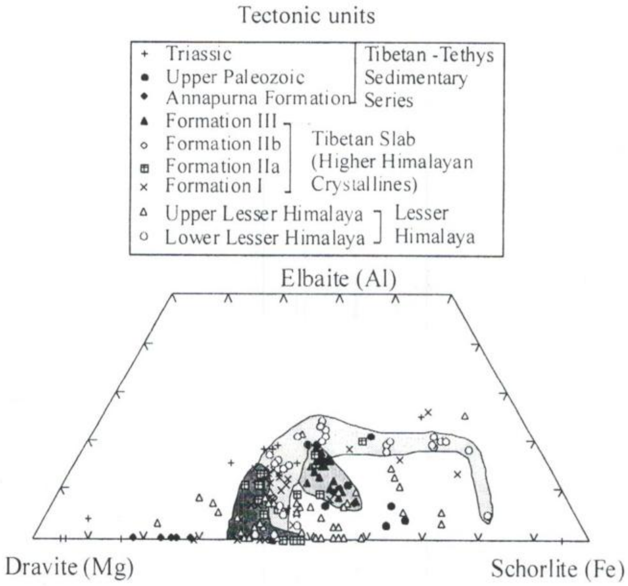

Fig. 4: Composition of tourmalines in different tectonic units of the central Nepal in the schorlite-dravite-elbaite diagram.

Table 3: Average composition of tourmalines in different tectonic units from the central Nepal. FI, Gneiss-Kakani (FI), FIIa-b, FIII: Higher Himalayan Crystallines, Les. Himalaya: Lesser Himalaya, C: Contact metamorphism, R: Regional metamorphism.

Tectonic unit	Rock type	Sample no.	No. of analyse	Elbaite (%)	Dravite (%)	Schorlite (%)
Lesser Himalaya						
Lower Lesser Himalaya	Mica schist (R)	L82, NL3	30	16	25	49
Upper Lesser Himalaya	Pelitic gneiss,	MB430,	3	7	65	28
	Mica schist (R)	NA407, NA367	23	2	51	47
	Quartzite	NA406	19	8	41	51
Tibetan Slab (Higher Himalaya)						
FI	Pelitic gneiss	L54	18	10	46	44
	Mica schist (R)	NL43	14	9	54	37
FII a	Migmatite	MB301, MB363, MB370	14	8	50	42
FII b	Mica schist (R)	NA361	1	7	53	40
FIII	Mica schist (R)	NA348	2	4	31	65
Tibetan-Tethys Sedimentary Series						
Annapurna	Calcic gneiss	XP115	1	0	62	38
	Marble	XP103	5	0	76	24
Upper Paleozoic	Mica schist (C)	D60	3	8	40	52
	Calcic gneiss	XG109, XG110	2	10	43	47
	Mica schist (C)	XP281, XP285	8	10	38	52
Triassic	Calcic gneiss	U381b	5	2	89	9
	Mica schist (C)	U453, U456, U468 XG04a, XG18	13	12	44	44
Manaslu/Kakani-Gneiss	Tourmalinite	U447, X56, 74120	36	15	25	60

in comparison to the tourmalines from the mica schist of the Formation II (Table 3). The content of Fe in tourmalines from mica schist increases from the Formation I to the Formation III (Table 3). This variation could be related to the decrease of the pressure from base to top of the Higher Himalayan Crystallines (Hodges et al. 1988; Rai et al. 1998).

Tibetan-Tethys tourmalines

The tourmalines from the calcic gneiss and marble of the Annapurna Formation are more dravitic than the tourmalines of the mica schist (Table 3). The tourmalines in amphibole-epidote calcic gneiss of the Upper Paleozoic unit are more dravitic than the tourmalines in two-mica calcic gneiss (Table 3). The tourmalines in the calcic gneiss from the Triassic unit are extremely dravitic (89%), as compared to the tourmalines (dravitic 44%) of the mica schist.

Generally, the tourmalines in the calcic gneiss from the Annapurna Formation and Triassic unit are more dravitic as compared to the tourmalines in the calcic gneiss of the Upper Paleozoic unit. The tourmalines from the mica schist show similar composition. The chemistry of tourmalines from the Tibetan-Tethys Sedimentary Series fall in the metapelite and metapsammite fields of Henry and Guidotti (1985).

METAMORPHISM AND CHEMISTRY OF TOURMALINES

No secondary outgrowth around the detritic tourmalines in the Lesser Himalaya is found in the chlorite isograd low-grade metamorphic rocks. With increasing grade of metamorphism from biotite to garnet isograd, the secondary outgrowth around the detritic grains of the tourmalines appear (Fig. 3a and 3b). At the same time, Mg content increases with the corresponding decrease of Fe with the increase of grade of metamorphism (Fig. 5). No secondary outgrowth of the tourmalines was found in the kyanite isograd rocks.

Generally, the tourmalines found from chlorite to kynaite isograd rocks show a systematic change in their composition with the change in metamorphic grade (Fig. 5). The increase of Mg content and the corresponding decrease of Al and Fe content is correlated to the increase of metamorphic grade (Fig. 5). However, the Al content is found to increase only from garnet to kyanite isograd.

The content of Fe in tourmalines from mica schist increases from Formation I to Formation III (from base to top) in the Higher Himalayan Crystallines. This variation could be related to the decrease of pressure from base to top

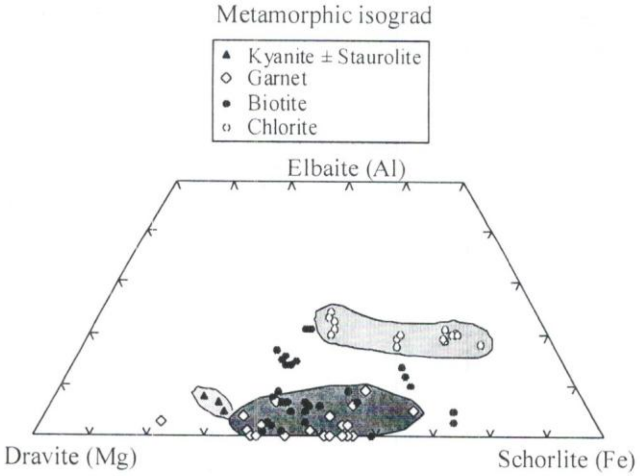

Fig. 5: Composition of tourmalines in the different rock types (quartzite, pelitic gneiss, mica schist) from the Lesser Himalaya corresponding to the grade of metamorphism.

of the Higher Himalayan Crystallines. The composition of tourmalines in the Tibetan-Tethys Sedimentary Series is controlled by the composition of the host rocks rather than the effects of metamorphism.

CONCLUSIONS

The compositional variation of the tourmalines of Central Nepal Himalaya as shown by the schorlite (Fe)–dravite (Mg)–elbaite (Al) end members diagram of Henry and Guidotti (1985) is found to be controlled by the composition of the host rocks, to the grade of the metamorphism and to the position in the structural edifice.

The chemical composition of tourmalines in various rock types shows that Mg-rich tourmaline (dravite) are found in calcic gneiss and marble, whereas Fe-rich tourmaline (schorlite) are found in tourmalinite. The composition of tourmalines from other rock types (pelitic gneiss, mica schist, migmatite, and quartzite) mostly lie in between dravite and schorlitic end members, with little elbaite component.

In the Lesser Himalaya, there seems to be a rather good correlation between the grade of metamorphism and the composition of the tourmalines. From chlorite isograd to kyanite isograd, there is a systematic increase in the Mg content and the corresponding decrease in the elbaite (Al) and schorlite (Fe) contents. In the Higher Himalayan Crystallines, from bottom to top, the composition of the tourmaline is found to evolve with an increase of Fe content and decrease of Mg and Al contents.

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REFERENCES

Bordet, P., 1961, Recherches geologiques dans l'Himalaya du Nepal, région du Makalu. Ed. Centre Natl. Rech. Sci., 275 p.

Brouand, M., 1989, Pétrogenese des migmatites de la Dalle du Tibet (Himalaya du Nepal). Ph. D. Thesis, University of Nancy. France, 224 p.

Caby, R., Pêcher, A., and Le Fort, P., 1983, Le grand chevauchement central himalayen: nouvelles donnés sur le métamorphisme inverse la base de la Dalle du Tibet. Revue de Geologie Dynamique et Geographique Physique, v. 24, pp. 89-100.

Colchen, M., Le Fort, P., and Pêcher, A., 1980, Carte geologique Annapurna-Manaslu-Ganesh, Himalaya du Nepal. Scale 1.200000. Nepal Central.

Colchen, M., Le Fort, P., and Pêcher, A., 1986, Recherches géologiques dans l'Himalaya du Nepal. Annapurna, Manaslu, Ganesh. Edit. C. N. R. S., Paris, 136 p.

Deer, W. A., Howie, R. A., and Zussman, J., 1962, Rock - Forming Minerals. Wiley, New York, v. 1, 687 p.

France-Lanord, F., 1987, Chevauchement, métamorphisme et magmatisme en Himalaya du Népal central. Etude isotopique H, C, O. Ph. D. Thesis, University of Nancy, France, 226 p.

Garzanti, E., Gorza, M., Martellini, L., and Nicora, A., 1994, Transition from diagenesis to metamorphism in the Paleozoic to Mesozoic succession of the Dolpo-Manang synclinorium and Thakkhola graben (Nepal Tethys Himalaya). Ecologae Geologae Helvetiae, v. 87/2, pp. 613-622.

Guillot, S. and Le Fort, P., 1995, Geochemical constraints on the bimodal origin of High Himalayan leucogranites. Lithos, v. 35, pp. 221-234.

Guillot, S., Le Fort, P., Pêcher, A., Barman, M. R., and Aprahamain, J., 1995, Contact metamorphism and depth of emplacement of the Manaslu granite, central Nepal, Implications for Himalayan orogenesis. Tectophysics, v. 241, pp. 99-119.

Henry, D. and Guidotti, C. V., 1985, Tourmaline as a petrogenetic indicator mineral: an example from the staurolite grade metapelite of NW Marine. Amer. Min, v. 70, pp. 1-15.

Hodges, K. V., Le Fort, P., and Pecher, A., 1988, Possible thermal buffering in collisional orogenes. thermobarometric evidence grom the Nepalese Himalaya, Geology, v. 16., pp. 707-710.

Hodges, K. V., Parrish, R. R., and Searle, M. P., 1996, Tectonic evolution of the central Annapurna Range, Nepalese Himalayas. Tectonics, v. 15, pp. 1264-1291.

Le Fort, P., 1975, Himalaya: the collided range. Present knowledge of the continental arc. Amer, J. Sci., v. 275A, pp. 1-44.

Le Fort, P., 1981, Manaslu leucogranite, a collision signature of the Himalaya. A model for its genesis and emplacement. Jour. Geophys. Res., v. 86, pp. 10545-10568.

Macfarlane, A. M., 1995, An evolution of the inverted metamorphic gradient at Langtang National Park, central Nepal Himalaya. J. Metam. Geol., v. 13, pp. 595-612.

Pêcher, A., 1978. Deformations et métamorphisme associés a une zone de cisaillement: Exemple du grand chevauchement central Himalaya (MCT). These d'Etat, University of Grenoble, France, 354 p.

Pêcher, A., 1979, Les inclusions fluides des quartz d' exsudation de la zone du M. C. T. himalayen au Nepal central. données sur la phase fluide du cisaillement crustal. Bull. Mineral. v. 102, pp. 537-544.

Pêcher, A., 1989, The metamorphism in central Himalaya. J. Metam. Geol. v. 7, pp. 31-41.

Rai, S. M., 1993, Pétrologie de la tourmaline et du bore dans l'Himalaya du Nepal central. Application aux transferts fluides et magmatiques. M. Sc. Thesis, Joseph Fourier University, Grenoble, France, 34 p.

Rai, S. M., 1998, Les nappes de Katmandou et du Gosainkund, Himalaya du Népal central (étude cartographique, structurale, métamorphique, géochimique et radiochronologique). Ph. D. Thesis, Joseph Fourier University, Grenoble, France, 244 p.

Rai, S. M., 2001, Geology, geochemistry, and radiochronology of the Kathmandu and Gosainkund Crystalline nappes, central Nepal Himalaya. J. Nepal Geol. Soc. Special Pub., v. 25, pp. 135-155.

Rai, S. M. and Le Fort, P., 1993, A boron and tourmaline point of view of the Central Nepal Himalaya. 8th Himalaya-Karakorum-Tibet Intl. workshop, Vienna, pp. 48-49.

Rai, S. M., Guillot, S., Le Fort, P., and Upreti, B. N., 1998, Pressure-temperature evolution in the Kathmandu and Gosinkund regions, central Nepal. Jour. Asian Sci., v. 16(2-3), pp. 283-298.

Reynolds, R. C., 1965, Geochemical bahevior of boron during the metamorphism of carbonate rocks. Geochim. Cosmochim. Acta, v. 29, pp. 1101-1114.

Schneider, C. and Masch, L., 1993, The metamorphism of the Tibetan series from the Manang area, Marsyandi valley, central Nepal. In: Treloar, P. J., Searle, M. (Eds.), Himalayan Tectonics, Geol. Soc. London Spec. Pub., v. 74, pp. 357-374.

Stocklin, J., 1980, Geology of Nepal and its regional frame. J. Nepal Geol. Soc., v. 137, pp. 1-34.