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Pre-alpine high-grade metamorphism in High Himalaya crystalline sequences: Evidence from Lower palaeozoic Kinnaur Kailas granite and surrounding rocks in the Sutlej Valley (Himachal Pradesch, India)

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Key words: Migmatitic doming, high-grade metamorphism, Kinnar Kailas Granite, Lower Palaeozoic intrusion, Himachal Pradesh, Himalaya

ABSTRACT

In the investigated area, the geometry of the main progressive ductile deformation (D2–D3) in the Higher Himalayan Crystalline sequences (HHCS) results from SW vergent doming and migmatisation. Structural and chronological relationships between the Kinnar Kailas (KK) granite and surrounding HHCS, provide strong evidence for a discordant intrusive contact because the KK granite crosscuts the high-grade deformation structures (D2–D3) but is locally affected by the late D4 extensional deformation. Moreover, the KK granite is undeformed and contains xenoliths of paragneiss exhibiting D2–D3 schistosity developed under upper amphibolite facies conditions. In several localities, the KK granite bears dark micro-dioritic and hybrid enclaves. The KK granite shows peraluminous, S-type granite and high K calc-alkaline characteristics. Published Rb/Sr whole-rock and new U-Pb data indicate a lower Palaeozoic age around 488 Ma for the KK granite and therefore implies an older age for high-grade metamorphic deformations D2/D3 in this part of the Sutlej Valley. These petrological and geochemical results on the KK granite reflect mixing of mantle and deep crustal melts which could be related to post orogenic extension during Ordovician time. These new results are of importance to discriminate between high-grade metamorphism and deformation related to pre-Alpine and Tertiary tectonic histories in HHCS.

RESUME

Dans la zone étudiée, la géométrie de la déformation ductile progressive majeure (D2-D3) dans la séquence cristalline du Haut Himalaya est la conséquence de la formation d'un dôme migmatitique à vergence Sud-Ouest. La chronologie relative des déformations et les relations structurales entre le granite du Kinnar Kailas (GKK) et les roches encaissantes soulignent le caractère intrusif du GKK: le granite recoupe les structures D2–D3 associées aux conditions de haut grade métamorphique mais il est localement affecté par la déformation tardive D4. De plus, le GKK est indemne de déformation et contient des xénolithes de paragneiss déformés sous les conditions du faciès amphibolitique (D2–D3). A plusieurs endroits, le granite présente des enclaves magmatiques micro-grenues sombres et des enclaves hybrides. Les caractéristiques géochimiques du granite montrent une tendance peralumineuse de type S et il se range dans le champs des séries calco-alcalines potassiques. Sur la base de données Rb-Sr roches totales publiées et de nouvelles données U-Pb, l'âge de l'intrusion se situe autour de 488 Ma. Cet âge Paléozoïque inférieur du granite implique que le métamorphisme et les déformations D2–D3 soient plus anciens dans cette région de la vallée de Sutlej. Ces résultats pétrologiques et géochimiques sur le GKK reflètent un mélange de sources mantelliques et de croûte continentale d'origine profonde qui pourrait être relié à une extension post-orogénique ordovicienne. Dans cette partie du Haut Himalaya, ces nouveaux résultats soulignent la nécessité de différencier la déformation et le métamorphisme associés à l'histoire pré-alpine et tertiaire afin d'améliorer nos connaissances sur cette portion de plaque indienne.

Introduction:

In most continental collision belts, superimposed metamorphism and deformation in basement rocks reveal polymetamorphic and polyorogenic evolutions (Alps: Romer et al. 1996; Biino et al. 1997; Himalaya: Gansser1981, Treloar et al. 1989). In the case of Alpine-Himalayan mountain belts, it is of great importance to separate the tectono-metamorphic Alpine and pre-Alpine histories to build coherent tectonic models for the former or the latter orogen. For instance, to interpret the relationships between inverted metamorphism, melting, thrusting and exhumation in the High Himalaya belt, it is important to separate the Miocene high grade metamorphism and associated crustal melting (see review in Harris & Massey 1994) from older tectonometamorphic evolution in basement rocks.

The Himalaya is the youngest and highest mountain range on the Earth. It forms an important part of the Alpine-Himalayan orogenic system, extending from Europe to the Indonesian arc and resulting from convergent plate tectonics since 55 Ma (Patriat & Achache 1984). Rocks of the Himalaya represent a long geological history of marine sedimentation, volcanism, granite plutonism, deformation and metamorphism on the northern margin of the Indian landmass. For example, the presence of migmatites at the lower contact of muscovite-tourmaline/biotite bearing granites in different parts of the Higher Himalaya attracted the attention of many workers (see

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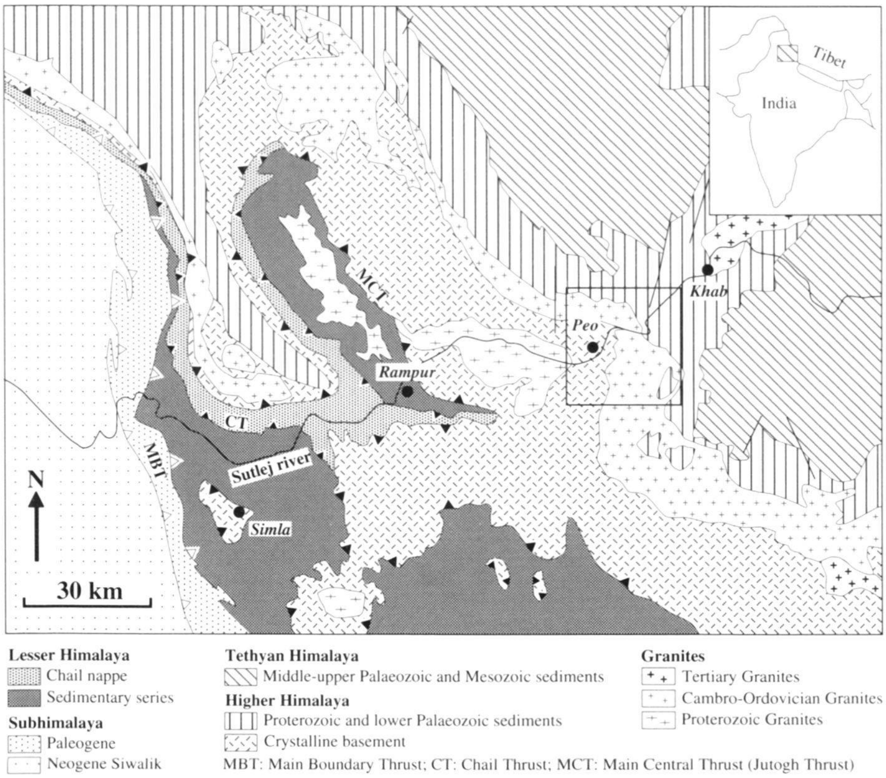


Fig. 1. General geological map of the Sutlej valley area in the western Himalaya. Modified after Thakur & Rawat (1992), Bhargava & Bassi (1994) and Vannay & Grasemann (1998). The square corresponds to the area of study

review in Harris & Massey 1994). Le Fort (1975) and many other workers (see references in Harris & Massey 1994, Dèzes et al. 1999, Guillot et al. 1999) showed that these migmatites were formed during the Tertiary peak of metamorphism, around 20Ma. Well-known and well-studied cases of inverted metamorphism in different part of the Himalayan belt (Thoni 1977, Le Fort 1981, Le Fort et al. 1987, Hodges et al. 1988) have been recently extended to the High Himalaya Crystalline in the western part of the Himalaya belt in the Sutlej valley (Vannay & Grasemann 1998). From our study and previous Indian work in this part of the belt (Bhanot et al. 1977, Mehta 1979), a Tertiary age of this high-grade metamorphism could be questionable (Chawla et al. submitted).

In polycyclic geological units, the recognition and the differentiation of the Alpine evolution from the pre-Alpine history remain a source of active debate (Biino et al. 1997). Careful deformation-metamorphism studies coupled with petrological and geochronological investigations could solve part of the controversy. The studied area is part of the Higher Himalaya of the Kinnaur district (Himachal Pradesh) and lies in the Kalpa and Sangla subdivisions (along Sutlej and Baspa river valleys, Fig. 1 and 4). The present study focuses on the deformation-metamorphism relationships in the basement rocks and the geometry of these deformations with respect to the calc-alkaline intrusion of the Kinnar Kailas granite in Sutlej valley (KK granite, Akpa granite from Sharma (1977)). This topic is of importance, because the age of this intrusion is attributed to Ordovician time (Kumar 1986, Chawla et al. submitted). In this paper, we describe the geometry, the kinematics of the basement rocks, and the emplacement style and the petrology of the KK granite. The metamorphic conditions are well described in the work of Vannay & Grasemann (1998) but their implicit attribution to Tertiary time is questionable. This work is devoted to the tectono-metamorphic study of this area and serves as a structural basis for the presentation of new geochronological analyses concerning the KK granite (Chawla et al. submitted).

Geological and tectonic setting:

The Higher Himalayan zone is commonly known as "Central Crystalline" (Gansser 1939) and consists of a 15–25 km thick pile of crystalline rocks comprising various metamorphic rocks, migmatites, and granites (Fig. 1). In this work, this zone, named High Himalaya Crystalline sequence (HHCS), is considered as basement rock consisting of Proterozoic and lower Palaeozoic metamorphic sediment on which Tethyan sediments have been deposited during upper Palaeozoic and Mesozoic times (Fig 2). These crystalline rocks and the Tethyan sediments are thrusted southwards along the Main Central Thrust (MCT), overriding the Lesser Himalayan formations during the Himalayan orogeny (Heim & Gansser 1939, Hodges et al. 1988). Small peraluminous granites were intruded into the north-eastern part of the HHCS at around

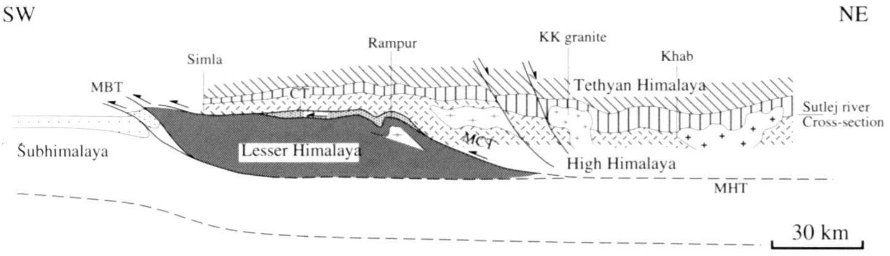


Fig. 2. Schematic localisation of the KK granite in a SW-NE cross-section in the Sutlej valley area. Same patterns as on Figure 1. The level of the Sutlej valley in indicated. Simla, Rampur and Khab are located on Figure 1. MBT, MCT, MHT and the moho discontinuity are defined at depth from Eastern INDEPTH results (Nelson et al. 1996; Hauck et al. 1998)

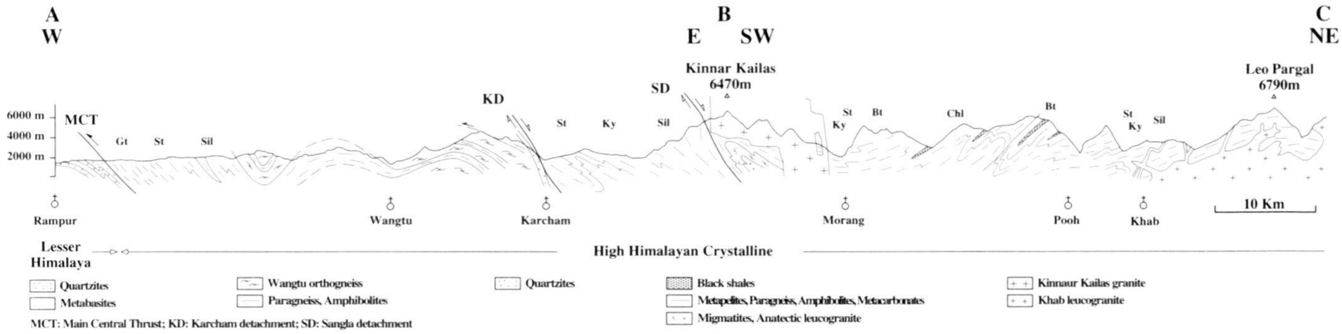


Fig. 3. Cross-section in the HHCS from the Main Central Thrust to the Leo Pargal intrusion. Based on our own observations and modified after Sharma K.K. (1977). Chl, Bt, Gt, St, Ky and Sil correspond to different metamorphic zones: chlorite, biotite, garnet, staurolith, kyanite and sillimanite, respectively (after Vannay & Grasemann (1998) and our own observations). AB, West-East section from Rampur to the KK granite and BC, SW-NE section from the KK granite to Leo Pargal intrusion (see location along the Sutlej valley on Figure 1).

20Ma, associated with syn-orogenic extensional shear zones classically separating HHCS from Tethyan Himalaya metasediments (Le Fort et al. 1987, Harris & Massey 1994, Dèzes et al. 1999).

The Himachal Himalaya is the eastern most part of the Punjab. A Considerable amount of work has been done in the western part of the Himachal Pradesh (Mehta 1977, Divakara Rao et al. 1978, Frank et al. 1977, Thoni 1977, Steck et al. 1993). Because it was an inaccessible area, the eastern part (Kinnaur region) is geologically still poorly known (Rameshwar et al. 1995, Vannay & Grasemann 1998). In the studied area, three main litho-tectonic units were previously described (Chawla 1995): the Jutogh Group, the Vaikrita Group and the Lower Haimanta Formation.

The Jutogh group is located in the western part of the area of study. These rocks are mainly composed of metapelitic schists, quartzites and alternating amphibolites and are regionally metamorphosed under lower to upper greenschist facies metamorphic conditions.

The Vaikrita group comprises kyanite-sillimanite bearing gneisses, migmatites, quartzites, schists, amphibolites, alternating calc-silicates and is intruded by the Lower Palaeozoic KK granite (Sharma 1977).

The Lower Haimanta formation occurs in the north-eastern part of the studied area and consists of low-grade pelitic carbonaceous schists, phyllites and quartzites, probably of Proterozoic and lower Palaeozoic ages (Fig. 1).

The distinction between Jutogh and Vaikrita groups were mainly defined by the location of the Vaikrita thrust (Sharma 1977). In this paper, this distinction is discussed at the end of the deformation section and is not considered on the geological map (Fig. 1: Higher Himalayan crystalline basement). Furthermore, a continuous metamorphic evolution is interpreted for this part of the High Himalaya metamorphic sequence evidencing no major tectonic contact in this area (Vannay & Grasemann 1998). So, these Jutogh and Vaikrita groups (Sharma 1977), belonging to the HHCS, are not differentiated in this paper.

Earlier workers postulated a gradual transition between the Tethyan Himalaya and underlying crystalline basement of the Higher Himalaya zone (Gansser 1964) (Fig. 1, 2). Several years later, some workers have observed a tectonic contact between the crystalline basement and the Tethyan zone in different parts of the Himalayan belt (Burg et al. 1984, Herren 1987, Thakur et al. 1990, Burchfiel et al. 1992). In the studied area, the location of this contact is unclear and is interpreted as a thrust, or a normal fault depending on the different authors (Sharma 1977, Kakkar 1988, Gururajan & Islam 1991). From our recent study and Vannay & Grasemann (1998), no major tectonic discontinuity occurs in this part of the Sutlej valley. The Lower Haimanta formation, lying continuously at the top of the metamorphic basement, is intruded by the KK granite and only exhibits intrusive relationships. Consequently, we interpret the low-grade metamorphic Haimanta formation locat-

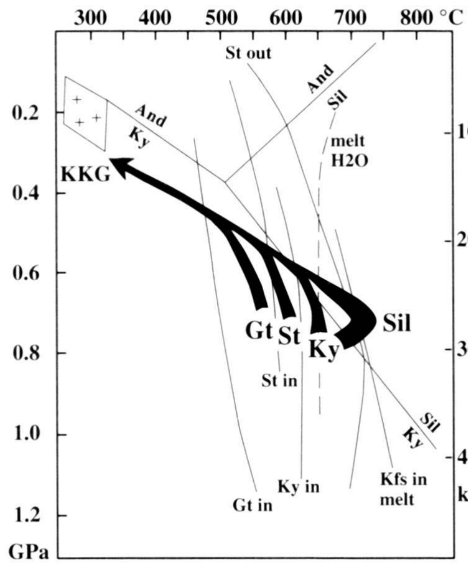
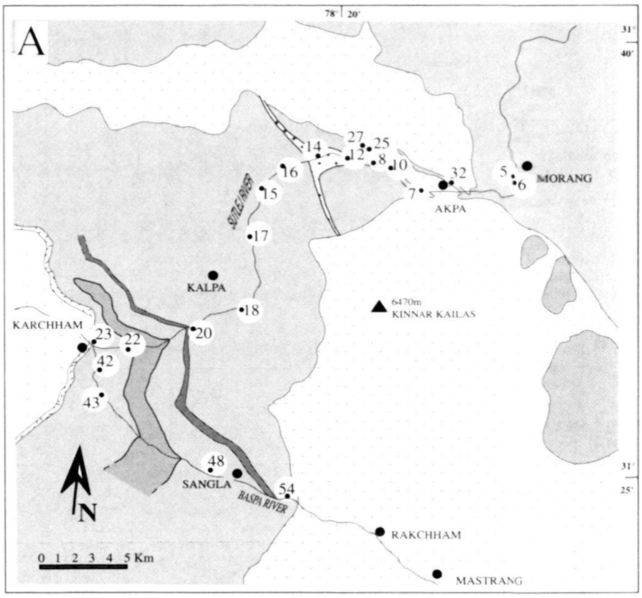


Fig. 4. PT paths for the basement rocks modified after Vannay & Grasemann (1998). The PT location of the KK granite is estimated and not petrologically constrained (see text for explanations).

ed East of the KK granite as a continuation of the HHCS. The extension of the South Tibetan Detachment System (STDS, Burchfiel et al., 1992), which is related to the significant Miocene exhumation of the south-western part of the HHCS and separates the Tethyan Himalaya and High Himalaya sequences, could be traced somewhere north in the Sutlej valley (north to the Khab-Leo Pargal Tertiary leucogranite (Fig. 3)) but not on the north-eastern side of the KK granite. Even if geological and P-T data indicate no important metamorphic break in this part of HHCS around the KK granite, evidence for extensional brittle-ductile faulting occur in the Sangla and Karcham areas (Fig. 3, SD and KD and see Post intrusion D4 deformation section) and Spiti valley. This late widespread extensional event could be related to the upper crustal activity of the STDS which is not exposed as an unique main detachment in the studied area.

Deformation in the HHCS:

In the area of the KK granite, four main phases of deformation are recorded in the old basement rocks. The three first phases of deformation occurred under high-grade metamorphic conditions, before the intrusion of the KK granite. The latest deformation is expressed by local shearing under low greenschist metamorphic conditions. The calibration of the PT conditions for the different mineralogical equilibrium are taken from the recent study of Vannay & Grasemann (1989) (Fig. 4) and are assigned to the stable parageneses observed in thin section for the different deformation phases defined in this paper (Fig. 5).



B Metapelites: Bt+Ms+Pl+Qtz+

Sample n°	D2 Assemblages Chl	Gt	St	Ky	Sil	Kfs	D3 Assemblages Sil	Grt	Kfls	D4 Assemblages Chl
8,10,14,25	-	x	-	x	-	-	x	-	-	-
16	-	-	-	-	-	-	x	-	x	-
17,32	-	-	-	x	-	-	x	-	-	-
15	-	-	-	-	-	-	x	-	-	-
27,54	-	-	-	x	-	-	-	-	-	-
12	-	x	-	-	-	x	-	-	-	-
18,20,48	-	x	-	x	-	-	-	-	-	-
5	-	-	x	x	-	-	-	-	-	-
22	-	x	x	-	-	-	-	-	-	-
6	-	-	x	-	-	-	-	-	-	-
23,42,43	-	x	-	-	-	-	-	-	-	x

Fig. 5. A: Geological map of the studied area and location of samples. B: Table of stable mineral assemblages with respect to the deformation phases in the located samples.

1. High grade deformation in the basement rocks:

1.1. D1 deformation

In the surrounding rocks of the KK granite primary structures are rarely preserved due to the strong overprints of the high-grade D2-D3 deformations. In some places, particularly where mafic rocks occur as dikes in the basement rocks, old isoclinal folds with axes P1 N 80–100 are preserved (stars on stereograms, Fig. 7A and 7B). The associated metamorphic minerals were completely overprinted during the D2–D3 amphibolite facies metamorphism. Therefore no PT conditions associated with the D1 deformation have been actually established in this area.

1.2. D2–D3 deformations

These penetrative ductile D2–D3 deformations represent the main tectonometamorphic event in this area. Basement rocks

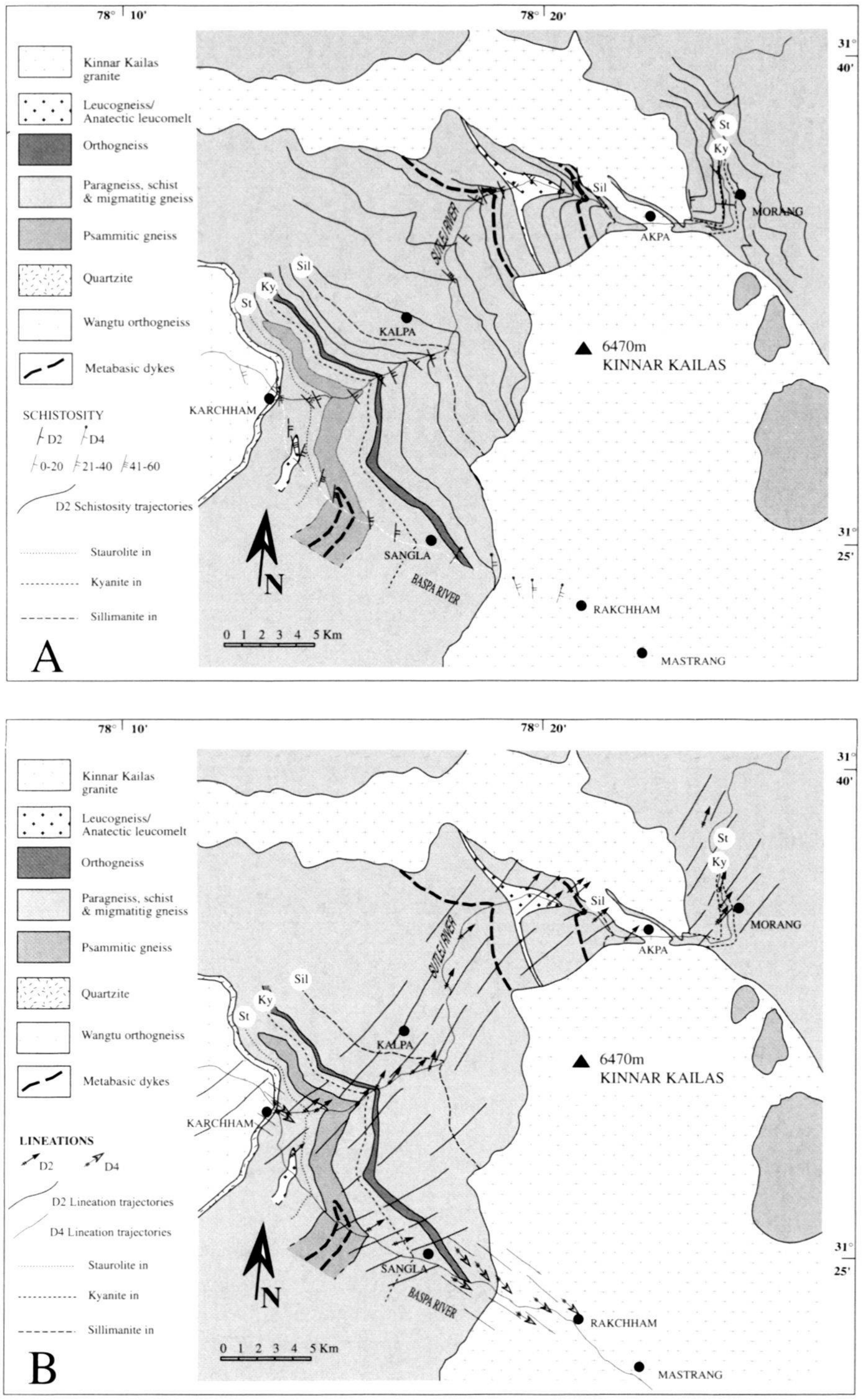


Fig. 6. Geological map of the area of study (geology and metamorphic isogrades based on Vannay & Grasemann (1998) and our own observations). A: D2 schistosity trajectories map. B: D2 stretching lineation trajectories.

underwent high temperature deformation (Vannay & Grasemann, 1998), with a progressive increase in metamorphic conditions from the Gt-St zone in the western part of the studied area (Karcham area) to migmatitic conditions located W of the KK granite (Akpa area) (Fig. 6). East of the KK granite, the metamorphic conditions progressively decrease, reaching the biotite zone several kilometres to the east of the Morang village (Fig. 3). At a large scale, this increase of metamorphism from greenschist facies up to anatectic conditions is centred on an asymmetric dome-like structure located west of the KK granite (Fig. 3, 7A).

At the scale of the area of study, the D2 deformation is strongly penetrative and is characterised by a gently dipping S2 schistosity towards the E-NE (Fig. 6A, 7: see open circles cor-

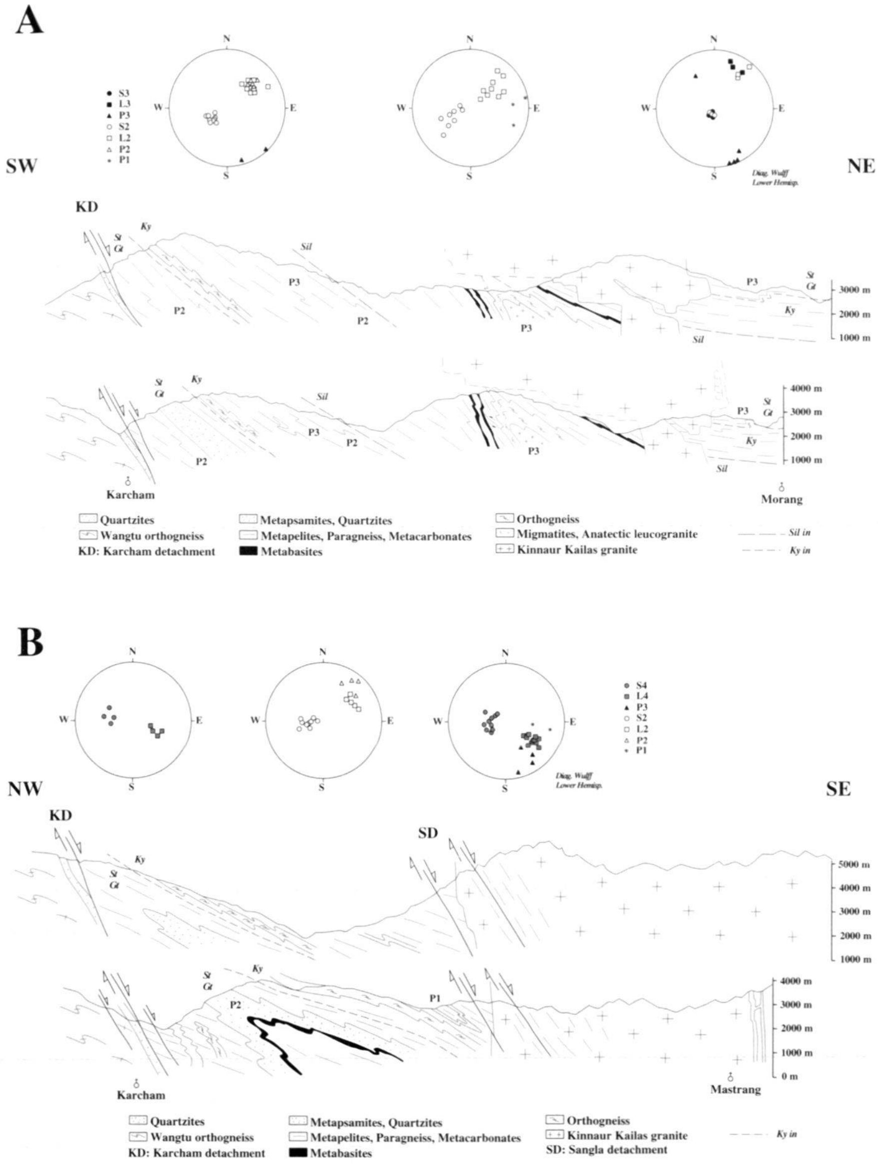


Fig. 7. Cross-sections in the area of study. A: SW-NE cross-sections in the Sutlej valley from Karcham to Morang (see localities on Fig 5). B: NW-SE cross-sections in the Baspa valley from Karcham to Mastrang (see localities on Fig 5). See text for explanations.

responding to the poles of S2 schistosity on stereograms), bearing syn-D2 metamorphic assemblages (Fig. 5). An associated stretching lineation L2 is oriented N40–45 (Open Square, Fig. 7). Large isoclinal P2 folding is associated with this deformation phase. In the field, inversion of fold vergences indicates the occurrence of a large scale P2 fold, well exposed in the Baspa valley (Fig. 7B). The P2 fold axes are oriented N40. Axes and axial planes are parallel to the L2 lineation and S2 schistosity, respectively. No clear and systematic asymmetric fabrics, that could be used as large scale kinematic indicators, were observed in the studied area. The metamorphic minerals defining the S2 schistosity emphasise a metamorphic gradient centred on a large scale D3 fold, west of the KK granite in the Sutlej valley (see Gt-St-Ky-Sil isograds, Fig. 6, 7).

The following D3 deformation shows a schistosity sub-parallel to S2 in the whole area and thus deciphering between S2 and S3, without the occurrence of superimposed structures or P3 folds, is difficult in some places. When it is recognised, the stretching L3 lineation is oriented N35 (Fig. 7A, black squares) and the S3 schistosity is characterised by identical Barrovian minerals as those crystallised during D2 (Fig. 5). P3 fold axes are oriented N140–160 with a sub horizontal plunge (Fig. 7A, 7B, black triangles). The D3 deformation is responsible for the large-scale southwest vergent antiform at the vicinity of the south-western KK granite boundary and the refolding of S2–L2 structures (Fig. 7A, 8A). West of Karcham, numerous asymmetric microstructures (e.g. C/S relationships, Berthé et al. 1979) have been observed in the Wangtu orthogneiss lead-

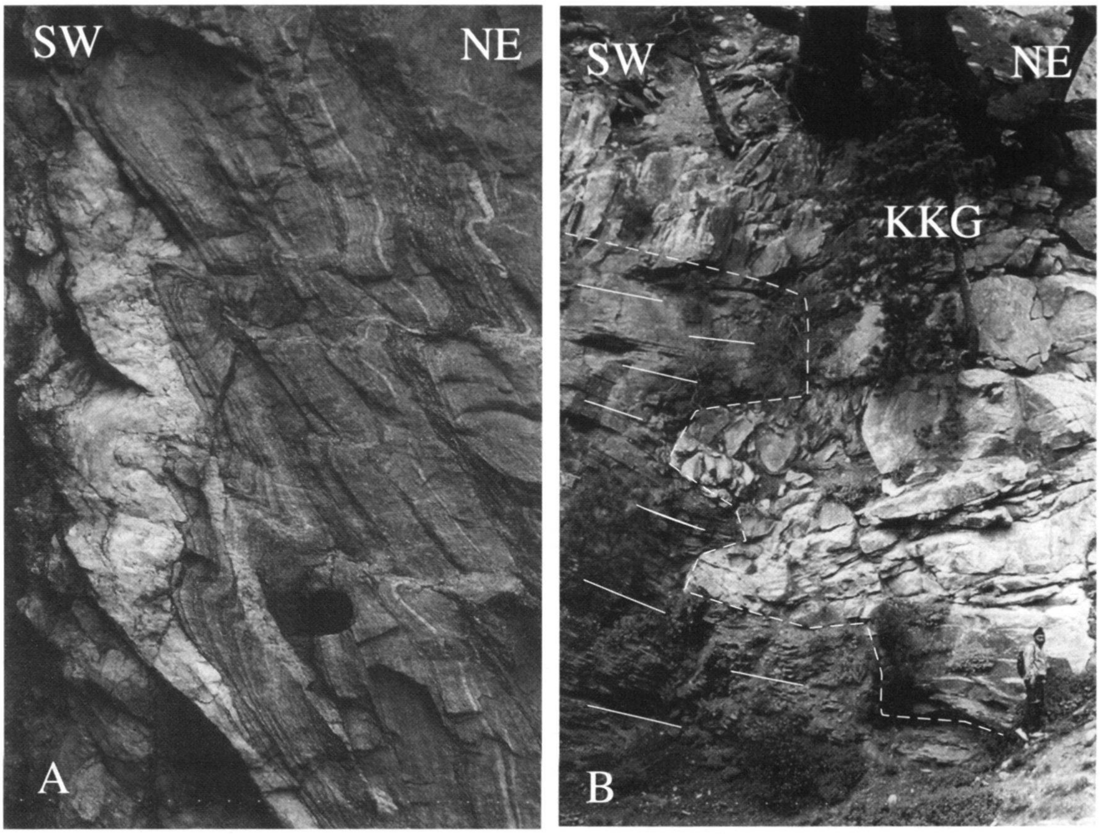


Fig. 8. A: D3 folds in paragneisses and anatectic leucocratic injections in the inverted limb of large scale antiformal D3 structure refolding D2 foliation (8 Km northwest of Akpa). Note that syn-D2 leucocratic injections are affected by D3 deformation but also cross-cut D3 folds. B: Discordant intrusive contact of the KKG in the high-grade paragneisses (Rarang, 4 km northwest of Akpa, 2950 m).

ing to a top to the southwest sense of shear (Fig. 3; also reported in Vannay and Grasemann 1998). The metamorphic grade, the stretching lineation and schistosity directions and the kinematics recorded by the Wangtu orthogneiss are compatible with the D3 deformation described in the paragneisses between Karcham and Morang (Fig. 3). During this D3 deformation, sillimanite partly replaces kyanite in migmatitic rocks and a large body of anatectic leuco-gneiss develops in the core of this antiformal dome–like structure (Fig. 6, 7A). In the inverted limb of this asymmetric antiformal structure, microstructural relationships show that these leucocratic melts were initiated during D2 deformation but also occurred syn- to post-D3 folding (Fig. 8A).

The D3 deformation has folded the previous D2 isograds under slightly higher metamorphic conditions located close to the antiformal structure, where anatectic melting occurs reaching T around 750 °C and P about 0.8 GPa (Vannay & Grasemann 1998) (Fig. 4). Because (i) D2 and D3 deformations present the same schistosity and stretching lineation orientations, (ii) they are recorded under continuous prograde metamorphic conditions with a slight change in temperature (see PT paths in Vannay & Grasemann (1998) and Fig. 4) and (iii) the peak of metamorphism responsible for D3 migmatites is centred on the D3 asymmetric antiformal structure, we interpret these two deformations as the result of a progressive migmatitic doming process.

2. Intrusion of the KK granite:

The KK granite is a magmatic intrusion showing strongly discordant contacts with the surrounding basement rocks at the map scale (Fig. 6, 7). Furthermore, the S2–S3 schistosity and L2–L3 lineation trajectories are clearly crosscut by the granite (Fig. 6A, 6B, 7). Locally, sharp discordant intrusive contacts emphasize these cross-cutting relationships with respect to the high-grade metamorphic paragneisses (Fig. 8B). In these areas, the granite textures reflect only slight orientation related to magmatic deformation and even at few centimetres from the intrusion contact, the granite appears undeformed in contrast to the surrounding highly foliated rocks. Roof pendants of basement rocks and phenomena of magmatic stoping are well developed on the north-eastern border of the intrusion

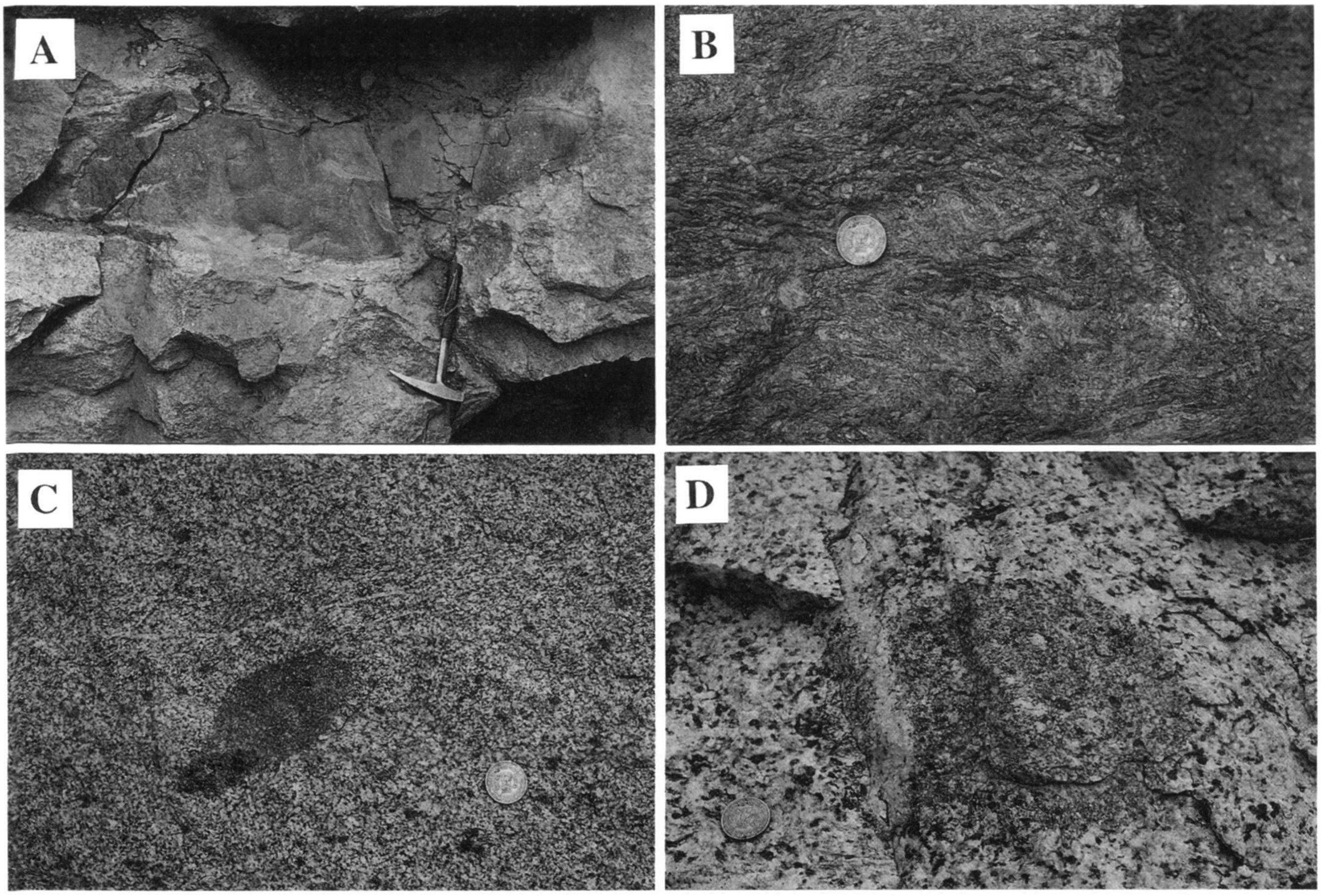


Fig. 9. Magmatic enclaves and xenoliths types occurring in the KK granite. A: Xenolith of deformed D2–D3 paragneiss; B: Ky-Sil xenocrysts bearing schistosity in paragneiss xenolith ; C: dark microgranular enclave; D: Hybrid enclave.

(Fig. 6). These observations were recognised by Vannay & Grasemann (1998) and no tectonic contact (ductile thrust or normal fault) was recognised east of the KK granite (Fig. 3). Many xenoliths of Ky-Sil bearing basement rocks are found in the KK granite (Fig. 9B). Above the Akpa village area, these xenoliths, with up to fifty meters width, have previously recorded the D2-D3 deformation and are embedded in undeformed KK granite (Fig. 9A). The discordant style of intrusion and the occurrence of metamorphic rocks as xenoliths in the KK granite reflect an emplacement type in a low temperature brittle basement at shallow crustal level (Fig. 4). This observation implies a time delay between the D2–D3 migmatitic doming process and the KK intrusion to take in account the cooling and exhumation of the migmatitic basement rocks.

3. Post intrusion D4 deformation:

The late D4 deformation is spatially localised close to the Karcham village at the level of the quartzite layer above the Wangtu orthogneiss and east of the Sangla village at the contact of the KK granite with surrounding high-grade gneisses (Fig. 6B). These deformation zones are described as the Karcham and Sangla detachments (SD after Vannay & Grasemann 1998) (Fig. 7: KD and SD). In these areas, the S4 Schistosity is N-S oriented dipping about 45° towards the E. The associated stretching lineation, mainly defined with white micas, chlorite and quartz-feldspar aggregates, plunges towards the SE (average of N120) on the schistosity plane. Numerous kinematics indicators as C/S and ECC microstructures (Berthé et al. 1979, Platt & Vissers 1980) developed in the SD and KD deformation zones, reflect a normal faulting lowering the south-eastern blocks. This ductile deformation is associated with low-grade metamorphic conditions with the occurrence of greenschist facies mineral assemblages with white micas, albite

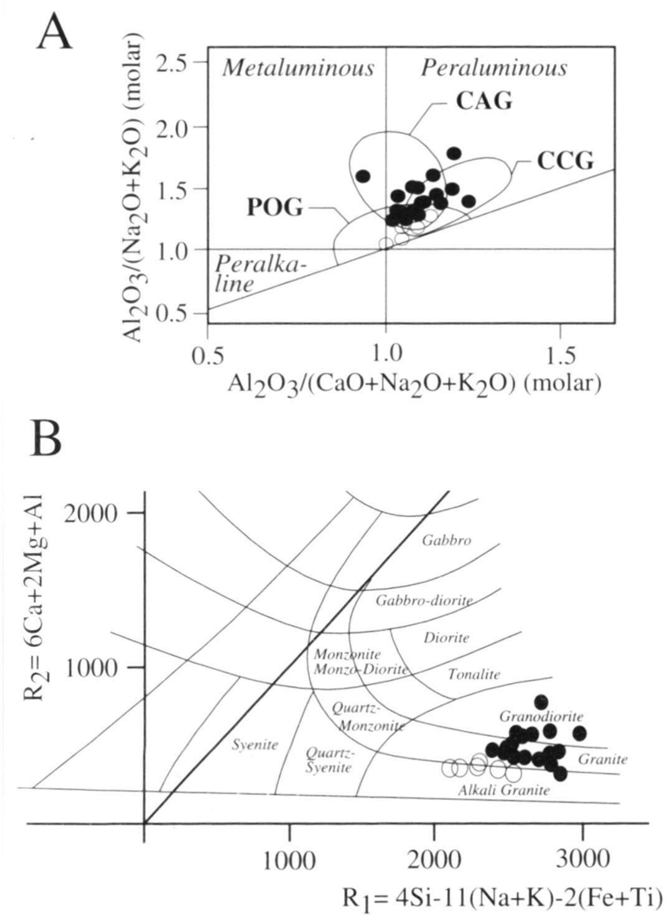


Fig. 10. Nomenclature of the KK intrusive rocks: A: Distribution of the KK intrusive samples with respect to the Shand's index modified after Maniar & Piccoli (1989). CAG: continental arc granitoids; CCG: continental collision granitoids; POG: post orogenic granitoids. B: R1-R2 diagram after de La Roche et al. (1980). Black dots: KK intrusive rocks; White circles: Himalayan Leucogranites for comparison (see table 1).

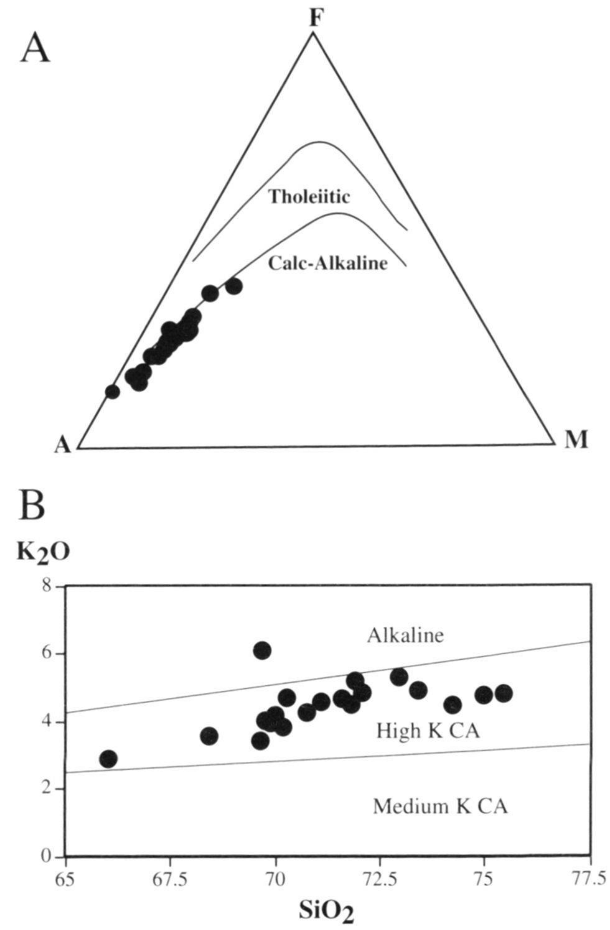


Fig. 11. Magmatic type of the KK intrusive rocks. A: AFM diagram. B: K2O/SiO2 Harker's diagram. The high-K and medium-K fields are defined after Peccerillo & Taylor (1976).

and chlorite crystallisations in the D4 microstructural sites in metapelites, gneiss and the KK granite.

An important Alpine tectonic contact has been described east of Karcham, the so-called Vaikritia thrust (Sharma 1977). This thrust does not appear in this work because asymmetric planar structures observed in the micaschist in this area are interpreted as reflecting S1/S2 schistosities relationships related to D2 folding rather than C/S structures. Furthermore, rocks and metamorphic conditions are equivalent on both sides of the "Vaikritia thrust". The Vaikritia thrust has been also questioned by Kakkar (1988) who proposed a thrust between the lower contact of quartzite and the Wangtu gneissic complex (Karcham thrust) few kilometres to the West. There, we see no major thrust contact but a normal fault has been recognised in this area east of Karcham (Fig. 3, 7, KD). This late normal faulting post-dates a strong high temperature penetrative fabric, associated with numerous top to the SW shear sense indicators (shear bands, S/C, asymmetric feldspar), at the top of the Wangtu Gneiss, also well described in Vannay & Grasemann (1998). This high temperature mylonitic zone is interpreted as the MCT by these authors. Alternatively, from field and structural relationships, this high strained zone could be related to the previously described D2–D3 high-grade deformations (Fig. 3) and therefore would correspond to an old deformation zone, following our interpretations.

Petrology of the KK granite:

1. Petrology and magmatic structures:

The huge body of the KK granite is a long NW-SE oriented intrusion (Fig. 1). In this large intrusion, several different facies

Table 1. Chemical analyses of the KK granite and Himalayan leucogranites for comparison. Himalayan Leucogranite XRF analyses are taken from Rameshwar & Sharma (1995). XRF analyses of the KK granite: * samples analysed at the Wadia Institute, Dehra Dun (Chawla, 1995) and others at the university of Fribourg (Switzerland).

	KK Granite													
	HPG537	HPG539	HPG536	HPG538	HPG619	HPG617	HPG618	HPG540	HPG529*	HPG568*	HPG104*	HPG131*	HPG577*	HPG101*
SiO2	69,82	69,88	69,91	70,08	70,74	71,59	75,00	74,20	65,99	69,62	68,39	69,68	70,24	71,08
TiO2	0,51	0,49	0,52	0,51	0,43	0,31	0,19	0,26	0,70	0,43	0,82	0,38	0,41	0,24
Al2O3	14,68	14,75	14,59	14,40	14,00	13,82	12,73	13,21	14,37	15,35	14,60	14,94	15,06	14,09
Fe2O3(T)	3,95	3,77	4,01	3,95	3,71	3,55	2,34	2,26	6,06	3,40	4,91	3,28	3,68	2,55
MnO	0,06	0,05	0,05	0,06	0,07	0,06	0,04	0,04	0,16	0,09	0,07	0,06	0,09	0,07
MgO	0,95	0,92	0,97	0,94	0,99	0,52	0,29	0,40	1,91	0,94	1,08	0,75	0,97	0,61
CaO	2,30	2,25	2,25	2,21	2,18	1,62	1,28	1,69	3,80	2,23	2,29	1,31	1,02	1,19
Na2O	3,09	3,05	3,11	3,05	2,97	3,17	3,02	2,91	3,42	3,41	2,55	2,59	3,44	2,88
K2O	3,99	4,12	4,01	3,95	4,31	4,62	4,76	4,50	2,87	3,42	3,59	6,11	4,68	4,54
P2O5	0,13	0,14	0,13	0,14	0,17	0,09	0,06	0,09	0,00	0,32	0,02	0,05	0,10	0,00
LOI	0,46	0,59	0,35	0,53	0,40	0,33	0,30	0,28						
Total	99,94	100,01	99,90	99,82	99,97	99,68	100,01	99,84	99,28	99,21	98,32	99,15	99,69	97,25
Ba	800	824	785	762	559	819	808	902						
Cr	218	202	218	209	228	247	252	218						
Cu	<5	<5	<5	19	<5	<5	<5	<5	64	28	3	11	10	33
Nb	17	17	18	16	14	19	19	13	14	13	28	22	9	27
Ni	15	15	15	17	14	15	13	11	15	7	26	15	6	8
Pb	36	42	39	38	32	37	41	36	35	34	30	19	33	25
Rb	221	225	224	233	236	272	259	209	148	227	195	257	245	239
Sr	149	151	148	144	116	106	87	121	181	108	143	86	89	87
V	56	51	54	55	55	26	13	19						
Y	31	29	33	31	19	59	46	32	37	38	25	32	41	35
Zn	43	43	47	46	45	57	39	27	63	45	78	91	34	48
Zr	200	189	193	185	171	168	156	158	180	143	226	93	124	115

							Higher Himalayan Leucogranites						
	HPG121*	HPG100*	HPG513*	HPG564*	HPG534*	HPG535*	Gopula	W.Lunama	Bhutan	Mansalu	Zanskar	Gangotri	Jaspa
SiO2	71,80	71,91	72,06	72,90	73,38	75,38	73,46	71,97	72,92	73,94	75,6	73,01	73
TiO2	0,24	0,22	0,30	0,15	0,16	0,03	0,12	0,18	0,1	0,07	0,03	0,07	0,14
Al2O3	14,61	15,50	14,13	14,53	14,77	14,74	14,87	15,56	15,13	14,76	13,9	15,24	14,4
Fe2O3(T)	2,55	1,98	3,42	1,65	1,72	1,11	0,86	1,45	0,96	0,81	0,49	0,79	1,85
MnO	0,07	0,03	0,07	0,05	0,06	0,05	0,02	0,04	0,03	0,02	0,01	0,02	0,06
MgO	0,55	0,34	0,76	0,40	0,13	0,00	0,05	0,12	0,12	0,13	0,16	0,12	0,31
CaO	1,19	1,37	0,87	1,16	1,19	0,49	0,71	0,82	0,81	0,46	0,36	0,58	0,5
Na2O	2,88	3,29	3,36	3,56	3,46	3,22	4,06	3,56	3,78	4,14	4,39	4,31	4,67
K2O	4,54	5,18	4,83	5,30	4,89	4,79	4,78	5,28	4,6	4,48	3,96	4,56	4,89
P2O5	0,00	0,10	0,00	0,33	0,20	0,00	0,09	0,07	0,13	0,13	0,12	0,25	0,27
LOI													
Total	98,43	99,92	99,80	100,03	99,96	99,81	99,02	98,58	98,94	98,94	99,02	98,95	100,09
Ba													
Cr													
Cu	11	12	16	23	12	6							
Nb	22	11	14	7	9	11							
Ni	9	0	6	4	4	3							
Pb	32	35	33	26	25	22							
Rb	260	214	188	286	283	300	357	394	347	358	278	416	384
Sr	57	89	78	57	63	21	74	98	67	62	30	44	46
V													
Y	37	25	39	39	32	34							
Zn	53	58	22	44	12	15							
Zr	113	127	136	90	99	84				43	8	35	77

exhibiting magmatic relationships occur in the area of study. The three main petrographic types recognised within the KKG are from the oldest to the youngest: a biotite rich, grey coloured aplitic facies, a coarse grained facies and a two micas, KFeldspar porphyritic facies. Numerous dikes of aplite and pegmatites bearing beryl (aquamarine), tourmaline, muscovite and garnet are present and crosscut both the KK intrusion and the basement rocks. Mafic and hybrid magmatic enclaves corresponding mainly to microdiorite composition, are abundant in all the different facies of the KK intrusion (Fig. 9C, 9D). These magmatic enclaves are lobate or round in shape, often including feldspar porphyroclasts from the host granite. The

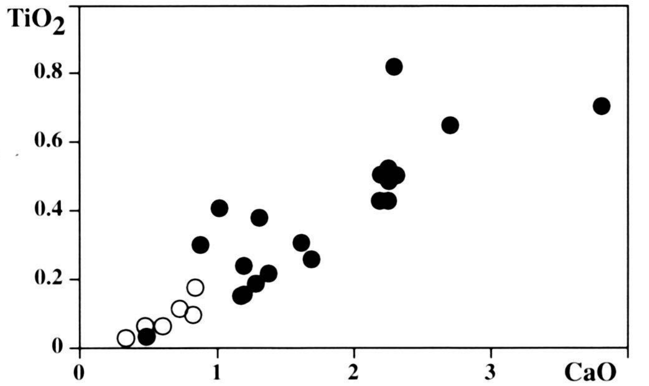


Fig. 12. Comparison between the composition of the KK intrusives rocks and Himalayan leucogranites in a TiO2/CaO diagram. Same symbols as in figure 10.

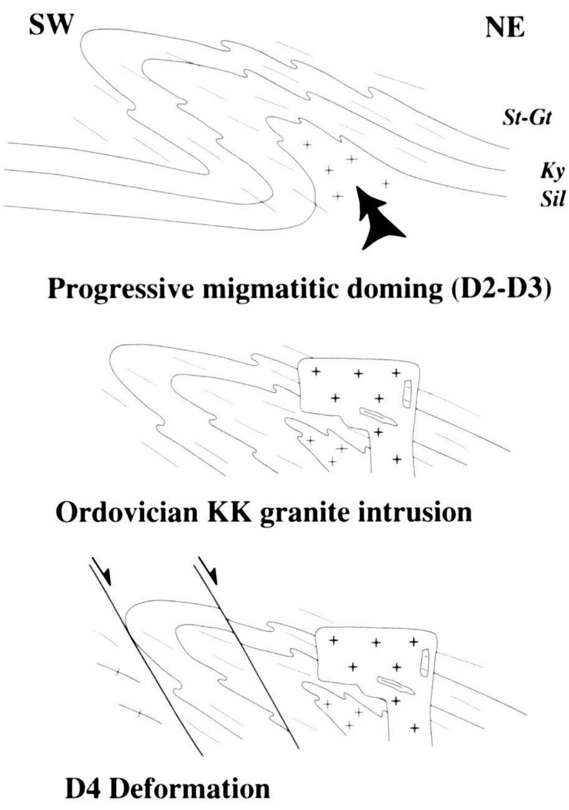


Fig. 13. Synthetic sketch of the tectonometamorphic evolution of the HHCS. Geometrical relationships and kinematics of the basement and the KK granite.

occurrence of these magmatic enclaves indicates mingling and mixing phenomenon and the participation of mantle derived melts during the KK magmatic evolution (Barbarin & Didier, 1992). Xenoliths of basement rocks are also present showing local contamination with garnet bearing granitic facies close to xenoliths.

Under the microscope, quartz grains are anhedral to subhedral in form and shows slight undulose extinction. The K-feldspar is generally a cross-hatched, high triclinicity (0.82–0.85) microcline, with occasional orthoclase showing single carlsbad twinning. Plagioclase is mostly oligoclase-andesine (An 22–32%) and occurs as subhedral crystals interlocked with K-feldspar and quartz. Biotite is the principal mafic mineral and at places altered to green chlorite.

Geochemistry of the KK Granite

Geochemical data of 20 representative samples covering the petrological varieties of the KK intrusive rocks, show a gradual increase in Al2O3 (14.1 to 16.4%), K2O, Na2O and decrease in TiO2, CaO, MgO, Fe2O with increase in SiO2 content ranging from 65% to 75% (Table 1). The KKG analyses lie in the field of granite and granodiorite in the R1–R2 diagram of de La Roche et al. (1980) (Fig. 10 B). Occurrence of normative corundum in the CIPW norms and high Shand's index (> 1.0) indicate that this granite is peraluminous (Fig. 10A). The chemical composition of the KKG show calc-alkaline affinity on the AFM diagram (Fig. 11A) and which is further confirmed in a K2O versus SiO2 variation diagram where KKG analyses plot within classical High-K calc-alkaline suite (Fig. 11B).

The majority of the analyses are plotted in the POG and CCG fields of Maniar & Piccoli (1989) (Fig. 10A) and in High-K calc-alkaline field (Fig. 11). These geochemical characteristics could be partly due to increased continental crust contamination and/or infracrustal melting generated by mafic magmatism at the basis of the crust which is emphasised by the occurrence of mafic microgranular enclaves (Marquer et al. 1998). The tectonic setting of these intrusions could be related to a post orogenic extension event responsible for basic magmas generated at depth by mantle melting and injection of acid melts contaminated by deep crustal sources in the upper part of the continental crust (Marquer et al. 1998).

The plot of the TiO2 versus CaO for the KKG analyses and the average values of various Higher Himalayan leucogranites show two distinctive geochemical population (Fig. 12, see also Fig. 10). From petrological observations exposed above and geochemical characteristics (see Tab. 1: e.g. lower Na_2O, MgO, TiO_2, Zr and higher CaO contents in KKG), along with the geochronological datations (see below, Kumar 1986, Chawla et al. submitted), it is clear that the KKG is different from the classical Higher Himalayan Leucogranites.

Tectonometamorphic evolution and implications:

From the previously described structural and petrographic data, the main high grade deformations (D2–D3) are interpreted as a progressive migmatitic doming leading to the occurrence of migmatites and anatectic leucogranite in the core of an antiformal D3 structure prior to the KK intrusion (Fig. 13). This migmatitic doming is responsible for a large scale SW vergent fold structure which was generated at metamorphic conditions corresponding to 550–750 °C and 0.7–0.8 GPa (Fig. 4). At a bulk scale, this progressive deformation and the associated high-grade metamorphism occurred from Karcham to the Khab area, where NE large vergent folds and an increase in metamorphic conditions are particularly well developed (Fig. 3). In this part of the cross-section a large granite intrusion (Leo Pargal leucogranite) is present, but not yet well dated.

The KK granite corresponds to a shallow seated intrusion, that implies an exhumation of the high-grade basement rocks in upper crustal level before the KK intrusion. The lack of broadly developed contact metamorphism and deformation fabrics at the border of the granite, the brittle style of intrusion and the occurrence of sharp angular xenoliths in the KK granite lead to an estimation of the depth of the emplacement in the upper crust around 10Km and at low temperature lesser than 300 °C for the country rocks (Fig. 4). The petrological characteristics of the KK granite reflects High-K calc-alkaline type magmatism, totally different from leucogranite compositions generated by only continental crust melting. The age of this intrusion is estimated around 488 Ma on the basis of Rb-Sr whole rock isochron (Kumar 1986) and new U-Pb analyses on zircons grains (488 ± 4 Ma, see Chawla et al. (submitted)). This age of the KK intrusion implies that the high grade tectonothermal evolution described the HHCS (D2–D3) is older than upper Ordovician time. A time delay of at least 20Ma is require to exhume the basement rocks at shallow depth level of the continental crust with respect to the observed PT path (Fig. 4) (England and Thompson, 1984). From these petrological and structural observations, the KK intrusion corresponds to a magmatic activity independent of the high-grade metamorphism and deformations developed in this part of the HHCS.

The D4 low grade deformation corresponding to wide angle ductile normal faulting is post KK granite intrusion and could be related to the effects of Alpine Tertiary deformation recorded in this area of study (Fig. 13). At a large scale cross-section (Fig. 2), this deformation which down throws the Eastern crustal block of HHCS, could lead to the preservation of Tethyan Himalaya sequence in the east of the KK granite area as it is reflected at the scale of Himalayan map (Fig. 1). From our recent field study and also from Vannay & Grasemann's work (1998), no major tectonic contact (thrust or normal faults) exists east of the KK granite between the HHCS domain and the lower Haimanta sediments classically attributed to the Tethyan Himalaya series. Furthermore, large-scale structures and associated metamorphism are continuous on a cross-section from Morang to Khab (Fig. 3). This leads to a new interpretation of the boundary between Tethyan Himalaya series and HHCS in the upper most part of the Sutlej valley (Fig. 1, 3). In this work, we propose to extend the HHCS domain up to the Leo Pargal intrusion (Khab granite) east of Khab village (Fig. 1). In this scheme the HHCS is covered by the Tethyan Himalaya series at the scale of a crustal cross-section of this part of the Himalayan belt (Fig. 2). The D4 normal fault system, defined as Karcham and Sangla detachments (KD and SD, Fig. 7) and also occurring in the Spiti valley, could represent local scale extensional structures related to the Miocene collapse and exhumation of the HHCS (Fig. 3) and could be partly coeval with the activity of the STDS (Burchfiel et al. 1992). In this part of the Himalayan belt, the main extensional structure corresponding to the STDS would be located north-east to the Tertiary Leo Pargal intrusion (a restricted military area which have never been investigated) or split into the different described brittle-ductile faults in a wide area. The clarity with which pre-Tertiary conditions are preserved in the Sutlej valley, could be due to the large distance of this part of the HHCS with respect to the main Tertiary penetrative deformation zones observed in other areas (e.g. Garhwal, Zanskar and Lahul) located closer to the MCT and STDS (Dèze et al., 1999, Guillot et al., 1999).

Conclusions

The KK granite is an Ordovician intrusion which compositionally ranges from granite to granodiorite. The geochemical characteristics of the KK granite are peraluminous and High K Calc-alkaline, emphasising composition differences with respect to the High Himalayan leucogranites. The KK granite cross-cuts the high grade metamorphic rocks of the HHCS, previously described as an example of inverted metamorphism. Therefore, the leucogranite (anatectic leucogneiss) centred in the migmatitic dome (D2–D3) is not associated with an Alpine tectono-metamorphic evolution in this area of study. This metamorphism-deformation study shows a progressive migmatitic doming under metamorphic conditions corresponding to a heated base of the continental crust (550–750 °C, 0.7–0.8 GPa) prior to upper Ordovician time.

The Alpine tectonics, resulting from the Tertiary lithospheric subduction of the Indian continental plate, seems to have relatively heterogeneous effects on the HHCS. The Tertiary deformation in this part of the Sutlej valley is weakly developed and only accommodated by the D4 deformation structures. At the scale of the HHCS, Tertiary deformation and mylonitisation seem localised in wide zones along the MCT and the STDS, as it was also described in adjacent areas (e.g., Zanskar and Lahul: Steck et al. 1998, Dèzes et al. 1999; Garwahl: Metcalfe 1993). Relicts of pre-Alpine structures and metamorphism are preserved in the core of the HHCS. The main tectonometamorphic imprints actually observable in the HHCS out-cropping in the Sutlej valley are related to a pre-Alpine tectonic evolution prior to the Lower Palaeozoic KK intrusion. This preservation of pre-Alpine conditions could be due to the distance of this deepest part of the HHCS occurring in the Sutlej valley with respect to the main Alpine deformation zones (MCT and STDS) observed in Garhwal, Zanskar and Lahul.

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