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Evidence for a pre-Himalayan metamorphism in the High Himalayan Crystalline of the Miyar Valley (NW India)

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Abstract

Most of the tectonic, metamorphic and geochronological data suggest that the Himalaya is essentially the consequence of a single orogenic cycle associated with the India-Asia collision during the Cenozoic era. Therefore, metamorphic assemblages and tectonic structures across the Himalayan range are systematically considered as post-collisional geological records. However, over the last decades, several observations arguing for geological events predating the continental collision have become increasingly recurrent in the literature. Nevertheless, although some of these arguments are thoroughly documented, they are unduly ignored in the construction of models drawing the tectono-metamorphic evolution of the Himalayan range. Yet, the occurrence of a pre-Himalayan history would have considerable consequences on the classical models for the building of the Himalaya. The recent discovery of inclusions of staurolite crystals in greenschist facies garnets from the Miyar Valley in Upper Lahul region (Himachal Pradesh; NW India) revives the debate on the existence of a pre-Himalayan metamorphism. Indeed, the occurrence of high-temperature staurolites included in greenschist facies garnets suggests that the High Himalayan Crystalline rocks experienced an amphibolite facies metamorphism prior the predominant Himalayan greenschist facies metamorphism observed in this part of the range. In this study, phase petrology, microtectonic investigations combined with preexisting geochronological data infer that the crystallization of the included staurolite predates the growth of Himalayan garnets. These original data bring new arguments to bear on the long lasting debate of the existence of a Pre-Himalayan orogenic cycle. They lead to the conclusion that the growth of staurolite predates the continental collision between India and Asia and reflects a metamorphic event that belongs to a pre-Himalaya orogenic cycle.

Keywords Pre-Himalayan metamorphism, High Himalayan Crystalline, Thermodynamic modelling

1 Introduction

The Himalaya is a young and still active mountain range. As such, it is considered as one of the best examples to study the evolution of an orogenic system associated with continent–continent collision and notably to study the interactions between metamorphism and tectonics

during orogenic processes. Therefore, the overwhelming majority of investigations led across the Himalayan range have been focused on the Himalayan tectono-metamorphic evolution since the Indian-Asian collision ca. 55 my ago (Patriat and Achache, 1984; Garzanti et al., 1987; Rowley, 1996). The large majority of these studies concludes that the HHC rocks were transformed into greenschist and amphibolite facies rocks (including local migmatization) during the Cenozoic metamorphic events and associated deformation phases (Figs. 1 and 2).

Nevertheless, over the last thirty years, sporadic arguments documenting a pre-Himalayan history have been reported, suggesting that the sediments deposited on the

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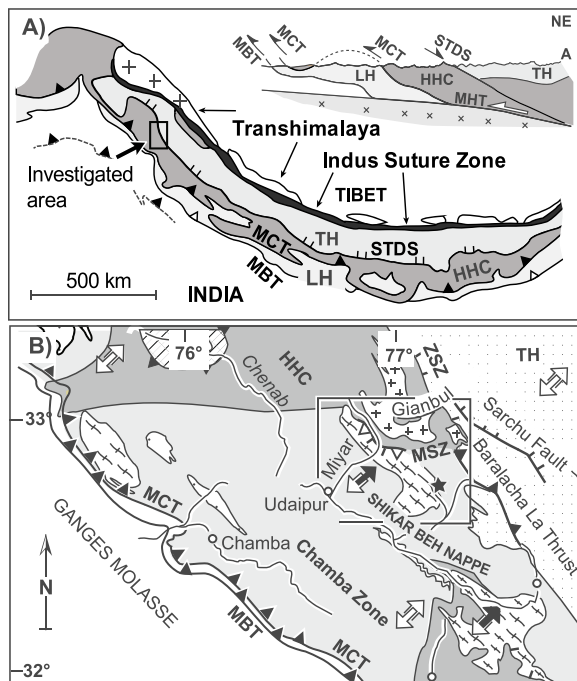


Fig. 1 **A** Generalized geological map of the Himalaya showing the main tectonic units and a synthetic cross section of the central Himalaya (modified after Vannay and Grasemann, 2001). HHC High Himalayan Crystalline, TH Tethyan Himalaya, LH Lesser Himalaya, MBT Main Boundary Thrust, MCT Main Central Thrust, MHT Main Himalayan Thrust, STDS South Tibetan Detachment System. **B** Geological map of the NW Indian Himalaya (after Steck et al., 1999) showing the location of the studied section along the Miyar Valley. The black star at the bottom right corner of the region of interest refers to the location of the illustration presented on the Fig. 3. MSZ Miyar Shear Zone

northern Indian margin were not necessarily preserved from metamorphism prior to the Cenozoic Himalayan orogenic cycle (Pognante and Lombardo, 1989; Argles et al., 1999; Marquer et al., 2000; Gehrels et al., 2003; Johnson, 2003; Thakur and Patel, 2012; Thakur, 2014). Most of the arguments for a polycyclic history of the rocks forming now the Himalayan range are based on the crosscutting relationships between non-deformed Ordovician granites and strongly deformed Precambrian sediments suggesting that the deformation occurred before the granite emplacement (Fig. 3). In the High Himalayan Crystalline (HHC) rocks of Garhwal, Marquer et al. (2000) and Thakur and Patel (2012) described deformed xenoliths of metapelites that are cross-cut by the Ordovician Kinnaur Kailash granite (477 Ma, U/Pb on zircon; Tripathi et al., 2012) leading to the conclusion that a pre-Himalayan metamorphism affected the sediments surrounding the Kinnaur Kailash granite. The same sorts of observation has been made in a more central part of the range by Johnson (2003). Farther to the east, in the

Himalaya of central Nepal, Gehrels et al. (2003) interprets the cross-cutting relations between garnet-bearing schists and lower Ordovician non-deformed dykes as an evidence of early Paleozoic tectonism. In addition, in the Upper Lahul region, relics of granulitic assemblages and textures in mafic bodies reveals that a high temperature metamorphic event predates the Cenozoic greenschist to amphibolite facies metamorphism that affected the sediments of the Himalaya of NW India (Pognante and Lombardo, 1989; Wyss, 1999; Thakur, 2014). Besides, Argles et al. (1999) reported Cambrian garnets (534 ± 24 Ma; Sm/Nd ages) in the Garhwal Himalaya suggesting that these rocks experienced a pre-Himalayan metamorphism during Lower Cambrian. Farther to the NW, in the Lesser Himalayan rocks of the Chaur area, garnets post-dating the regional foliation yield ages of 485 ± 19 Ma. indicating a regional metamorphic event during the Lower Ordovician period (Bhargava et al., 2016). Furthermore, zircons collected in migmatites from the HHC rocks of Eastern Garhwal show a period of growth at 465 ± 6.4 (Mohan et al., 2022). According to these authors, this age clearly states for the existence of a pre-Himalayan metamorphism in the HHC rocks. In the Pakistan Himalaya, Palin et al. (2018) associate kyanite to sillimanite-grade metamorphism with Pre-Himalayan deformation resulting from an Ordovician orogeny. The examples aforementioned constitute a non-exhaustive list of the numerous examples strongly suggesting a widespread thermal event throughout the Himalaya during the pre-Himalayan Cambro-Ordovician period. However, and despite the rather compelling arguments for a pre-Cenozoic Himalayan history reported in the aforementioned studies, the pieces of evidence are too often thought as isolated, local anomalies. Hence, the testimonies of a pre-Himalayan history are systematically overlooked and the tectonic structures and metamorphic assemblages are, de facto, interpreted as belonging to the Cenozoic post-collision Himalayan history. However the existence of a pre-Himalayan metamorphism would have considerable consequences on the classical models for the building of the Himalayan range, since it would be then necessary to significantly reinterpret the thermal history of the Himalayan range by withdrawing data from the Himalayan orogenic cycle to transpose them into the pre-Himalayan cycle.

A recent field campaign led in the Upper Lahul and SE Zaskar allowed gathering a whole series of observations leading to the conclusion that the HCC rocks of this region may have experienced a pre-Himalayan history. Among these observations, the two most eloquent are: 1) crosscutting relationships between strongly deformed Precambrian sedimentary enclaves preserved in locally non-deformed Kade Ordovician granites along

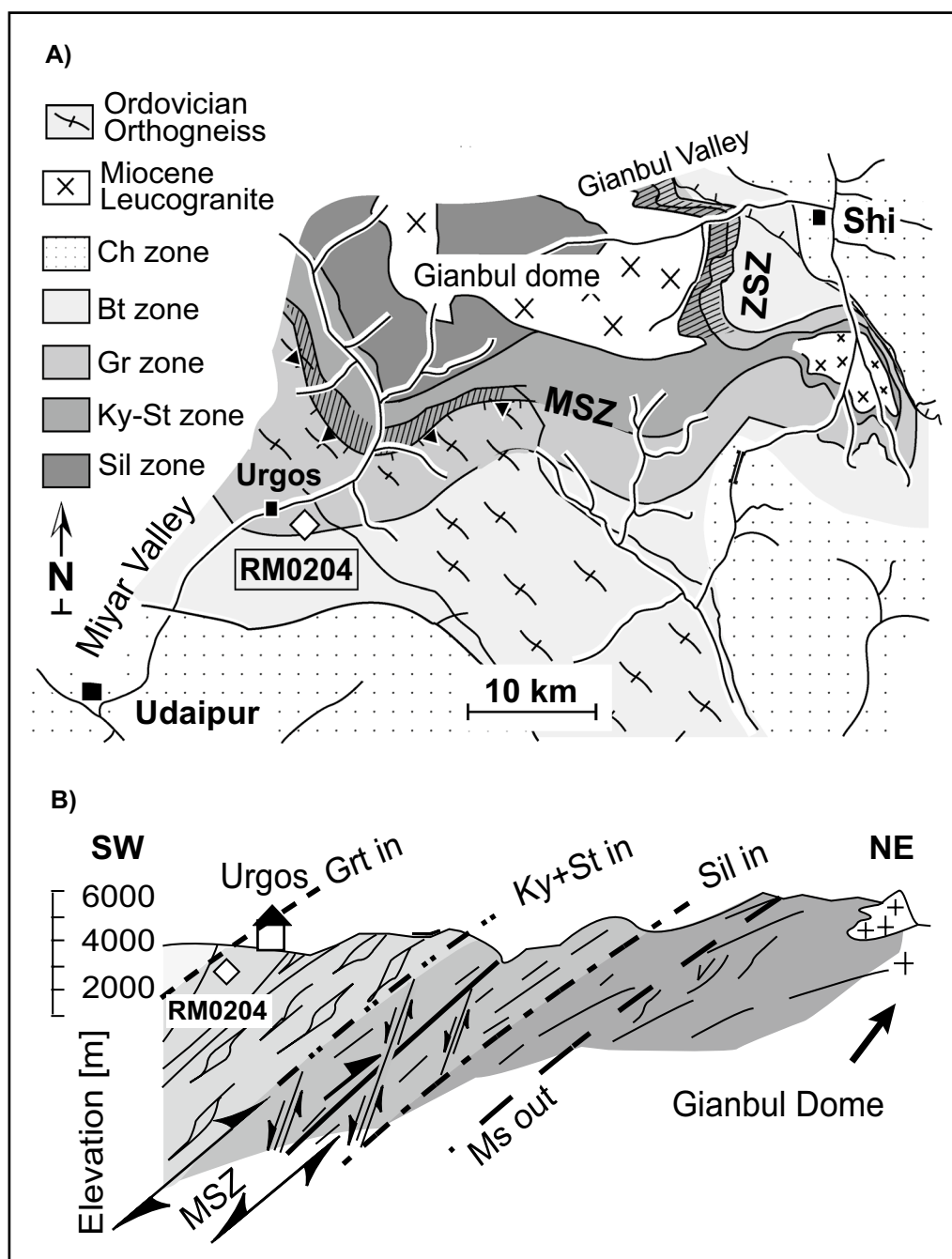


Fig. 2 **A** Metamorphic map of the Miyar Valley- Gianbul Valley that crosscut the Gianbul dome. The white diamond near the village of Urgos represents the location of the studied sample. **B** Schematic cross-section along the Miyar Valley showing the gradual increase of the metamorphic condition northward

the Shingo La section in SE Zaskar (Figs. 1 and 3); and (2) the discovery of staurolite crystals included in greenschist facies garnets from the Miyar Valley in Upper Lahul region (Himachal Pradesh; NW India). This latter observation is probably one of the strongest arguments observed so far in the Himalayas arguing for an

ante-Himalayan metamorphism. Indeed, the occurrence of fairly high-temperature staurolites enclaved in greenschist facies garnet strongly suggest that these HHC rocks experienced an amphibolite facies metamorphism prior to the formation of the Himalayan greenschist assemblages.



Fig. 3 Strongly deformed Precambrian to Cambrian metasediments crosscut by the locally undeformed Ordovician Kade orthogneiss. See Fig. 1 for sample location

This study focuses in detail on the latter case by combining phase petrology, microtectonic investigations together with preexisting geochronological data. These original data infer that the crystallization of the included staurolite predates the growth of Himalayan garnet, bringing new evidence to bear on the long lasting debate of the existence of a Pre-Himalayan orogenic cycle.

2 Tectonic and metamorphic setting of the Miyar Valley section

The Miyar Valley in the Upper Lahul region (NW India) (Figs. 1 and 2) offers an ideal natural cross-section through the structures and metamorphic zonations of the HHC of Zaskar. The HHC corresponds to the metamorphic core zone of the Himalayan orogeny. It consists of a 5–40 km thick sequence of Precambrian and lower Cambrian detrital sediments, including graywackes, siltstones, and pelites, now transformed into greenschist facies to amphibolite and migmatitic paragneiss. In the central part of the valley, the stratigraphic sequence is interrupted by the intrusion of the Kade granite at ca. 470 Ma (Pognante et al., 1990).

A typical Barrovian metamorphic field gradient is preserved in the metapelites of the Miyar Valley. Going up the valley from Udaipur northward, the successive crystallization of chlorite, biotite, garnet, kyanite \pm staurolite

and sillimanite mineral in the HHC rocks reflects a continuous and regular increase of the metamorphic conditions toward the north (Robyr et al., 2002; Robyr et al., 2006) (Fig. 2).

The kinematic evolution of the HHC along the Miyar Valley is controlled by an Early Eocene NE-directed crustal thickening phase that leads to the development of a ca. 3 km thick major shear zone called the Miyar Shear Zone (MSZ) (Steck et al., 1999; Robyr et al., 2002; Robyr et al., 2014; Robyr and Lanari, 2020). Microstructural analyses combined with geochronological data indicate that the onset of the movements along the MSZ and the associated metamorphic imprint started during early Eocene (Robyr and Lanari, 2020), slightly after the continental collision at ca. 55 Ma. Across the MSZ, the NE-directed contractional structures are superimposed by SW-dipping extensional structures indicating that the MSZ initially acted as a thrust zone before to be reactivated as a ductile zone of extension during Early Miocene (Robyr et al., 2006; Robyr et al., 2014) (Fig. 4).

Three main phases of deformation have been identified (Steck et al., 1999) in the hanging wall of the MSZ, in the downstream part of the valley, where the metamorphism does not exceed the greenschist facies. According to Steck et al. (1999), the two earliest phases of deformation D1 and D2 are associated with NE-directed thrusting. They are responsible for the development of the schistosities S1 and S2. F1 folds are rare in contrast to F2 folds, which correspond to large-scale folds observed along the Miyar valley. In the greenschist facies, in the hanging wall of the MSZ, the main structures associated with the phases of deformation D1 and D2 are superimposed by a D3 phase of deformation mainly marked by the development of sub-horizontal crenulation cleavage (Fig. 4). Within the footwall of the MSZ, a fourth phase of deformation is very well marked. It corresponds to a schistosity S4 resulting from extensional movements associated with the exhumation of the Gianbul dome in the upstream part of the Miyar Valley (Robyr et al., 2006) (Fig. 2). In a detailed and systematic study of the relations between porphyroblast crystallisation and phases of deformation in the metapelites of the Miyar Valley, Robyr and Lanari (2020) identified the relative timing of the metamorphic minerals growth with respect to the four phases of deformation that affected the rocks of the HHC

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Fig. 4 Field photograph of the Himalayan tectonic structures observed in the Miyar Valley. **A** Mylonitic sandstone with σ -type porphyroclasts of quartz showing a top-to-the NE shear sense in the footwall of the Miyar Shear Zone. **B** Top-to-the SW σ -type porphyroclasts in the footwall of the Miyar Shear Zone illustrating that the Miyar Shear Zone initially acted as a thrust zone before to be reactivated as an extensional shear zone. **C** S1 and S2 interference pattern in the greenschist facies rocks of the downstream part of the Miyar Valley (hanging wall of the Miyar Shear Zone) (modified after Steck et al., 1999). **D** F1–F2 fold and S1–S2 interference pattern in the hanging wall of the Miyar Shear Zone (modified after Steck et al., 1999). **E** Discrete S3 crenulation cleavage and associated F3 fold overprinting the main S1 + S2 foliations

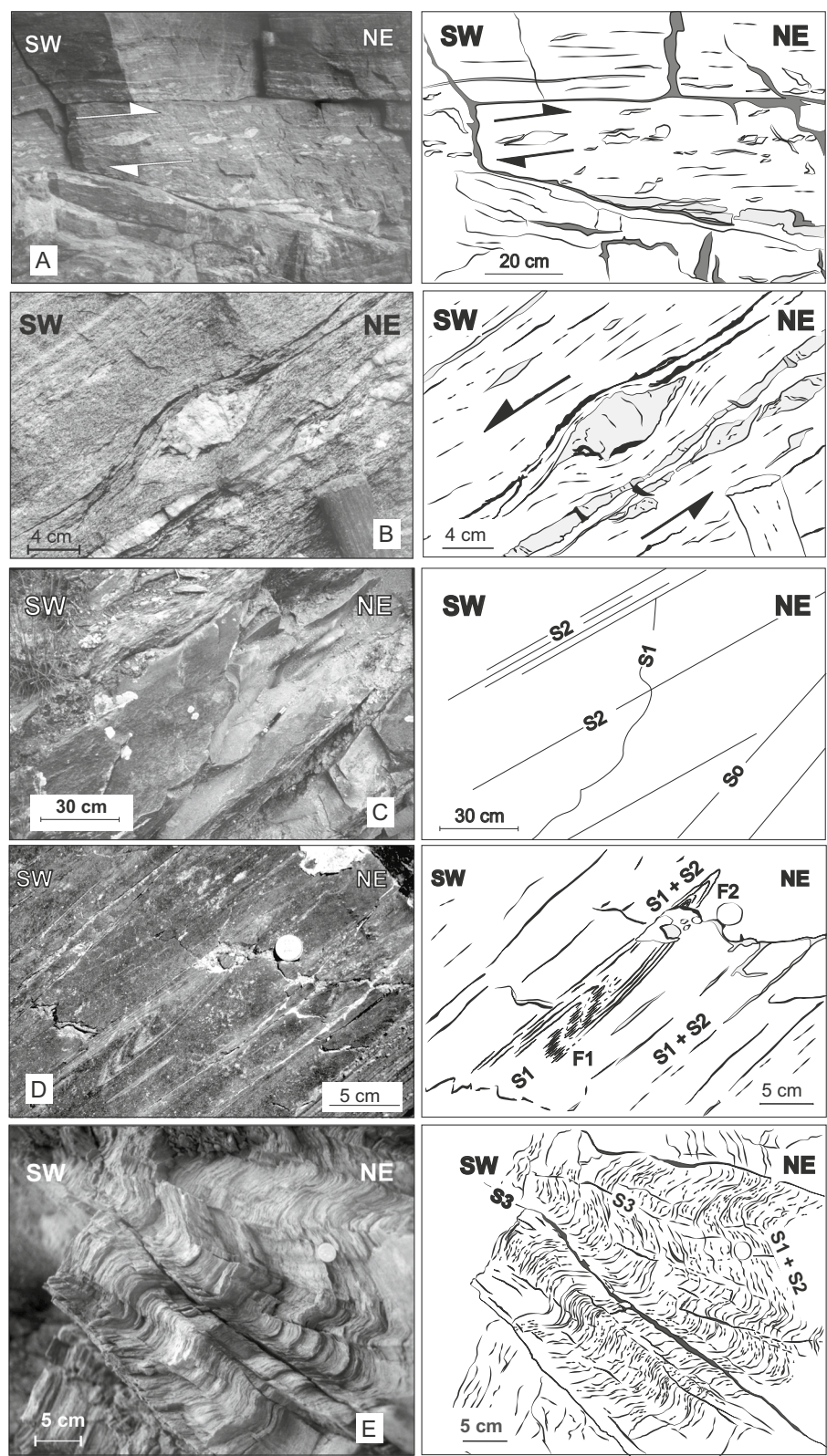


Fig. 4 (See legend on previous page.)

of this region (Fig. 5). In the greenschist facies zone, the growth of garnet occurred contemporaneously with the development of the first schistosity S1 during the earliest phase of deformation D1. The concomitance between the growth of garnet and the phase of deformation D1 is attested by the presence of sigmoidal inclusion trails in the core of the garnet indicating a simultaneous growth and rotation of the crystal during its crystallisation (e.g. Robyr et al., 2009). At the entrance of the staurolite zone, ca. 10 km farther north, Robyr and Lanari (2020) demonstrated that the crystallization of the first staurolite crystal occurred during an intertectonic period between the phases of deformation D3 and D4. In addition, a thorough study on the chemical and physical conditions for the crystallization of allanite and monazite along the Miyar Valley section revealed that the growth of the first monazite takes place at the expense of allanite during the crystallization of staurolite (Goswami-Banerjee and Robyr, 2015). Monazite geochronology on samples from the staurolite zone yields ages ranging between 40.1 Ma and 42.8 Ma (Robyr and Lanari, 2020). As monazite and staurolite are contemporaneous, these ages reflect the crystallization of staurolite as well, and consequently the timing of the intertectonic period between the phases of deformation D3 and D4. Yet, the crystallization of garnet in the metapelites of the Miyar Valley is systematically associated with the phase of deformation D1, regardless the metamorphic zone. Based on the geochronological data and microstructural analysis, Robyr and Lanari (2020) come to the conclusion that the D1 phase of deformation largely predates the growth of staurolite and likely occurred shortly after the India-Asia continental collision at ca. 55 Ma (Patriat and Achache, 1984; Garzanti et al., 1987; Rowley, 1996). Whatever the precise timing of this event, the phase of deformation D1 and the associated garnet crystallization constitute the first tectono-metamorphic episode identified so far in the history of the Himalayan orogenic cycle. Therefore, the recent discovery of inclusion of staurolite in D1 garnet from greenschist facies zone questions the real primacy of the D1 event in the tectono-metamorphic history of the HHC of NW India. Indeed, according to many studies devoted to the microstructural investigation of inclusions in porphyroblasts, these are mostly passively incorporated

into the porphyroblast during its growth (e.g. Passchier and Trouw, 2005 and references therein). This statement leads to the hypothesis that the staurolite included in garnet predates the crystallization of the D1 garnet.

In order to rigorously establish the relative timing of the crystallization of the garnet with respect to the staurolite inclusion, the garnet bearing sample containing staurolite inclusion has been thoroughly explored through textural and chemical investigation combined with thermodynamic modelling. This survey aims notably to evaluate the hypothesis of a contemporaneous growth of the garnet and staurolite during the D1 phase of deformation.

3 Sample characterization

3.1 Petrography and texture

Moving upsection from Udaipur northward, the first garnet appears near the village of Urgos in decimetric mafic horizons, intercalated within the pelitic layers. These mafic levels contain the mineral assemblage of garnet + hornblende + plagioclase + biotite + titanite and epidote. Thermobarometry performed on these mafic samples indicates peak conditions of ca. 510 °C/6 kbar for the garnet zone (Robyr et al., 2002). A few hundred meters further upstream, the first pelitic garnet bearing sample crops out just across from the village of Urgos (sample RM-02-04; N 32°51.158' / E 076°48,387'; Fig. 2). This sample contains the mineral assemblage of garnet + quartz + plagioclase + biotite + muscovite ± chlorite with minor ilmenite and apatite. More importantly, allanite is the stable REE accessory phase in this rock, both as inclusion in the garnet porphyroblast and as stable mineral in the matrix assemblage (Fig. 6). Even more interesting, these garnets are particularly remarkable since, besides allanite and other minerals, they contain inclusions of tiny staurolite crystals whereas staurolite is completely missing from the matrix assemblage (Fig. 7). A detail account of the textures and microstructures of this sample is given in Robyr and Lanari (2020). The preferred orientation of biotite and muscovite crystal marked the main foliation S2. An earlier foliation defined as S1 is preserved as inclusion trail in garnet porphyroblast, revealing that the garnets crystallized during a deformational phase accompanied with NE-directed movements.

(See figure on next page.)

Fig. 5 **A** D1 syntectonic garnet from the sample RM-02-04 in the greenschist facies zone of the Miyar Valley. **B, C** Staurolite—garnet bearing sample collected in the staurolite zone. The geometry of the internal foliation S2 preserved in the staurolite porphyroblast indicate a static growth of the staurolite on the S2 foliation after the phase of deformation D3. **D** Relative chronology between the deformation phases and related structures and crystallization of the index metamorphic minerals for samples from the greenschist (left) and staurolite zone (right). Terra-Wasserburg diagram for U-Pb analyses of monazite for the staurolite bearing sample constraining the growth of staurolite at ca. 41 Ma (illustration modified from Robyr and Lanari, 2020)

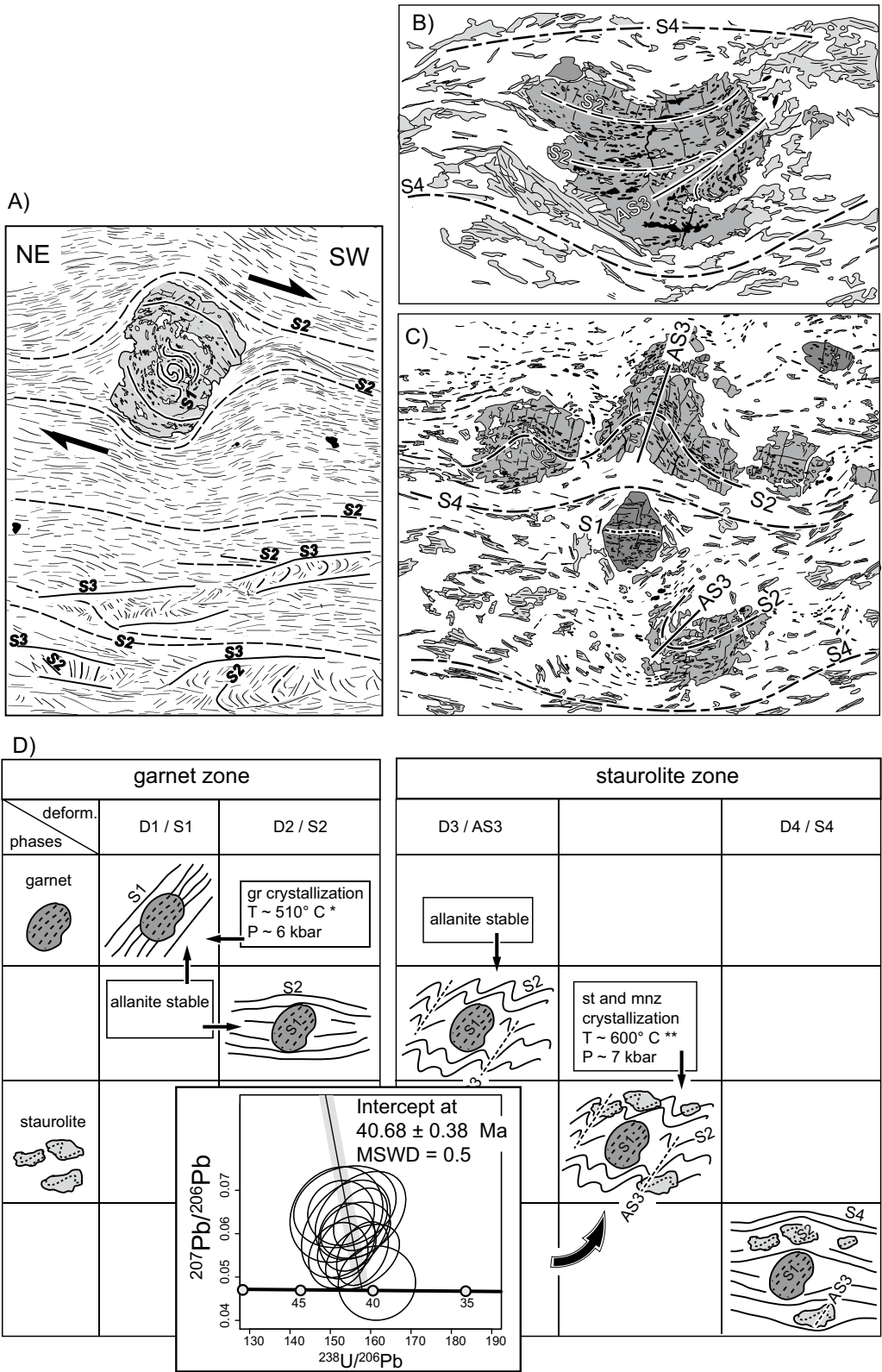


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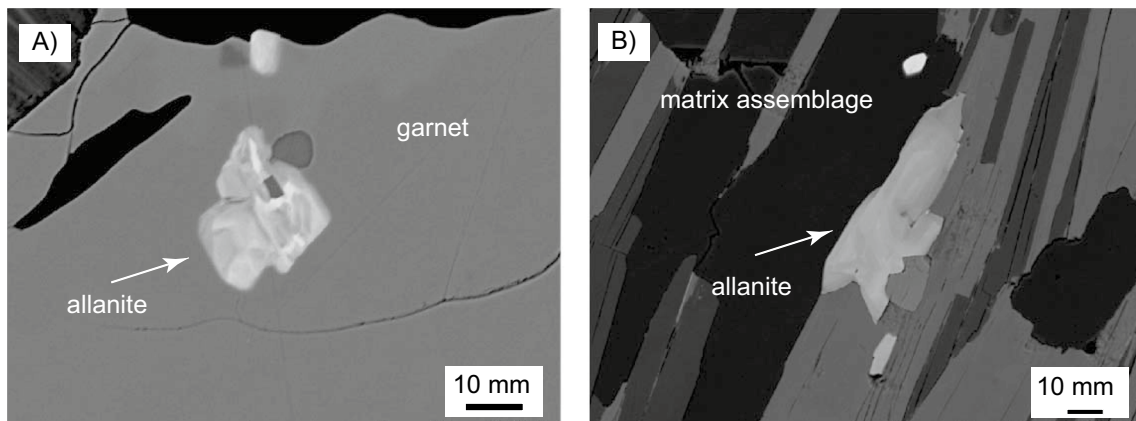


Fig. 6 BSE image of allanite grains as inclusion in garnet (**A**) and as grain in the matrix assemblage

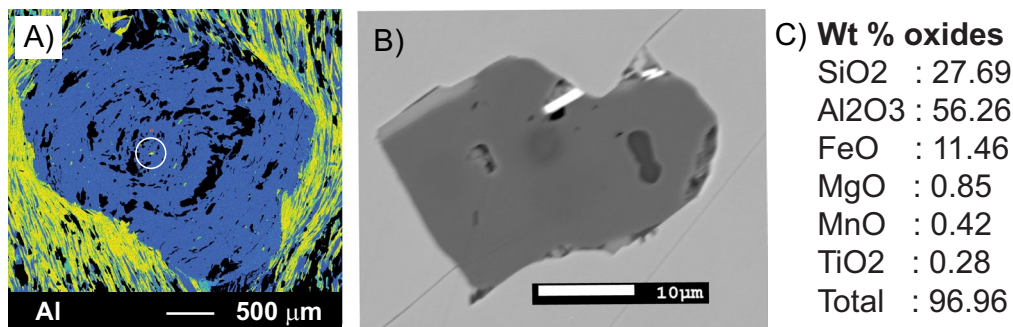


Fig. 7 **A** Al X-ray elemental map for garnet in sample RM-02-04 showing the location of the staurolite inclusion. **B** BSE image of the staurolite grain included in garnet, with its chemical composition. **C** Chemical composition of the included staurolite obtained through electron probe microanalyses

This NE-directed shearing phase developed during the emplacement of a nappe referred to as the Shikar Beh nappe (Steck et al., 1993; Robyr et al., 2002). The vergence of the tectonic structures linked to this event is in marked contrast to the SW-directed deformation that predominates in the Himalaya since the continental collision between India and Asia. This NE-directed crustal thickening phase is collectively interpreted as the first Himalayan tectonic event recorded in the Precambrian to Cambrian sediments of the HHC in Upper Lahul and SE Zaskar regions (Steck et al., 1993; Vannay and Steck, 1995; Robyr and Lanari, 2020).

3.2 Garnet chemistry

X-ray compositional maps on garnet from the greenschist facies, obtained with a JEOL JXA-8350F microprobe at the University of Lausanne, reveal a broadly concentric zonation in the major divalent cations Ca, Mn, Fe and Mg (Fig. 8). The chemistry of the garnet is characterized by a gradual decrease in Mn and Mg toward the rim of the grain, counterbalanced by a simultaneous increase in Ca.

The zonation of Fe shows a more complex pattern with an initial decrease of Fe content in the central part the grain followed by a sudden rise toward the rim of the garnet crystal. Quantitative profiles indicate that the compositional range of garnet evolves from 64 to 68% for the almandin component, from 12 to 16% for the spessartine content, from 8 to 10% for pyrope, and from 8 to 14% for the grossular content (Fig. 8).

3.3 Thermodynamic modelling

In order to establish the pressure and temperature stability field for staurolite and garnet in the garnet bearing rocks of the garnet zone, an equilibrium phase diagram and isopleth diagram were calculated using the bulk composition of the rock (Fig. 8). The bulk composition of sample RM-02-04 was obtained by XRF analysis at the University of Lausanne (Fig. 8). Thermodynamic modelling was performed with the 2009 version of Theriak-Domino software (de Capitani and Petrakakis, 2010) using the Berman database (Berman, 1988, 1990). The calculations were done using the following solution

model: Berman (1990) for garnet, Fuhrman and Lindsley (1988) for feldspar, Keller et al. (2005) for white mica and Berman (1988) for biotite. Ideal mixing models were used for chlorite and epidote. Diagrams were computed for saturation with a pure H₂O fluid.

The stability field for the compositional range of garnet of sample RM-02-04 as measured with the microprobe (i.e. Alm_{64–68}, Spess_{12–16}, Pyr_{10–8}, Gross_{8–14}) is very well constrained to temperature ranging between 500 °C and 550 °C (Fig. 8). In contrast, as the isopleths for the major divalent cations Fe, Mg, Ca, and Mn in garnet are essentially temperature controlled, the pressure range is much more difficult to constrain. As an alternative, the computation of the albite molar proportion in plagioclase allows constraining the pressure between 5.5 kbar and 6.5 kbar. (Fig. 8). Thermodynamic modelling identifies the pressure–temperature (P–T) stability field for garnet in sample RM-02-04 in a range of pressure and temperature that is in good agreement with the P–T estimates for garnet from the mafic horizons (510 °C/6 kbar; Robyr et al. (2002)) exposed few hundred of meter downstream. Also, the P–T data for garnet RM-02-04 fit the metamorphic field gradient for the Miyar Valley inferred from P–T estimates for samples collected in the garnet, staurolite and kyanite and sillimanite zone after Robyr et al. (2002) (Fig. 9). According to the equilibrium phase diagram, the stability field of staurolite for the chemistry of the sample RM-02-04 ranges between 550 °C and 650 °C for a pressure comprised between 4 kbar and 5.5 kbar (Figs. 7 and 8). This data reveal that the stability field of staurolite matches neither the P–T conditions prevailing for the crystallisation of garnet in this sample nor the metamorphic field gradient for the Miyar Valley (Fig. 9). In other words, this means that, in the sample RM-02-04, staurolite and garnet grew during two distinct metamorphic events.

4 Monazite, witness to the crystallization of staurolite

Along the pelitic sequence of the Miyar valley section, Goswami-Banerjee and Robyr (2015) identified that allanite was the stable REE accessory phase over

the biotite and garnet metamorphic zones but was systematically replaced by monazite beyond the staurolite zone. Yet, allanite coexists with monazite as inclusion in staurolite, but only monazite is preserved in the matrix assemblage. The coexistence of both allanite and monazite as inclusion in staurolite indicates that both REE accessory phases are stable at the onset of staurolite crystallization. The absence of allanite in the matrix leads to the conclusion that the allanite-monzonite substitution in the metapelitic sequence takes place during the crystallization of staurolite. This observation reveal that monazite may serve as a proxy for temperature in the metapelites since its occurrence require that the rocks has reached *ca.* 600° C, the temperature conditions prevailing for staurolite crystallization (Goswami-Banerjee and Robyr, 2015). In the studied sample RM-02-04, allanite is present as inclusion in the core and the rim of the garnet crystal but also in the matrix assemblage whereas monazite is completely absent form this assemblage (Fig. 6). Therefore, the lack of monazite in this sample testifies that this rock never reached the conditions for staurolite crystallization during, but also after the growth of garnet.

5 Discussion of the data

The structural and textural analysis clearly indicate that the growth of the garnet in the studied sample is associated with the earliest Himalayan phase of deformation (D1) and metamorphism identified so far in the rocks of the HHC in Upper Lahul and SE Zaskar region (Robyr and Lanari, 2020) (Fig. 5). The structural and textural analysis also demonstrate that, along the Miyar Valley section, the growth of the first staurolite that marks the entrance into the staurolite metamorphic zone took place at *ca.* 41 Ma. This age reflects the timing of an intertectonic period between the phases of deformation D3 and D4 (Robyr and Lanari, 2020). Therefore, the development of the D1 structures and the growth of the associated metamorphic minerals must have occurred significantly earlier, likely slightly after the continental collision at *ca.* 55 Ma (Robyr and Lanari, 2020).

Based on these evidences, the occurrence of staurolite inclusion in the earliest Himalayan garnets may only

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Fig. 8 On the left: Garnet end-member isopleths expressed as mole fraction of Mn, Mg, Ca and Fe respectively and calculated with the whole rock composition of the sample RM-02-04. The whole rock composition of the sample RM-02-04 is shown on the top of the figure. The dark grey P–T domains correspond to the garnet stability field with respect to the mole fraction measured in the studied garnet. The bottom diagram represents the plagioclase isopleth expressed as mole fraction of albite. The stability field for staurolite as calculated with the whole rock composition of the sample RM-02-04 is illustrated on the diagram for the albite isopleths (bottom left). The rectangle with dashed line corresponds to the P–T stability field for the chemistry of the garnet in sample RM 02-04. The compositional profile for the major divalent cation are shown in the central column. On the right side: X-ray elemental maps of the hosting garnet. The white line crossing the spessartine elemental map corresponds to the location of the compositional profile for Mn, Mg, Ca and Fe (central column). The location of the compositional profile for Na in plagioclase is illustrated in the albite X-ray map. Mineral abbreviations after Kretz (1983)

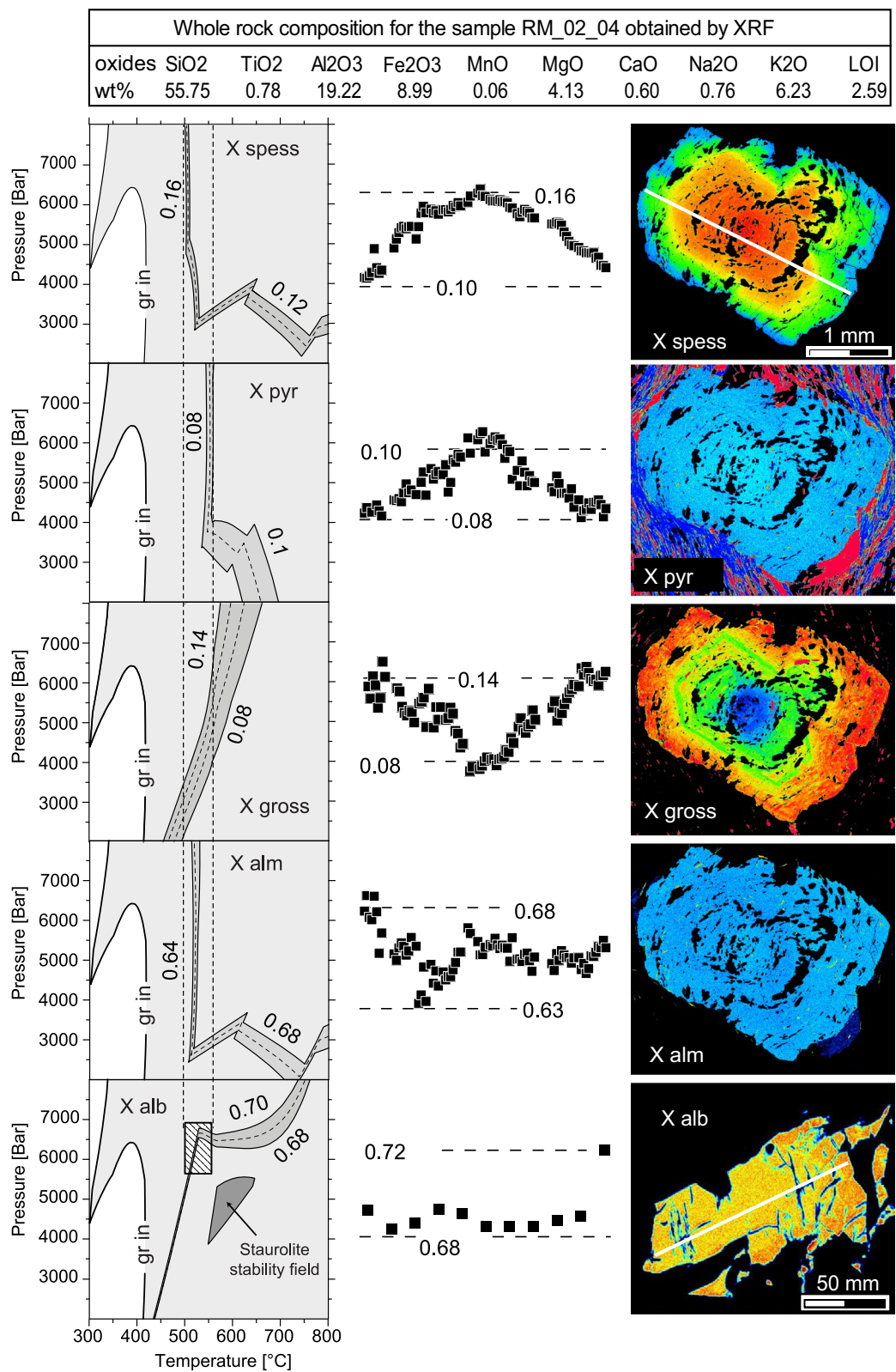


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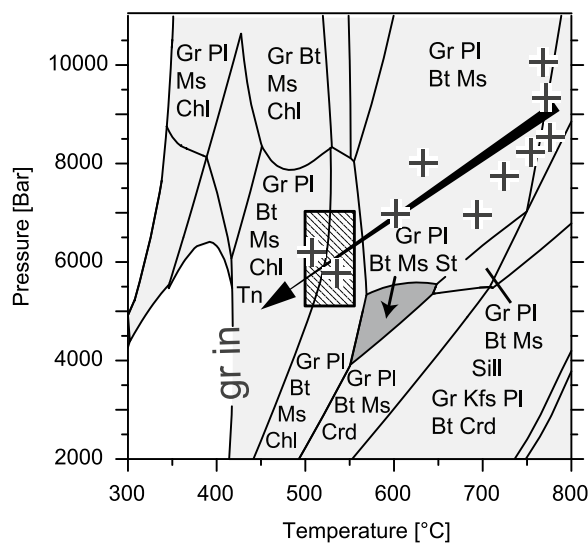


Fig. 9 Equilibrium phase diagram based on the bulk chemistry of sample RM-02-04. The dashed and dark grey domains correspond to the stability field of garnet and staurolite respectively for the bulk chemistry of the sample RM-02-04. The crosses correspond to P–T estimates for samples from the garnet, staurolite and kyanite and sillimanite zone of the Miyar Valley after Robyr et al. (2002). The black arrow corresponds to the metamorphic field gradient assuming a lithostatic gradient of 2.7 kbar/km (Steck, 2003). Mineral abbreviations after Kretz (1983)

reflect two alternatives; either the staurolite inclusion is older than the surrounding garnet or it is contemporaneous. Following the first scenario, the anteriority of the growth of the staurolite with respect to the earliest Himalayan garnet would not only mean that staurolite is older than garnet but also that staurolite crystallized during an ante-Himalayan metamorphic event. The simultaneous growth of staurolite and garnet during the first phase of deformation D1, such as predicted by the second scenario, would imply that the metamorphic conditions were favorable for the coeval crystallization of both mineral, garnet and staurolite.

Thermobarometric modelling and textural relation between the syntectonic garnet D1 and the included staurolite clearly lead to the conclusion that the P–T stability field for the growth of staurolite does not match the P–T stability field prevailing for the crystallization of garnet. In addition, were staurolite and garnet to grow simultaneously, then the presence of staurolite crystal would be expected as part of the matrix assemblage such as observed in the staurolite metamorphic zone farther to the north. The lack of staurolite in the matrix consequently implies that staurolite is not stable any more once the garnet crystallized. This strongly suggests that the included staurolite is the relic of a previous metamorphic event preserved in garnet.

Considering the data and argument aforementioned, the growth of staurolite and garnet cannot be coeval, ruling out de facto the second scenario. Therefore, the hypothesis of a crystallization of staurolite predating the growth of the garnet, such as predicted by the first scenario, is the one that matches at best the textural observation and the thermodynamic modelling. This scenario is in line with the classical view for the preservation of inclusions in porphyroblast namely that the inclusion are mainly included passively into the growing porphyroblast (e.g. Passchier and Trouw, 2005).

Added to this arguments are the observation that monazite is not present in this rocks attesting that the conditions for staurolite crystallization were not reached during and after the crystallization of the garnet porphyroblast (Goswami-Banerjee and Robyr, 2015). In conclusion, structural and metamorphic observations, thermodynamic modelling but also field data show unequivocally that the crystallization of staurolite predates the crystallization of garnet. As garnet crystallization is associated with the first, i.e. the oldest, D1 Himalayan tectonic event, staurolite crystallization must be associated with an event that is part of a pre-Himalayan history.

6 Tectonic and metamorphic implications

The vast majority of geological data collected in the Himalayan range seems to indicate that the rocks forming now the HHC experienced a single orogenic cycle associated with the continental collision between India and Asia from Early Eocene, ca. 55 My ago. The data presented in this study demonstrate that it is not necessarily the case. The occurrence of staurolite included in greenschist facies garnet strongly suggests that these rocks experienced, at a certain time of their history, a higher-grade metamorphism in the amphibolite facies that predates the continental collision.

The original data presented in this study adds to a growing body of evidence testifying to the occurrence of a metamorphic event prior to the Cenozoic Himalayan Orogeny. Indeed, testimonies of a pre-Himalayan metamorphism are documented all along the Himalayan range with however a clear majority of elements coming from the northwestern part of the Himalaya, from the Pakistan Himalaya to the Garwahl Himalaya (e.g. Argles et al., 1999; Thakur and Patel, 2012; Bhargava et al., 2016; Palin et al., 2018; Mohan et al., 2022). The distribution of these testimonies over a large region of the Himalayan range clearly indicates that the thermal event responsible for this metamorphism was not a minor local epiphenomenon, but on the contrary that this event was a large-scale impacting tectono-metamorphic episode. This raises the question on the nature of the tectonic event responsible for this pre-Himalayan metamorphism.

Two main pre-Himalayan tectonic events have been identified to date. The first event relies to the emplacement of the Ordovician granites that dot the HHC along strike. The second event corresponds to a pre-Ordovician tectonic phase that is recorded in the numerous Precambrian to Cambrian sedimentary enclaves preserving a well-developed schistosity within locally non-deformed Ordovician granites (e.g. Gehrels et al., 2003 and personal observation Fig. 3).

Ordovician granites are repeatedly exposed over the entire Himalayan range and are part of a vast magmatic belt spreading all along southern Asia (Le Fort et al., 1986). The production of such a large amount of magma has to be linked with continental-scale tectonism. The characteristics and the timing of the emplacement of the Ordovician Himalayan granites lead to the interpretation that the Himalayan granites could be related to a post-orogenic extensional episode following the Pan-African orogeny that affected a large part of the Gondwanian terrains (Garzanti et al., 1986; Girard and Bussy, 1999; Miller et al., 2001). However, according to the classical paleo-reconstruction, only the southern part of the Indian plate was involved into the Pan-African events (Stern, 1994). Alternatively, and as no information are available on the nature of the crust situated on the northern part of India before the opening of the Paleo and Neotethyan oceans, a connection of the Ordovician magma emplacement and a zone of subduction cannot be definitively ruled out. This leads to the idea that the accretion of an oceanic arc complex to the north of the Indian margin during the Cambrian era could be responsible for a pre-Himalayan orogeny referred to as the Kurgikh orogeny. This early Paleozoic orogen is recurrently designated as a potential source of the detrital sediments forming now the rocks of the HHC (e.g. Myrow et al., 2016 and references therein; Spencer et al., 2019). Based on biostratigraphy, the deformation within the Kurgikh orogeny occurred between 495 and 460 Ma (Gehrels et al., 2006; Myrow et al., 2016). According to Wyss (1999) a mechanism of magma emplacement involving magmatic underplating associated with a large zone of extension in the northern margin of the Indian plate could be the cause of the Ordovician granite production. In this scenario, the production of the Ordovician granite at 470 Ma (Pognante et al., 1990) could result from the post-collisional extensional episode following the Kurgikh orogeny. Although it is poorly constrained, a Late Precambrian event associated with the Kurgikh orogeny is recurrently suggested to explain the origin of the pre-Himalayan relics preserved in the HHC rocks (Gehrels et al., 2003; Myrow et al., 2016; Spencer et al., 2019). This event appears thus as one of the best candidates that may have triggered the crystallization of pre-Himalayan metamorphic minerals.

Alternatively, it cannot be ruled out that the staurolite crystallization is linked to a contact metamorphism associated with the emplacement of the Ordovician granite. However, the current location of the studied sample at *ca.* 1 km from the closest granitic outcrop seems too far away so that this sample may have experienced a temperature high enough for staurolite crystallization, albeit the 3D geometry of the granitic body right below the sample is unknown.

Yet, the two tectonic events aforementioned took place in very early times, more than 400 my before the onset of the Himalayan orogeny. Assuming that staurolite crystallized during one of these events and that garnet growth occurred during an Eohimalayan event, then the grains of staurolite must have been preserved in the sediments for more than 400 million years before to be included in garnet. Yet, the propensity of staurolite to easily react with fluids and to weather into muscovite or chlorite makes the preservation of the grains of staurolite all the while difficult to conceive. The preservation of staurolite grains in garnet consequently seems to indicate a crystallization fairly close in time between staurolite and garnet, raising *de facto* the question of a pre-Himalayan growth for garnet as well. So far, the crystallization of those garnets was thought to be Eohimalayan based on their association with the oldest tectonic event preserved in the Haimantas sediments. Thus, they were, as a matter of fact, considered as Himalayan garnets as well. The results of this study raise the question of whether this is necessarily the case. At this stage of knowledge, the geological evidences are still too occasional to allow drawing more specific assumptions on the geological events that could have generated the pre-Himalayan metamorphism. However, the mere fact that pre-Himalayan index metamorphic minerals such as staurolite or garnet are preserved in sedimentary series involved in the Himalayan orogeny must alert us to the fact that not all metamorphic minerals are inevitably Himalayan.

7 Synthesis and conclusions

During the last three decades, an increasing amount of observation suggests that the rocks of the Himalayan range have experienced a polycyclic history. Most of these observations consists of structural relationships between highly deformed Cambrian sediments preserved in locally non-deformed Ordovician granites (Marquer et al., 2000; Thakur and Patel, 2012). Cambrian garnets yielding ages of 534 Ma have been reported as well (Argles et al., 1999). The rarity and lack of impact of these arguments on the proposed models for the tectonic evolution of the Himalayan range turn out that these data are most of the time totally neglected and not taken into consideration. The results of this study clearly show that

a metamorphism in the amphibolite facies occurred during the pre-Himalayan cycle. The occurrence of relict metamorphic minerals in the Cambrian sediments implies that both Cambrian and Cenozoic metamorphic minerals are mixed in the sediments forming now the HHC. The index metamorphic minerals such as garnet, staurolite, kyanite, and sillimanite are collectively used to evaluate the degree of metamorphism and to establish the metamorphic field gradient along a specific section. This is valid as long as the different index minerals results from the same metamorphic event. By ignoring the presence of pre-Himalayan minerals, there is the risk that the tectonic models for the Himalayan evolution are built from thermal profiles that rely on P–T estimates resulting from mixed assemblages, gathering Cambrian and Cenozoic metamorphic minerals. Therefore, one of the main resulting challenges to face is to assess the extent of the Pre-Himalayan metamorphism. In the case of a polycyclic metamorphic history, it becomes necessary to be able to determine the index minerals belonging to the first orogenic cycle from those that were generated during the second cycle.

The identification and quantification of a pre-Himalayan tectono-metamorphic history does not only constitute wishful thinking for many Himalayan geologists, but constitute a real advance in our understanding of Himalayan geology. What would have been our image of the geology of the Alps if the complete Variscan history had been systematically ignored when establishing the models of the tectono-metamorphic evolution of the Alps? Our vision of the formation of the Alps would have been be strongly distorted. The same applies to the elaboration of models for the tectono-metamorphic evolution of the Himalayan range. Indeed, so far all the models consider that the Himalaya is essentially the consequence of one single orogenic cycle associated with the India-Asia collision during the Cenozoic era. Integrating pre-Himalayan data into these models would modify them significantly since it would then be necessary to withdraw data from the Himalayan orogenic cycle to transpose them into the pre-Himalayan cycle.

Abbreviations

HHC	High Himalayan Crystalline
TH	Tethyan Himalaya
LH	Lesser Himalaya
MBT	Main Boundary Thrust
MCT	Main Central Thrust
MHT	Main Himalayan Thrust
STDS	South Tibetan Detachment System
MSZ	Miyar Shear Zone

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Availability of data and materials

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Declarations

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The author declares that he has no competing interests.

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