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“20 years of geological mapping of the metamorphic core across Central and Eastern Himalayas”

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Abstract

The largest crystalline unit representing the mid-crust in the Himalayan belt is the Greater Himalayan Sequence (GHS) which stretches all over the 2400 km of length of the belt. The GHS, recognised since the first geological explorations of the Himalayas, has been considered for a long time as a coherent tectonic unit, exhumed by the contemporaneous shearing along the Main Central Thrust and the South Tibetan Detachment System in the time span ~ 25-17 Ma. A multidisciplinary approach, integrating geological mapping, structural analysis, petrology and geochronology allowed to better constraints on its internal architecture characterised by several levels of tectonic-metamorphic discontinuities on the regional scale with a top-to-the-S/SW sense of shear and active since ~ 40 Ma. The GHS is consequently divided in three main tectonic units exhumed progressively from the upper part to the lower one by ductile shear zones, later involving the Lesser Himalayan Sequence.

Above the Main Central Thrust a cryptic tectono-metamorphic discontinuity (Higher Himalayan Discontinuity; HHD) has been recognized and mapped in Central-Eastern Himalaya. The mapping of the HHD has been allowed by the use of a multidisciplinary approach involving structural analysis, geochronology and petrography. A new map of Western Nepal is presented.

In this framework the popular models of exhumation of the GHS mainly based on the contemporaneous activity of the two bounding shear zones (Main Central Thrust and the South Tibetan Detachment) and considering the GHS as a coherent tectonic unit, should be reconsidered. An in-sequence shearing tectonic model, from the deeper to the upper structural levels, further affected by out-of-sequence-thrusts, is more appropriate to explain the deformation, metamorphism and exhumation of the mid-crust in the Himalayan belt.

Geological mapping of the Himalayan belt is very far away to be exhaustively completed. Anyway during the last 20, and particularly during the last few years, it has been notably improved due to a new multidisciplinary approach.

Keywords: Himalaya; geological maps; tectonic and metamorphic discontinuities; Greater Himalayan Sequence; exhumation; ductile shear zone; in sequence shearing.

1. Introduction

Geological mapping is a basic tool for the understanding of the 3D geology, construction of geological models and for the interpretation of the geological evolution. Geological mapping is devoted to map lithological sequences, sedimentary and tectonic units as well as the boundaries among them and geological structures mappable at the chosen scale. The state of the art of mapping in different countries of the world is remarkably different due to the variable amount of money the governments allocate to it and to the presence of ore deposits. A paradox is the Himalayan belt, the most classical collisional orogen, studied since the last two centuries where tectonic models have been constructed but the availability of geological maps is extremely variable resulting in a discontinuous coverage of maps. Anyway geological mapping in the Himalayas is hampered by the elevated snow-covered altitudes reaching 8000 meters, rugged terrains, steep slopes, vegetation in the lower part and limited accessibility due to the scarcity of roads and even trails or footpaths. Political problems often hamper the access of the researchers into wide regions for several years (e.g. Tibet).

By contrast many researchers from all over the world actively worked on the geological evolution of the Himalayas, representing an exceptional geological natural laboratory. Moreover, several tectonic models have been proposed starting from the Himalayan belt (Fig. 1) such as the very interesting, but widely discussed, “channel flow” model for the exhumation of the mid crust (Beaumont et al., 2001; see discussion in Kohn, 2008; Carosi et al., 2012, 2016; He et al., 2015; Montomoli et al., 2013 and other orogenic belts (e.g. Darbyshire et al., 2017). The efforts in understanding the geological evolution of the belt led to the application of a multidisciplinary approach and to the use of the most modern techniques such structural geology, petrology and geochronology (Kohn 2008; Montomoli et al., 2013; 2015; Larson et al., 2013; Cottle et al., 2015) with direct consequences on the mapping of main structures or tectonic boundaries.

Following field mapping of the metamorphic sequences in central Himalayas (e.g. Nepal, Sikkim and Bhutan) in the last 20 years we can observe a clear evolution from the classical geological maps, mainly based on field work, toward a new generation of geological maps based on integrated field work, remote sensing, meso- and micro-structural analysis, petrology and in situ geochronology. This approach led to the mapping of “hidden or cryptic discontinuities” in the metamorphic core of the belt (Carosi et al., 2010, 2016; Montomoli et al., 2013, 2015; Cottle et al., 2015; Iaccarino et al. 2015, 2017a; Wang et al., 2015, 2016; Larson et al. 2017 with references) which had primary consequences on the tectonic and metamorphic evolution of the belt and could be used as guidelines for mapping similar discontinuities in other modern and ancient orogenic belts. The “hidden discontinuities” are both in-sequence-thrust sense shear zones or thrusts (Carosi et al., 2016 with references) acting after the collision between India and Asia and out-of-sequence-thrusts (Ambrose et al., 2015; Mukherjiee, 2015) affecting the Greater Himalayan Sequence after the activity of the Main Central Thrust.

A switching point can be envisaged at the beginning of this century when Kohn et al. (2004) recognized the activity and the age of the Langtang thrust in Central Nepal by detailed chemical analyses of monazites in its footwall and hanging wall. Carosi et al. (2007, 2010) mapped in Western Nepal a high-temperature shear zone (Toijem shear zone), investigated by structural analysis with the recognition of mylonites and kinematic indicators (Fig. 2a), and different P-T-t paths of the footwall and of the hanging wall rocks. Montomoli et al. (2013, 2015) and Iaccarino et al. (2015, 2017a) found a close relation between the age of the prograde and retrograde paths with a shifting of the P-T peaks of several million years in the hanging wall and footwall rocks, as envisaged by Kohn et al. (2004). The integration between classical geological mapping, structural geology, petrography and geochronology led to a sort of geological mapping 2.0, where field observations and structural analysis are integrated by further multidisciplinary analyses to draw on the map new tectono-metamorphic discontinuities, which were not easily or univocally recognizable only by field observations.
The most evident example of this integrated approach is the finding of a mid-crustal tectonic and metamorphic discontinuity, recognized and mapped in more than 20 different localities within the GHS in Central and Eastern Himalaya (Figs. 3, 4) (Carosi et al., 2007, 2010, 2016; Groppo et al., 2009; Corrie and Kohn, 2011; Yakymchuk and Godin, 2012; Imayama et al., 2012; Rubatto et al., 2013; Kohn et al., 2004; Kohn, 2008; Larson et al., 2010, 2013, 2015; He et al., 2015; for a review see Montomoli et al., 2013, 2015a; Cottle et al., 2015; Khanal et al., 2015; Iaccarino et al., 2015, 2017 a; Wang et al., 2015, 2016; Zeiger et al., 2015; Agustsson et al., 2016; Shresta et al., 2017; Walters and Kohn, 2017). This "new" discontinuity, named as the Higher Himalayan Discontinuity (HHD) after Montomoli et al. (2013; 2015) can be mapped from Western Nepal up to Bhutan for more than 1000 km along the strike (Cottle et al., 2015; Carosi et al., 2016 with references; Wang et al, 2016) (Fig. 3). Hence actual paradox is to have the most classical orogenic belt partially ~~un~~covered by detailed geological maps but where the most modern approach is locally present.
In addition to this, mapping the Himalayas encompasses the problem of definition of the formation or units within the metamorphic core of the belt and unresolved problem of the definition and localization of the Main Central Thrust separating the Greater Himalayan Sequence from the lower Lesser Himalayan Sequence (Searle et al., 2008 with references; Mukhopadhyay et al., 2017). For example in Sikkim the MCT has been mapped entirely in the GHS at the base of the upper portion of the GSH corresponding to the sillimanite bearing gneiss and micaschist. In lower Kali Gandaki valley (Central Nepal), as well as in other portions of the belt, the MCT has been originally mapped by Le Fort (1975), Colchen et al. (1986), Carosi et al. (2014), Iaccarino et al. (2015) at the kyanite –in isograd at the base of the GHS and recently mapped by Searle (2010) and Parsons et al. (2016a, b) in the Lesser Himalayan Sequence, at the chlorite-in isograd where Himalayan deformation is weak or vanish. The structural distance between the positions of the MCT is nearly 10 km resulting in a very different position of the MCT trace on the geological maps (~ 15 km of horizontal distance in the map).
Taking into account the above mentioned problems, this paper focuses on the evolution of the geological maps in the last 20 years in the metamorphic core of the Himalayas in the Nepalese and Sikkimese-Bhutanese Himalayas (Central-Eastern Himalaya) with special attention to the tectonic and metamorphic

discontinuities bounding the GHS both at the top and at the bottom and the HHD occurring within the GHS (Fig. 2).

2. Overview of the geology of the Himalayas

The Himalayan belt is the most classical example of collisional orogen (Le Fort, 1975) derived from the nearly frontal collision between India and Eurasia plates at ~ 59 Ma (Hu et al., 2016) after the entire consumption of the Neo-Tethyan ocean below the Eurasian plate. After the collisional stage deformation continued by pushing and indenting the northern margin of India in the Eurasia with lateral extrusion of the SE China and Indochina. The Himalaya is a belt characterized by a E-NE shallowly dipping subduction in which the subduction hinge converges relative to the upper plate slightly faster than the shortening in the Himalayas (Doglioni et al., 2007; Doglioni and Panza, 2015).

During the collisional and post-collisional stages the tectonic units derived from the northern Indian plate were deformed and metamorphosed at different levels to the south of the Indus suture zone and stacked to build up the highest collisional orogen in the world.

Most deeply metamorphosed rocks represent the mid-crust and occur in one of the major tectonic units of the belt known as Greater Himalayan Sequence (GHS) or Higher Himalayan Crystalline (Fig. 1).

Since long time three main tectonic units have been recognized all along the Himalayan belt (Fig. 1) (Heim and Gansser, 1939). These tectonic units from bottom to top are: (i) Sub-Himalaya, (ii) Lesser Himalayan Sequence (LHS), (iii) Greater Himalayan Sequence (GHS) and (iv) Tethyan Sedimentary Sequence (TSS). They are bounded by northward dipping orogenic-scale tectonic discontinuities, such as the Main Boundary Thrust, the Main Central Thrust (Gansser, 1964; Searle et al., 2008) and the South Tibetan Detachment System (Burg et al., 1984; Burchfiel et al., 1992, Carosi et al., 1998, Searle et al., 2003). These sequences have been formerly deposited on the Indian passive margin and later deformed during the India–Asia collision.

The lowermost tectonic unit, the Sub-Himalaya, is made by Tertiary molasses (Siwalik Group) deposited in the foreland basin accreted to the growing orogen. The LHS is made by very-low grade to lower amphibolite facies metamorphic rocks (Upreti, 1999; Hodges, 2000) and mainly represented by impure quartzite, marble, phyllites, orthogneiss and metamafic rocks. The LHS is subdivided in two groups (Upreti, 1999), separated by an unconformity: (i) the “Lower Lesser Himalaya”, made by Paleo-Protorezoic to Meso-Proterozoic sedimentary rocks and orthogneiss and (ii) the “Upper Lesser Himalaya” made by sedimentary rocks of middle Proterozoic age, unconformably overlain by rocks of Gondwanan affinity of Upper Paleozoic to Cenozoic in age.

The GHS, tectonically overlying the LHS with a km-wide top-to-the-south ductile shear zone and as the named Main Central Thrust Zone (MCTZ), is a 20-30 km thick sequence of medium to high-grade metasedimentry and meta-igneous rocks. Since the original works of Le Fort (1971, 1975) it has been classically subdivided into three main lithotectonic units (Searle and Godin, 2003) showing a good lateral continuity along the belt. The lowermost (Unit 1) is comprised of metasedimentary rocks mainly represented by garnet to kyanite-bearing paragneiss and micaschist with subordinate calc-schists, quartzite, impure marble and migmatite in the upper part. Above, Unit II is a sequence made mainly by calcsilicate gneiss and marbles with minor pelitic and psammitic rocks. The uppermost portion, Unit III, is made by orthogneiss and aluminosilicate-bearing migmatitic rocks.

One peculiarity of the metamorphic core of the Himalaya is the presence of an inverted metamorphic field gradient at its base, with the highest metamorphic grade rocks structurally above the lowest grade ones (Gansser, 1964; Searle and Rex, 1989). Along the belt the structural thickness of the GHS ~~unit~~ is quite variable, reaching minimum value of 2-3 km in western Nepal (Carosi et al., 2002, 2007) up to 30 km in Eastern Nepal and Bhutan (e.g. Daniel et al., 2003).

The GHS is intruded in its upper part by Oligo-Miocene granites (Visonà and Lombardo, 2002; Visonà et al., 2012; Searle, 2010; Weinberg, 2016 with references). The granites are mainly subdivided into two groups (i) two mica ± tourmaline leucogranite and (ii) tourmaline leucogranite, yielding U-Th-Pb monazite and U-Pb zircon ages spanning from 24-19 Ma (Searle and Godin, 2003; Carosi et al., 2013) with few younger leucogranites between 14 and 7 Ma (Leech, 2008; Kellett et al., 2010; Weinberg, 2016; Montomoli et al., 2017a). Whereas most of the leucogranites, intruding the GHS are deformed in the ductile portion of the STDS (Montomoli et al., 2017a), an undeformed km-size granite has been recently found in western Nepal with ~~the~~ peculiar characteristics of cross-cutting the STDS, intruding both GHS and Tethyan Sedimentary Sequence at ~ 24 Ma (Bertoldi et al., 2011; Carosi et al., 2013).

The uppermost tectonic unit is the Tethyan Sedimentary Sequence, lying tectonically above the GHS through a top-to-the-North ductile to brittle extensional structures, known as the South Tibetan Detachment System (Burchfiel et al., 1992). The Tethyan Sedimentary Sequence is made up of the Neo-proterozoic (?) - Cambrian to Eocene marine sediments deformed under very-low to low-grade metamorphic conditions (Crouzet et al., 2007; Myrow et al., 2009; Antolin et al., 2011; Dunkl et al., 2011) and reaching amphibolite facies metamorphic condition towards the Indus Suture Zone (Montomoli et al., 2017b). To the North it is bounded by the Indus Yarlung Suture Zone (Fig. 1), made by flyschs and ophiolites derived from the Neotethys Ocean (Hodges, 2000; Yin 2006).

3. Location of the Main Central Thrust: a never ending enigma?

The MCT is one of the major tectonic discontinuities stretching for nearly 2400 km along the strike of the belt (Fig. 1). The definition of the MCT has changed since it was first proposed by Heim and Gansser (1939) as “the thrust fault that places high-grade metamorphic rocks of the Greater Himalayan Sequence southward over low-grade rocks of the Lesser Himalaya”.

Different definitions of the MCT have been proposed after the initial one by Heim and Gansser (1939), based on (a) structural and metamophic criteria (Searle et al. 2008, Martin 2017, with references; Montemagni et al., 2016; Mukhopadyay et al., 2017); (b) metamorphic and rheological (Searle et al. 2008) and rheological (e.g. Gibson et al., 2016; Parson et al., 2016a); (c) chronological (Webb et al., 2013); and (d) compositional assuming that the MCT is a high-strain zone separating distinguishable protoliths by geochemical composition (e.g. Martin et al., 2005; Martin, 2016). The MCT, active for several Myr, records a long-lasting deformation, from ductile to brittle (Carosi et al., 2007), and affects several different lithologies and units along strike.

For other authors the MCT is a wide, km-thick ductile shear zone, classically delimited by two systems of reverse faults, named as the Main Central Thrust Zone (MCTZ), that in different portions of the belt assumes different names. Arita (1983) defines the MCT-1 as the structurally lower thrust and the MCT-2 as the upper one of the MCTZ. Saklani et al. (1991) refers to the lower one as MCT2. DeCelles et al. (2000), Robinson et al. (2001) and Robinson (2008 and references therein) define the MCT “sensu stricto” as the upper thrust, which often (e.g. Colchen et al., 1986) is placed near the kyanite isograde and refers the lower thrust as Ramgarh Thrust. In the Garhwal region (NW India) the two bounding thrusts are named as the Munsiari Thrust (MT) at the bottom (Valdiya, 1980) and Vaikrita Thrust (VT) at the top (Valdiya, 1980; Gururajan and Chaudhuri, 1999; Jain et al., 2014).

According to Searle et al. (2008) previous authors such as Bordet (1961), Le Fort (1975), Gansser (1983), Colchen et al. (1986), Parrish and Hodges (1996), Harrison et al. (1997), Ahmad et al. (2000), DeCelles et al. (2000), Catlos et al. (2001, 2002), Robinson et al. (2001), Daniel et al. (2003), Martin et al. (2005), Richards et al., (2005), provided useful information on age, stratigraphy and metamorphism, but none of these criteria are able to correctly and univocally identify the location of the MCT (Montemagni et al., 2016). According to Searle et al. (2008), the main criteria to define the MCT is the identification of a strain gradient where a clear strain localization (evident from field and microstructural analyses) of deformation is present. Moreover, the former authors also pointed out that the MCT roughly coincides with a wide zone characterized by Barrovian inverted metamorphism (Searle and Rex, 1989; Davidson et al., 1997; Walker et al., 1999; Searle et al., 2008). Larson and Godin (2009) regarded the Ramgarh Thrust or MCT I or Munsiari thrust as the MCT at the base of pervasively sheared rocks of the GHS, affected by inverted metamorphism, following the definition proposed by Searle et al. (2008).

Martin (2017) proposed a different definition of the MCT based on the recognition of a protolith boundary where high-strain zone showing a reverse kinematics is present.

P-T conditions of nearly peak metamorphism within the MCTZ is bracketed between c. 0.6-1.0 GPa and 520-650°C (Hubbard, 1989; Vannay and Grasemann, 1998, 2001; Catlos et al., 2001; Kohn et al., 2001; Vannay et al., 2004; Montemagni et al., 2016; Iaccarino et al., 2017a). The peculiar feature of the MCTZ is that it coincides with the zone of “inverse metamorphic grade” ranging from the biotite to the kyanite/sillimanite zone moving structurally upward (e.g. Searle et al., 2008; Kohn, 2014 with references).

As stated above, the main consequences of the so different definitions of the MCT are the different geological map localization of the MCT itself and, as a consequence, the variable thickness of the GHS and LHS. For example in the Kali Gandaki valley (Central Nepal) the position of the MCT at the base of the garnet + kyanite-bearing gneiss of the GHS by Le Fort (1975), Colchen et al. (1980), Vannay and Hodges (1996) and Carosi et al. (2014) is nearly 15 km north-with respect to the position of the MCT used by Searle (2010) and Parsons et al. (2016a, b) who located the MCT in the Pre-Cambrian quartzites of the "classical" LHS unit where deformation attributed to the MCT vanishes to the south. In Sikkim, the MCT has been, instead, shifted upwards, towards the upper portion of the GHS at the base of the sillimanite + K-feldspar zone, well inside the migmatites of the upper GHS (Mottram et al., 2014; Chakraborty et al., 2016, 2017 with references).

So the uncertainty related to the position of the MCT is really high including several kilometers of thickness of the LHS as well as all the lower parts of the GHS. This uncertainty in the definition and location of the MCT is reflected also in its age spanning from ~23 Ma (Godin et al., 2006 with reference) to ~ 3 Ma (Catlos et al., 2002).

Montomoli et al. (2015) noted a partial overlap-in the age of the MCT and the HHD so that it is possible to confuse the MCT with the HHD in the literature. In fact recent data show that the HHD can be located above the MCT with ages spanning from c. 28 to 17-16 Ma (Montomoli et al., 2013, 2015) whereas the most recent ages of the MCT in the sections where the HHD is clearly recognized are younger (17-16 Ma onward; Montomoli et al., 2013; Mottram et al., 2014; Kohn 2014 with references; Iaccarino et al., 2015; Walters and Kohn, 2017).

Correct identification of in-sequence tectonic and metamorphic discontinuities along the same cross sections of the LHS and GHS is a fundamental key to better and correctly locate the MCT and to unravel the tectonic and metamorphic history.

4. How many units in the GHS?

Due to the strong emphasis on the role played by the STDS and the MCT in all the proposed tectonic models for the exhumation of the GHS (Montomoli et al., 2013) little attention was paid to the internal architecture and tectonic discontinuities inside the GHS. Because they are reverse thrusts or shear zones occurring in a structural position above the MCT, they were usually interpreted as out-of-sequence-thrusts (Mukherjee, 2015, with references). Classic examples of out-of-sequence-thrusts (Fig. 4), recognized in the Himalaya so far, are: the Kalopani and the Modi Khola shear zones in Central Nepal (Vannay and Hodges, 1996; Hodges et al., 1996), the Kakhtang and Laya thrusts in Bhutan (Daniel et al., 2003; Grujic et al., 2011) and the Nyalam thrust in the Shishapagma area (Central Nepal) (Wang et al., 2013) with a minor and late role in the exhumation of the GHS.

Some kind of discontinuities named "hidden discontinuities" have been identified in Eastern Nepal by recognition of the occurrence of discontinuities in the metamorphic path and/or metamorphic gradients of the rocks involved (Groppo et al., 2009; Mosca et al., 2012; Rapa et al., 2016).

The GHS has been regarded as a coherent tectonic unit since the beginning of the studies in the Himalayan belt for long time (Fuchs and Frank, 1970, Hodges, 2000; Yin, 2006) (Fig. 1). Several tectonic discontinuities in the GHS have been recently recognized and/or reinterpreted based on new geochronological data and metamorphic evolution along the Himalayan belt from Western Nepal, and Eastern and Central Nepal, through Sikkim to Bhutan. Some of these discontinuities, such as the "Bhanuwa Thrust" (Corrie and Kohn, 2011), the "Tama Kosi P-T-t-d discontinuity" (Larson et al., 2013) and the ”Hidden discontinuity 1" of Groppo et al. (2009) are in fact localized within the wide zone of deformation of the Main Central Thrust Zone at the base of the GHS (Montomoli et al., 2015). The other discontinuities, identified as the HHD and localized within the GHS well above the trace of the MCT, divide the GHS into two portions, an upper one (Upper Greater Himalayan Sequence- GHS_U) and a lower one (Lower Greater Himalayan Sequence- GHS_L) (Montomoli et al., 2013, 2015).

These thrust-sense discontinuities are mainly characterized by mineral lineations trending perpendicular to the main foliation of the belt, with a top-to-the-south to southwest sense of shear, and put in contact the hanging wall and footwall rocks which are characterized by different metamorphic imprints. However, in the last ten years more detailed investigation of structural observations at the meso- and ~~at the~~ microscale and the P-T-t path of the hanging wall and footwall rocks with *in situ* geochronological investigations allowed to recognize the occurrence of a sort of "cryptic" discontinuities in the GHS (Figs. 2, 4). They have been first identified in Nepal by different monazite ages in hanging wall and footwall (Kohn et al., 2004; Corrie and Kohn, 2011; Kohn, 2014, 2016), strain analysis (Goscombe et al., 2006), structural observations (Carosi et al., 2007) and different metamorphic imprints (Groppo et al., 2009).

The first attempt to reconcile the structural, metamorphic and geochronological observations along the same shear zone has been made by Carosi et al. (2010) by recognizing the activity of the Toijem shear zone in Western Nepal between 26 and 17 Ma in a structural position above the MCT and few Ma before of it. The Toijem shear zone was also responsible to trigger the different P-T-t paths of the rocks belonging respectively to its hanging wall and footwall (Carosi et al., 2010).

The recognition of the HHD in Western and Central Nepal was followed by the discoveries of similar discontinuities in many other areas of the belt extending the HHD to the East up to Sikkim and Bhutan (Fig. 3) (Kohn, 2004; 2008; 2014; Groppo et al., 2009; Yakymchuck and Godin, 2012; Imayama et al., 2012; Larson et al., 2010, 2013, 2015; Imayama, 2014; Montomoli et al., 2013, 2015 for a review; Ambrose et al., 2015; Cottle et al., 2015; Khanal et al., 2015; He et al., 2015; Iaccarino et al., 2015, 2016, 2017; Wang et al., 2015; Agustsson et al, 2016; Chakraborty et al., 2016, 2017; Larson et al., 2017).

However, it is worthwhile to note that the HHD, has been recognized by different Authors using three different criteria (structural, metamorphic, geochronologic or a combination of them), hence ~~their~~ correlation sometimes is not so straightforward. According to Montomoli et al. (2015), the HHD shows ~~some~~ the following important distinctive features:

- the hanging wall rocks (GHS_U) are usually sillimanite or kyanite bearing migmatite, or partially molten rocks, showing a higher degree of melting with respect to the footwall rocks (GHS_L);
- different P-T paths have been recorded for footwall and hanging wall; often hanging wall rocks exhibit lower equilibration pressure values at Tmax, commonly in the sillimanite-stability field than the footwall rocks with nearly 0.2-0.3 GPa of difference (Montomoli et al., 2015; Iaccarino et al., 2015, 2017a);
- kinematic indicators show a top-to-the south/southwest sense of movement. Mylonitic foliation is characterized by the syn-kinematic growth of high-temperature minerals, such as sillimanite and brown-reddish biotite. Moreover, quartz microstructures are within the GMB_{II} regime of Stipp et al. (2002);
- the discontinuities are active in a time interval of several Ma, but started their activity earlier than the Main Central Thrust (from ≈ 28-26 Ma, Goscombe et al, 2006; Carosi et al., 2010; Imayama et al., 2012; Wang et al., 2015, 2016) so that they can be regarded as “in-sequence shear zones” (He et al., 2015; Carosi et al., 2016; Webb et al., 2017).

Taking into account all the common aspects of the recognized discontinuities, Montomoli et al. (2015) correlated them across the belt and addressed a regional extent of the HHD for a length of nearly 800 km along strike.

Montomoli et al. (2013, 2015) showed that deformation shifted in space and time from the HHD to the MCT at lower levels. However, an unambiguous identification of the two shear zones (HHD vs MCT) and to univocally characterize tectonic discontinuities it is necessary to use a multidisciplinary approach incorporating structural, metamorphic and geochronological investigations for both hanging wall and footwall rocks and high-strain zone (Carosi et al., 2010; Montomoli et al., 2013, 2015; Iaccarino et al., 2015, 2017; Wang et al., 2016).

The activity of the HHD starting from ~ 27 Ma affected the metamorphic path of the rocks of the GHS causing differences in the P-T conditions of the rocks separated by the HHD. Following collision at ~59 Ma the GHS underwent general prograde metamorphism. The structural, metamorphic and geochronological data on the hanging wall and footwall of the HHD allow to identify the retrograde path of the hanging wall rocks corresponding to the exhumation caused by the top-to-the SW and thrust-sense of shearing at ~ 27 – 18 to 17 Ma of the HHD (Montomoli et al., 2013, 2015 with references therein; Carosi et al., 2016). Ductile deformation in the hanging wall of the HHD ceased as documented by undeformed leucogranite dykes, cross-cutting the ductile fabric and emplaced at 17 Ma (Carosi et al., 2010). When deformation was localized at a lower level in the footwall of the HHD (i.e. MCT zone) thrust-sense shearing allowed the hanging wall of the MCT (the footwall of the HHD) to change its P-T-t path and to be exhumed (Montomoli et al., 2013; 2015).

All these data are in accordance with a downward and southward progressive migration of deformation and ductile shearing within the GHS allowing the progressive exhumation of crustal slices of the GHS (Montomoli et al., 2013, 2015; Carosi et al., 2016). This framework has been recently confirmed by other authors working in Central-Eastern Himalayas such as: He et al. (2015), Ambrose et al. (2015), Cottle et al. (2015 with references), Khanal et al. (2015), Larson et al. (2015), Wang et al. (2015, 2016), Agustsson et al. (2016), Chakraborty et al. (2016) and Webb et al. (2017).

The current tectonic models adopted for the GHS are not able to explain the regional tectonic and metamorphic activity of the HHD. Most of them such as extrusion of a rigid or ductile GHS, channel flow, channel flow followed by ductile extrusion, or channel flow followed by critical taper, wedge insertion and even critical taper (see Montomoli et al., 2013 for a review) are mainly based on the contemporaneous activity of the upper STDS and the lower MCT (active between 23-17 Ma, Godin et al., 2006). In this framework the GHS was entirely exhumed by STDS and MCT.

Even if critical taper model do not require their simultaneous activity, STDS and MCT play always a primary role in the exhumation of the GHS. The new data emerging from different parts in the Central Himalaya highlight the occurrence of a regional HHD whose age supports a top-to-the-south in-sequence shearing progressively involving crustal slices of the Indian crust.

The recently recognized activity of the top-to-the-south Kalopani shear zone in Central Nepal, constrained at 41-28 Ma (Carosi et al., 2016), confirmed and reinforced the proposed in-sequence shearing models, which permitted this tectonic scenario back up to the Eocene nearly 15 Ma after the collision (cf., Montomoli et al., 2013). The recognized timing of the Kalopani shear zone and of the HHD fits well the in-sequence shearing starting from the upper portion of the GHS towards its base and progressively involving slices from the Indian plate at the time of the activation of the MCT and later. The maximum P and the shape of the P-T-t paths, reached by the successive slices, decreases to the south and, when LHS was involved, the slice were characterized by hairpin shape and progressively lesser pressure up to the higher structural levels.

In this framework, the P-T-t paths of the slices of the GHS, delimited by the top-to-the-SW shear zones show the same shape but they are diachronous because the slices were initially underthrust to the NE, but exhumed at different times coinciding with the activation of the shear zone underneath the exhumed slice (Montomoli et al., 2013). The timing of exhumation shows a difference of several million years between the hanging-wall and footwall of the HHD (e.g. 5-6 Ma, Montomoli et al., 2013, 2015).

The diachronous activation of contractional top-to-the-S and SW shear zones within the GHS, while it experienced an overall underthrusting, is able to explain the relatively low peak P recorded by the hanging-wall compared to that of the footwall rocks (Carosi et al., 2010; 2016; Montomoli et al., 2013, Iaccarino et al., 2015, 2017a). The difference in pressure (at peak temperature) is estimated to be ~ 0.2-0.3 GPa (Kohn, 2008; Montomoli et al., 2013, 2015). In this framework, older “retrograde” ages (up to ~ 28 Ma) are found in the upper portion of the GHS (Kohn et al., 2005; Corrie and Kohn, 2011; Kohn, 2008, 2014, 2016; Imayama et al., 2012; Montomoli et al., 2013; Ambrose et al. 2015; Wang et al., 2015, 2016).

5. Central-Eastern Himalaya

Hereafter the main geological features, resulted in published geological maps, of well-studied and representative areas of the Central-Eastern portion of the belt will be presented, starting from West to East; i.e. from Nepal to Bhutan. Particular attention is paid to the recognition and mapping of the tectonic discontinuities both at the boundaries of the GHS (i.e. MCT and STDS) and inside it, i.e. HHD recognized by a multidisciplinary approach.

5.1 Western-Central Nepal

The first modern geological studies in Western Nepal are due to Fuchs (Fuchs, 1964, 1977; Fuchs and Frank, 1970) who produced detailed geological maps of the base of the GHS and of the LHS in the sixties and ~~in~~ seventies mapping the different formations the LHS and their tectonic setting. After a long time with very few geological investigations, due to the difficult of the access and political problems in the area, geological maps have been produced by DeCelles et al. (2001) and Robinson et al. (2006) focusing on the thrust tectonics of the LHS and later, by Carosi et al. (2002, 2007), that investigated the GHS and the Tethyan Sedimentary Sequence with schematic geological maps. A tectonic discontinuity in the core of the GHS was reported here for the first time, structurally above the MCT, and was named as the Toijem shear zone (Carosi et al., 2007) (Figs. 2, 5).

A multitechnique approach, using structural geology, petrology and geochronology allowed Carosi et al. (2010) to map the Toijem shear zone in lower Dolpo (Figs. 2, 5) and to indentify it as a tectonic and metamorphic discontinuity affecting the P-T-t paths of both hanging wall and footwall rocks. A difference in the P values was reported in the P-T-t paths of the hanging wall and footwall. Moreover by using U-Th-Pb geochronology on monazite age as older as 26 Ma has been detected for the Toijem shear zone. The 26 Ma age is notably older with respect to the oldest age of the MCT detected in western Nepal (Carosi et al., 2010 with references).

Further expeditions in the Mugu-Karnali to establish the continuation of the Toijem shear zone to the west, allowed the identification of an even thicker (up to four km) high-temperature shear zone, named as the Mangri shear zone (Fig. 2b, e, f and Fig. 5) close to Mangri village (Montomoli et al., 2013; Iaccarino et al., 2017a). *In situ* U-Th-Pb geochronology, along with the recognition of Y, Th, U zoning in monazite, allowed to clearly detect a different age in the prograde and retrograde paths of rocks in the hanging wall and in the footwall triggered by the activity of the thrust-sense shear zone at c. 25-17 Ma.

5.2 Central-Eastern Nepal

The geological knowledge of the Cho Oyu, Everest and Makalu region dates back to the beginning of the 20th century by Heron (1922 a-c) and Wager (1934) investigating the source area of the Arun river (Carosi et al., 1999). Heron mapped the area between Shishapagma and Yarlung Tsangpo at the scale 1:750.000. The northern slope of the Mt. Everest and the Rongphu valley have been mapped by Odell (1925, 1948) at the scale 1:100.000.

According to Carosi et al. (1999) geological knowledge of the Mt. Everest area increased from the Fifties onward when Nepal opened to foreign climbers and monographs have been published such as Lombard (1958) and Hagen (1969) and the books by Bordet (1961), Hagen (1963) and Hashimoto (1973) (Carosi et al., 1999). A corner stone is the geological and tectonic maps of the Sagarmatha (Everest)-Makalu region by Bordet and Latreille (1958a, b). The area to the South of Everest-Makalu was studied by Italian and Czech joint ~~to~~ climbing expeditions (Bortolami et al., 1976, 1977, 1983; Jaros and Kalvoda, 1976, 1978; Palicova et al., 1982). Italian teams concentrated on the South of Nuptse and Lhotse Mts, with the publication of a geological map of the Imja Khola at the detailed scale 1:25.000 by Polino (1983).

At the same time, Chinese expedition in the sixties and seventies to Mt. Everest allowed Yin and Kuo (1978) to summarize the geological results in a 1:100.000 map of the area north of Mt. Everest up to Dzakar Chu and Rongphu valley. In the same period monographs from Academia Sinica (1979) and the Bureau of Geology and Mineral Resources of Xizang Autonomous Region (1993) summarized the geology of southern Tibet. The most important information as part geological maps were about detailed stratigraphy and paleontology of the Tethyan sediments which offered excellent outcrops on the Tibetan side.

It is worth to note that the contact between Tethyan Sedimentary Sequence and the lower metamorphics of the GHS was mapped as a thrust by Academia Sinica (1979). J. P. Burg was the first to recognize and to map a top-to-the-north extensional brittle fault (South Tibetan Detachment) at the boundary between the Tethyan Sedimentary Sequence and the GHS in the geological map attached to the PhD thesis (Burg, 1983). This discovery highly influenced the view of the Himalayan belt and the development of tectonic models in the international community during the following 35 years and it is nowadays one of the main topic in the study of the Himalayan range.

In a paper published on the Geological Society of America Memories, Burchfiel et al. (1992) mapped the STDS (at least the upper brittle fault) in many places along strike of the Himalayas from India to Bhutan.

It is only in 1998 that Carosi et al. (1998) clearly recognized that the STDS is made by a system of faults and shear zones characterized by a lower ductile shear zone and an upper low-angle normal fault, cut by high-angle normal faults in the Mt. Everest-Rongbuk area.

After several expeditions on the Nepalese and Tibetan side of the Mt. Everest-Mt. Cho Oyu and Mt. Makalu area by Italian teams by Pisa, Torino and Padova Universities and CNR a geological map at the scale 1:100.000 has been published by Carosi (1999) including the lower portion the GHS and the bottom of the Tethyan Sedimentary Sequence, including the brittle and ductile strands of the STDS.

The eastern part of the same area has been mapped by Searle (2003) at the scale 1:100.000 clearly tracing the two portions of the STDS: the lower ductile shear zone, Lhotse detachment, and the upper brittle fault indicated as Qomolangma Detachment, as it cross cuts the top of Mt. Everest named, in Chinese language, Qomolangma. The new edition of the Searle (2003) map includes the Mt. Baruntse (7168 m) and Mt. Makalu areas (8475 m).

A new map of the Cho-Oyu, Gyachung Kang, Everest and Makalu area at the scale 1:100.000, including the lower part of the GHS up to the bottom of the Tethyan Sedimentary Sequence, has been presented at the 29th HKT workshop 2014 (Lucca, Italy; Pertusati et al., 2014) and is now in press.

Investigations in the Nyalam region (Wang et al 2015; 2016), Langtang (Kohn et al., 2004; Kohn, 2008, Corrie and Kohn 2011), Tama Kosi (Larson et al., 2010; Larson and Cottle, 2014), Likhu Khola (Shresta et al., 2017), Arun Window (Groppo et al., 2009) and Kanchenjunga (Goscombe et al., 2006; Imayama et al., 2010, 2012; Ambrose et al., 2015) led to the identification of two tectonic and metamorphic discontinuities in the GHS: a lower one roughly corresponding to the MCT and an upper one at the base of the sillimanite grade corresponding to the HHD of Montomoli et al. (2015) (Fig. 3) and representing its extension toward the east. In the Kali Gandaki valley Iaccarino et al. (2015) recognized the HHD (here named as Chomrong Thrust) >1 km north of the MCT as mapped by Colchen et al. (1986) and Vannay and Hodges (1996) in the kyanite-bearing migmatitic paragneiss of the GHS.

In the Marshyangdi valley (between the Mt. Manalsu and the Annapurna Range) two strands of the HHD have been recently recognized: un upper one located in the uppermost GHS (Walters and Kohn, 2017) and a lower one, in the mid part of the GHS, at the base of the sillimanite-in isograd (Carosi et al., 2017). According to Walters and Kohn (2017) the uppermost shear zone could be connected to the HHD by a lateral ramp or non-continual thrust planes (Corrie and Kohn, 2011).

Ambrose et al. (2015) and Larson et al. (2015) determining different monazite ages of the exhumation of the rocks of the GHS, identified and mapped out-of-sequence-thrusts (OOST) corresponding to the High Himalayan Thrust of Goscombe et al. (2006) in Eastern Nepal. The age of the OOST was constrained at < 20-18 Ma as they cross cut all the previous tectono-metamorphic discontinuities in the GHS.

5.3 Sikkim

As reported above in the paragraph 3, dedicated to the MCT, in Sikkim Himalaya an extensive discussion exists on the location of the MCT placed by different Authors in very different positions, ranging form the base wide zone of inverted metamorphism (base of the chlorite + biotite isograd) and the middle-upper part of the GHS (base of the sillimanite +K-feldspar) (Mukhopadhyay et al., 2017 with references). In particular the location of the MCT at the level of the sillimanite+K-feldspar in the GHS is unique in the Himalayan belt and such a clearly recognized tectono-metamorphic discontinuity could be better interpreted as a splay of the HHD (Fig. 3) whereas the MCT could be shifted downward at least at the level of the kyanite-in isograd (eg. Location B: MCT of Lal et al., 1981; Mohan et al., 1989 in Chakraborty et al., 2016). The age of the lower

MCT, at the base of the imbricate zone of the MCTZ is nearly ~ 17 Ma (Mottram et al., 2014, 2015) whereas the inferred age of the MCT localized in an upper position at the beginning of the sillimanite+K-feldspar zone is older and occurred at 28-25 Ma, the age of the exhumation of the hanging wall rocks of the tectono-metamorphic discontinuity (see Mukhopadhyay et al., 2017). The latter age is in good agreement with the age of the HHD found along the Himalaya (Montomoli et al., 2015) and confirms both a younger activation of thrust-sense shear zones progressively to the south (Carosi et al., 2016) and the occurrence of the HHD also in Sikkim.

The discontinuity reported by Rubatto et al. (2013) at the base of the age of melting in the upper part of the GHS, separating two GHS blocks well above the sillimanite+K-feldspar isograd, could correspond to the activity of a normal-sense shear zone probably related to the STDS. The P recorded in the upper block is in fact higher with respect to the one recorded in the lower block but the lower block recorded an earlier exhumation with respect to the upper one, that is exactly the opposite of what happens in the hanging wall and footwall of the HHD. The discontinuity could be a more complex structure characterized by an earlier thrust-sense shear zone followed by a normal-sense shear zone.

5.4 Bhutan

The first comprehensive and detailed geological map of Bhutan Himalayas has been produced by Gansser (1983) painted by hand but accurately reporting the geology of all the accessible (by walking) places in Bhutan. A more recent map of Bhutan has been published by Long et al. (2011) at the scale 1:500.000 containing more detailed observations and structural data in the LHS, whereas the rest of the map is markedly similar to Gansser’s map.

A debated question in Bhutan remains the interpretation of the contact between Tethyan Sedimentary Sequence and the lower GHS in the outer klippe of the Tethyan Sedimentary Sequence ~~in~~ on the southern slope of the range. Long et al. (2017 with references) interpret the boundary between the two units as a conformable one without any tectonic and/or metamorphic discontinuity on the basis of a gradual transition in deformation and metamorphism (Long and McQuarrie, 2010). Most of the Authors regard the contact as a tectonic one, affected by a top-to-the-north normal sense shear zone linked to the STDS (Grujic et al. 1996, 2002, 2011; Daniel et al., 2002; Kellett et al. 2010; Chambers et al. 2011; Togbay et al., 2012; Greenwood et al., 2016). Greenwood et al. (2016) emphasized a different structural evolution between GHS and Tethyan Sedimentary Sequence that rules out a possible original conformable contact. In addition to this they detected a Lower Paleozoic age for quartzite at the base of the Tethyan Sedimentary Sequence, the same age found in the lower gneiss of the GHS.

Moreover the gradual metamorphism between GHS and Tethyan Sedimentary Sequence decreasing upward could be only “apparent”. Long et al. (2017) assume that the measured deformation and metamorphism in a section from the lower GHS to the upper Tethyan Sedimentary Sequence are contemporaneous and they do not consider a possible diachronic development. As highlighted by Carosi et al. (2016 with references) in Western and Central Nepal, joining structural, petrological and geochronological observations, GHS is not a unique unit ~~being~~ as it is separated by several tectonic-metamorphic discontinuities and divided in several sub-units. Moreover each slice of the GHS shows a different timing in prograde and retrograde metamorphism played by the detected tectonic discontinuities, so that even the shape of the P-T-t paths are the same even if the timing is different, ruling out the occurrence of a simple gradual upward decreasing metamorphism in the GHS. The contact between GHS and Tethyan Sedimentary Sequence could have been complicated by the occurrence of the growth of post-tectonic minerals in the lower Tethyan Sedimentary Sequence such as static biotite (Gansser, 1983; Carosi et al., 2002, 2007) attributed by the late heat transfer from the lower GHS (Carosi et al., 2007; Greenwood et al., 2016). Such a late "static" recrystallization should have reinforced the apparent field gradual transition in metamorphism between GHS and Tethyan Sedimentary Sequence.

The GHS in Bhutan exposes the thickest section (~ 30 km) throughout the Himalaya, being doubled by a top-to-the-south thrust sense shear zone as an out-of-sequence thrust, named Kakhtang Thrust (Swapp and Hollister, 1991, Grujic et al., 1996, 2002, 2011; Davidson et al., 1997; Daniel et al 2003; Long and McQuarrie, 2010; Chambers et al., 2011) or Laya Thrust in Western Bhutan (Warren et al., 2011). The Kakhtang Thrust was firstly identified by Swapp and Hollister (1991) as a discontinuity in the core of the GHS between the lower staurolite and kyanite-bearing mica schist and paragneiss and the upper sillimanite + K-feldspar ± cordierite bearing migmatite ("Bhutan Thrust"). Even in absence of geochronological data the Authors suggested that the proposed discontinuity predated the last motion on the Main Central Thrust because it occurred at higher temperature compared to the deformation temperature of most of the rocks along the MCT in Bhutan.

It is worthwhile to note that the Kakhtang-Laya Thrust has been recently reanalyzed and is reinterpreted as a tectono-metamorphic discontinuity in the middle GHS corresponding to the HHD, and older than the MCT (Zeiger et al., 2015; Agustsson et al., 2016).-It was active at 27-16 Ma, and thus stretching the presence of the HHD from Western Nepal to Eastern Bhutan (Fig. 3).

6. Tectonic evolution of the GHS: in-sequence shearing model

The occurrence of two tectono-metamorphic discontinuities above the MCTZ and below the STDS with the uppermost one (e.g. Kalopani shear zone in Central Nepal; Carosi et al., 2016) active before the lower one (HHD), allowed a better constrain to the in-sequence shearing model proposed by Montomoli et al. (2013, 2015) and Iaccarino et al. (2015, 2017a).

To avoid a possible confusion caused by different methods and approaches or from the diachronicity of deformation of shear zones in the GHS, we describe a tectonic model starting from Central-Western Nepal, where consistent data by the same approach have been obtained along the same transects (Montomoli et al., 2013, 2015; Carosi et al., 2010, 2015, 2016; Iaccarino et al., 2015, 2017a).

In the GHS in the Kali Gandaki (Central Nepal) the occurrence of two tectono-metamorphic discontinuities within the GHS has been observed.

The HHD is localized in the kyanite-bearing gneiss of Unit 1, and was active from ~ 25 to 18 Ma, as is identified by monazite U-Th-Pb ages (cf., Iaccarino et al., 2015). Along the same transect, above the HHD, the Kalopani shear zone, localized in the upper part of the GHS, became active between ~ 41 and 28 Ma (Carosi et al., 2016).

The new data can be reconciled with a three-stage exhumation of the GHS starting from ~ 41 Ma and driven by the progressive activation of contractional top-to-the-S/SW ductile shear zones from the upper to the lower parts of the GHS (Fig. 6).

<u>Fist stage (Fig. 6A)</u>: Kalopani shear zone activity. After collision at ~ 59 Ma all the GHS undergo prograde metamorphism by underthrusting of the Indian crust below the Asian plate, with increasing P and T conditions. At the time of activation of the Kalopani shear zone only the portion of the GHS confined in the hanging-wall of the Kalopani shear zone underwent exhumation whereas its footwall continued to underwent higher P and T up to ~ 27-26 Ma. At this stage the first melting processes, occurred during increasing metamorphic conditions, as is recorded in kyanite-gneiss from the lower part of the GHS (~ 41-36 Ma by U-Th-Pb on monazite; Carosi et al., 2015). The shift in attaining maximum metamorphism of the two portions of the GHS separated by the Kalopani shear zone, i.e. between its hanging wall and footwall, was therefore triggered by the motion of the Kalopani shear zone between ~ 41 and 31 Ma.

<u>Second stage (Fig. 6B)</u>: HHD activity. Later, at ~ 26-25 Ma deformation ceased along the Kalopani shear zone and shifted downward with the activation of the HHD, both the hanging wall and footwall of the Kalopani shear zone (now incorporated in the hanging wall of the HHD) were exhumed. The footwall of the HHD (the portion of GHS delimited by the HHD and the MCT) continued to undergo increasing P and T moving downward to the North. At this time the intrusion of the first High Himalayan Leucogranites occurred (~ 25-24 Ma) facilitated by the decompression of the upper part of the GHS (e.g. Bura Buri leucogranite in Western Nepal; Carosi et al., 2013).

<u>Third stage (Fig. 6C)</u>: MCTZ activity; 17-13/11Ma. In the time span 17-13 Ma in Western Nepal (Montomoli et al, 2013), 22-16 Ma in Central Nepal (Catlos et al., 2001) and 17-11 Ma in Sikkim (Anczkiewicz et al., 2014), deformation along the HHD ceased (Carosi et al., 2010) and the MCTZ became active resulting in the overall exhumation of the GHS. At this stage, the metamorphism was shifted to the Lesser Himalayan Sequence. When deformation shifted further downward reaching the MCTZ, the entire GHS underwent exhumation and then retrogression. Overall generalized decompression of the GHS facilitated the generation of melts mainly emplaced in the upper GHS between ~ 24 and 17 Ma.

The later incorporation of slices which were of the LHS in the belt is marked by P-T paths with significantly lower peak pressures and different shapes (hairpin P-T paths, e.g. Kohn et al., 2001, 2008; Rolfo et al., 2015; Iaccarino et al., 2017a). Subsequently, additional slices of the LHS were incorporated in the crustal wedge recording progressively lower P-T values and activating a duplexing mechanism (Larson et al., 2013; Robinson and Martin, 2014; Mottram et al., 2015).

7. What is the role of the STDS in the exhumation of the GHS?

The STDS has been often regarded as a continuous system of normal-sense shear zones and low- to high-angle normal faults active at the same time all over the length of the belt (Godin et al., 2006). In the last few years new data show a more complex deformation history with different times of activation of the STDS in different parts of the belt (e.g. Leloup et al., 2010; Montomoli et al., 2017b; Iaccarino et al., 2017b). According to Carosi et al. (2013) in Western Nepal a large body of High Himalayan leucogranite intrudes the STDS at ~24 Ma, with no evidences of later brittle reactivation neither in the leucogranite nor in the country rocks above it. Further to the North / North-East the intrusion of the Mugu granite (Western Nepal) occurred later at ~ 19 Ma (Harrison et al., 1999) so that the STDS was active before ~ 24 and ~ 19 Ma respectively. According to Liu et al. (2017) the motion of the STDS terminated before ~ 20 Ma in the Yadong area. Younger ages at ~16 Ma for the ductile strand of the STDS have been recently reported by Cottle et al. (2015) in the Mt. Everest section and ~ 13 Ma for the upper brittle fault of the STDS by Schultz (2017). Ages up to ~13-11 Ma in Western Bhutan have been reported by Kellett et al., (2009, 2010) and Montomoli et al. (2017a). This suggests the lack of a continuous and contemporaneous activity of the structures of the STDS along the strike of the Himalaya (Kellett et al., 2013). As a consequence the STDS cannot play the role of the main shear zone required to exhume all the GHS at the same time. The different ages of the STDS suggest that it can be episodically activated as a consequence of the transient thickening of the belt as shear zones or thrusts are activated to the south. This process is diachronous along the belt as testified by different timing of activation of the STDS and could be sporadically coupled with the MCT, as proposed for Eastern Himalayas by Chambers et al. (2011). According to Weinberg (2016) the whole Himalayan belt is like a self-organizing system activating different structures in different times and not all the thrusts or shear zones (both normal and thrust-sense) show the same age in response to the continuous northward indentation of India into Asia.

8. Conclusions

Geological mapping of the Himalayan belt is far away to be exhaustively completed. Anyway during the last 20, and particularly during the last years, it has been notably improved due to a new multidisciplinary approach.

The classical geological maps, mainly based on field work, are going to be substituted by a new generation of geological maps based on the integration of field work, remote sensing, meso- and micro-structural analysis, petrology and in-situ geochronology.

This new approach led to recognise and to map a regional-scale discontinuity in the GHS (HHD) from Western Nepal to Bhutan active between c. 27 and 17/16 Ma, well-comparable with the MCT. This tectonic structure plays a fundamental role in ~~a~~ better understanding of the tectonic and metamorphic evolution of the mid-crust involved in the Himalayan belt for two main reasons. GHS is now divisible by the HHD in two tectonic units: the upper GHS and the lower GHS.

Recent studies in several transects perpendicular to the belt clearly demonstrated a shift from upper to lower GHS in the activation of thrust-sense shear zones. At 41-28 Ma deformation likely concentrated in the upper GHS (e.g. Kalopani shear zone stage) and at 27-17/16 Ma deformation shifted downward localizing along the HHD. Further deformation shifted downward and concentrated along the MCT zone. A progressive shift of deformation form upper GHS to the lower GHS at the regional scale involved the P-T-t evolution of crustal-scale slices. The P-T-t paths of the three main slices making the GHS are of similar shape but the peak P-T are shifted by several Ma in each slice. This mechanism better explains the tectonic and metamorphic evolution of the GHS and LHS starting soon after the collisional stage (Carosi et al., 2016).

The mechanism of shifting the deformation from top to bottom could help in clarifying the position of both the HHD and the MCT. In the section of the belt where the HHD has been clearly detected, mapped and dated there is a clear separation between their structural positions: the HHD is located in corresponding ~~of~~ the sillimanite isograd and at the base of the migmatites in the upper GHS and the MCT is at the base of the lower GHS at the bottom of the garnet + kyanite-bearing paragneiss and mica schist. A clear distinction also occurs in the ages of the two discontinuitites: the HHD is active starting from 27 Ma to 17/16 Ma whereas the MCT is active mostly between 17 and 13/11 Ma.

These new multidisciplinary data could help to unravel the long lasting problem of the location of the MCT in the belt. In Sikkim the location and age of the MCT in the uppermost position in the GHS at the base of the sillimanite+K-feldspar zone could be more properly interpreted as a strand of the HHD whereas the MCT should be shifted in a lower structural position.

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Figure captions

Fig. 1. Schematic geological map of the Himalayan belt showing the main units and tectonic boundaries (modified after Law et al., 2004 and Weinberg, 2016). MFT: Main Frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; STDS: South Tibetan Detachment System; P: Peshawar basin; S: Sutlej basin.

Fig. 2. Features of the HHD segments in Western and Central Nepal at different scale. (A) Panoramic view of the Toijem Shear Zone described in Carosi et al. (2007, 2010); (B) outcrop view of Mangri Shear Zone mylonite described in Montomoli et al. (2013) (modified after Montomoli et al., 2015); (C) kinematic indicators (white mica fishes) pointing a top-to-the-SW sense of shear within the Toijem Shear Zone mylonites (after Carosi et al., 2007); (D) close view of sillimanite-bearing shear bands and kyanite relicts (after Carosi et al., 2002); (E) kinematic indicators (mica fishes and foliation fishes) pointing a top-to-the-SW sense of shear within the Mangri Shear Zone mylonites (after Montomoli et al., 2015); (F) quartz within Mangri Shear Zone mylonites, showing chessboard extinction patterns (after Montomoli et al., 2015) that suggests a minimum deformation temperature of c. 650°C (Kruhl, 1996). Mineral abbreviations as follows: Bt=biotite, Grt=garnet, Ky=kyanite, Pl=Plagioclase, Qtz=quartz, Sill=sillimanite, Tur=tourmaline, Wm= potassic white mica.

Fig. 3. Geological sketch map of the Central and Eastern Himalaya showing the trace of the HHD from Western Nepal, through Sikkim, to Bhutan and its age (modified after Yin, 2006 and Wang et al., 2016). See text for details.

Fig. 4. Schematic geological cross section of the Central-Eastern Himalayan belt showing the main tectonic and metamorphic discontinuities (modified after Wang et al., 2016). Abbreviations as in Figs. 1, 2 plus: MHT: Main Himalayan Thrust; MFT: Main Frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; HHD: Higher Himalayan Discontinuity; OOST: out of sequence thrust; STD: South Tibetan Detachment; HHL: Higher Himalayan Leucogranite; NHD: North Himalaya Dome; GCT: Great Counter Thrust: Oph: ophiolites; LB: Lhasa Block; GB: Gandgese Batholith; SG; Siwalik Group; LHS: Lesser Himalayan Sequence; GHS_L: lower Greater Himalayan Sequence; GHS_U: upper Greater Himalayan Sequence: TSS: Tethyan Sedimentary Sequence.

Fig: 5. Geological map of Western Nepal showing the trace of the HHD recognized along several transects (modified from Fuchs, 1964; Fuchs and Frank, 1970; Carosi et al., 2002, 2007, 2013; Bertoldi et al., 2011; Montomoli et al., 2013; Iaccarino et al., 2017).

MCTz: Main Central Thrust zone; HHD: Higher Himalayan Discontinuity; MSZ: Mangri shear zone; TSZ: Toijem shear zone; STDS: South Tibetan Detachment System; NHD: North Himalaya Dome; LHS: Lesser Himalayan Sequence; GHS_L: lower Greater Himalayan Sequence; GHS_U: upper Greater Himalayan Sequence; HHL: Higher Himalayan Leucogranite; TSS: Tethyan Sedimentary Sequence.

Fig. 6. Sketch of the evolution of the Greater Himalayan Sequence in Western-Central Nepal by progressive activation of top-to-the SW thrust-sense shear zones from the uppermost part of the Greater Himalayan Sequence to the lower part and to the MCT (modified after Montomoli et al., 2013, 2015; Iaccarino et al., 2016 and Carosi et al., 2016).

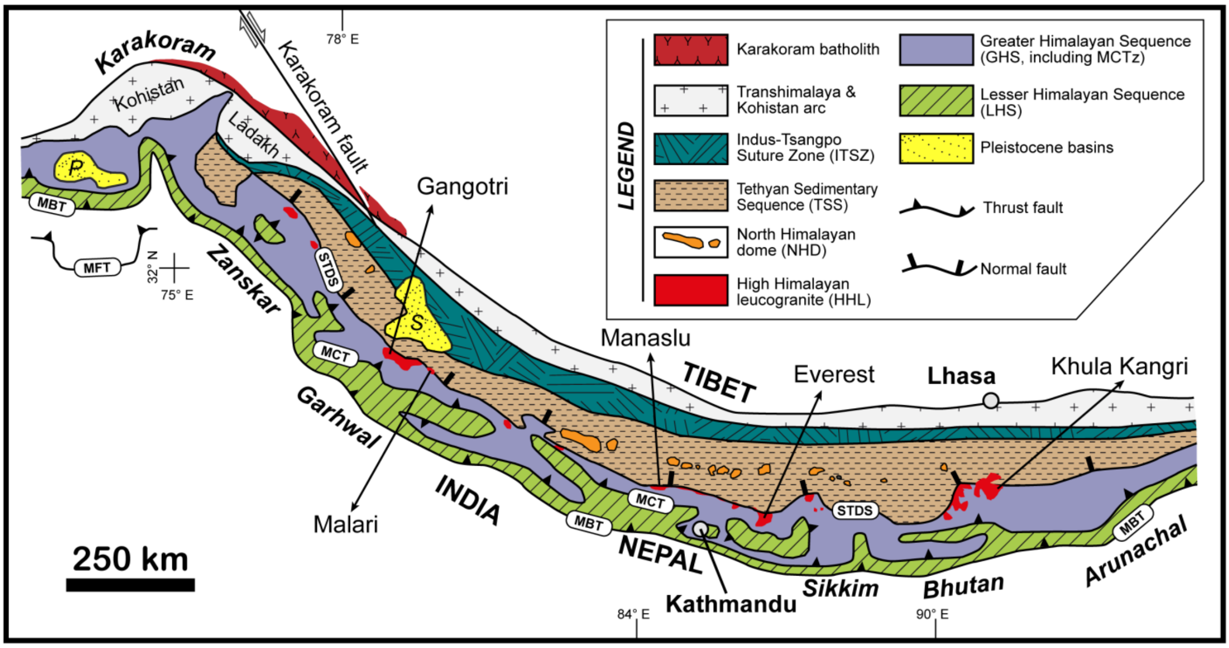
The kinematic path of particles in the hanging wall and footwall of the shear zones in the Greater Himalayan Sequence is shown by dots with different colors. The graphs inserted in the right higher part of each stage represent the schematic evolution of the P-T-t data of the portion of the GHS where the points a, b and c are located. P-T data from Montomoli et al. (2013, 2015), Carosi et al. (2010, 2016) and Iaccarino et al. (2017).

Stage A. After the collisional stage at ~ 59 Ma all the Greater Himalayan Sequence underwent burial and consequent prograde metamoprhism. At c. 41–30 Ma, the uppermost portion of the Greater Himalayan Sequence, located in the hanging wall of the uppermost thrust-sense shear zone (Kalopani shear zone) and below the Tethyan Sedimentary Sequence, was exhuming, whereas the Greater Himalayan Sequence upper and lower, in the footwall, was still undergoing prograde metamorphism.

Stage B. At c. 26–25 Ma, following the activation of the Higher Himalayan Discontinuity, uppermost and upper Greater Himalayan Sequence, now in the hanging wall of the Higher Himalayan Discontinuity started exhumation, whereas rocks in the footwall of the Higher Himalayan discontinuity (Greater Himalayan Sequence lower) were still buried. The older leucogranite (Bura Buri leucogranite in orange color) intruded at ~ 24-25 Ma in the upper part of the Greater Himalayan Sequence cross cutting the STDS (Bertoldi et al., 2011; Carosi et al., 2013) followed by younger Higher Himalayan Leucogranites (orange color) (e.g. Mugu granite at 20-19 Ma; Visonà et al., 2012; Iaccarino et al., 2016).

Stage C. At c. 17–13 Ma, the activation of the Main Central thrust caused the exhumation of all subunits of the Greater Himalayan Sequence (uppermost, upper and lower Greater Himalayan Sequences), and the Lesser Himalayan Sequence was incorporated in the belt, but reaching lower P and T with respect to the Greater Himalayan Sequence. Only from this stage onward the Greater Himalayan Sequences behaved as a unique tectonic unit.

TSS: Tethyan Sedimentary Sequence; Kalopani s.z: Kalopani shear zone; HHD—Higher Himalayan discontinuity; MCT: Main Central Thrust; LHS: Lesser Himalayan Sequence. Not to scale.


Karakoram
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Garhwal
Malari
INDIA
250 km
Manaslu
TIBET
Everest
Lhasa
Khula Kangri
MCT
MBT
STDS
NEPAL
Kathmandu
Sikkim
Bhutan
Arunachal
MBT
84° E
90° E
LEGEND
Karakoram batholith
Transhimalaya & Kohistan arc
Indus-Tsangpo Suture Zone (ITSZ)
Tethyan Sedimentary Sequence (TSS)
North Himalayan dome (NHD)
High Himalayan leucogranite (HHL)
Greater Himalayan Sequence (GHS, including MCTz)
Lesser Himalayan Sequence (LHS)
Pleistocene basins
Thrust fault
Normal fault

Figure 1

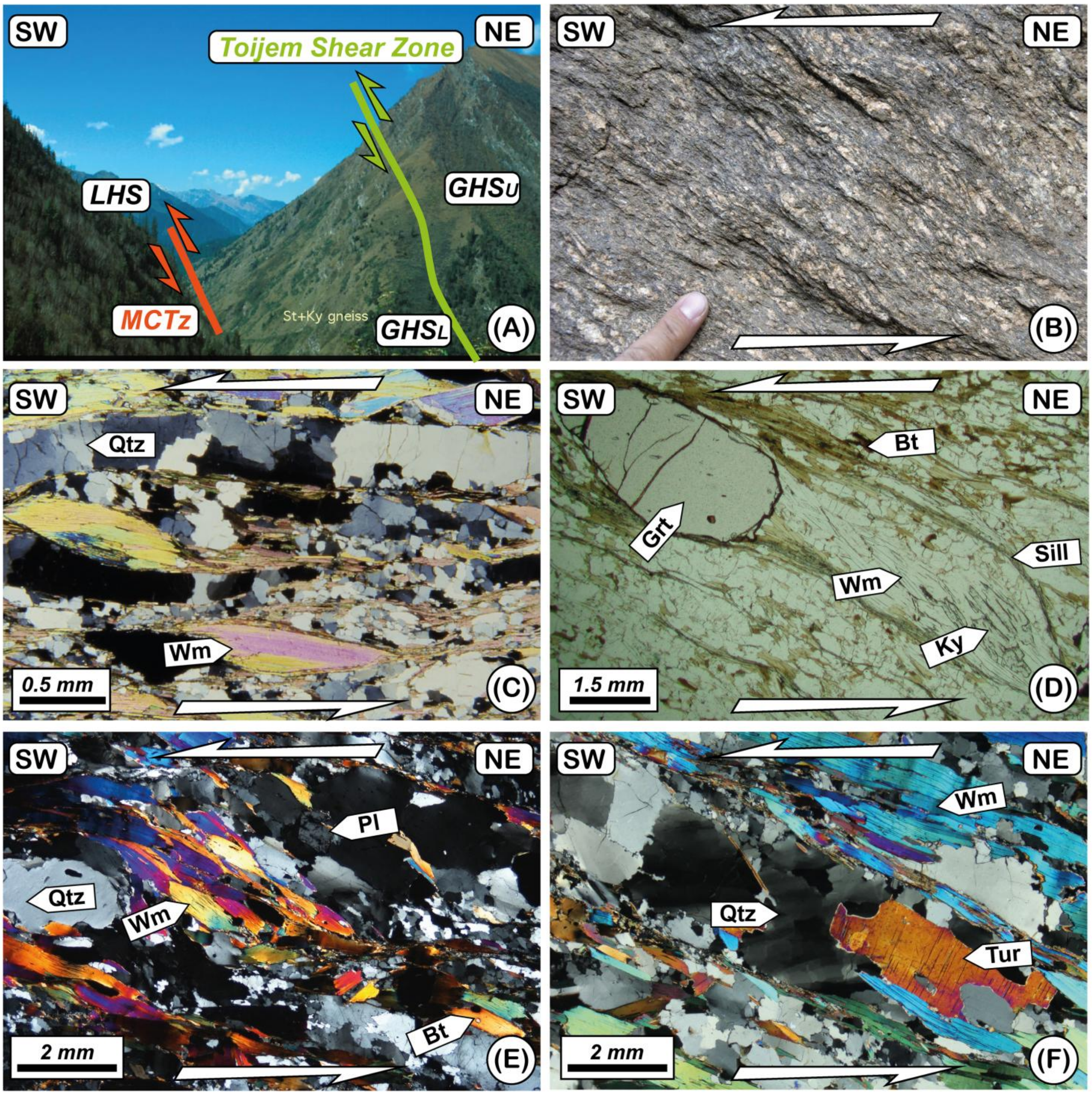
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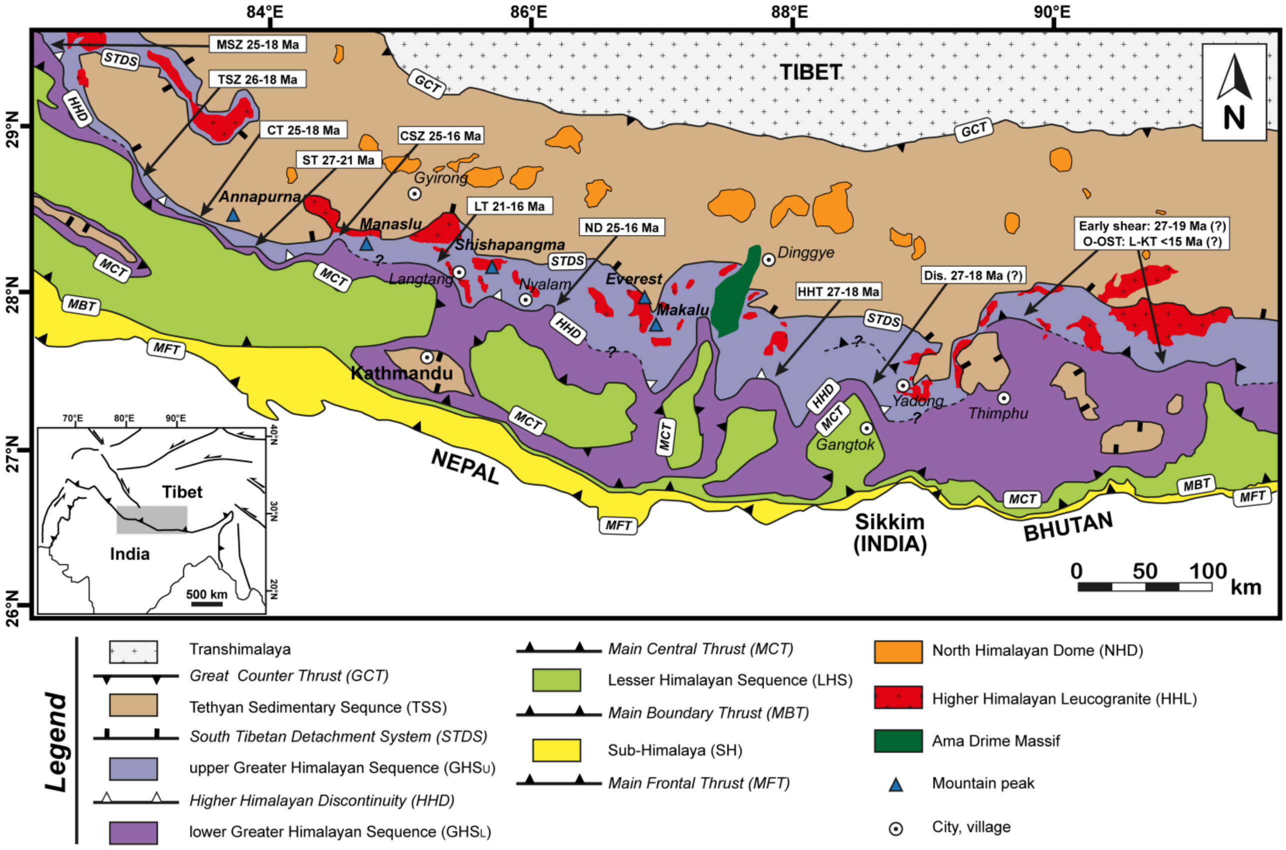
Figure 2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CSZ 25-16 Ma
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LT 21-16 Ma
ND 25-16 Ma
HHT 27-18 Ma
Dis. 27-18 Ma (?)
Early shear: 27-19 Ma (?)
O-OST: L-KT <15 Ma (?)
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MCT
MBT
MFT
Annapurna
Manaslu
Shishapangma
Gyirong
Langtang
Nyalam
Everest
Makalu
Dinggye
Kathmandu
Yadong
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India
500 km
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Transhimalaya
Great Counter Thrust (GCT)
Tethyan Sedimentary Sequnce (TSS)
South Tibetan Detachment System (STDS)
upper Greater Himalayan Sequence (GHSu)
Higher Himalayan Discontinuity (HHD)
lower Greater Himalayan Sequence (GHSL)
Main Central Thrust (MCT)
Lesser Himalayan Sequence (LHS)
Main Boundary Thrust (MBT)
Sub-Himalaya (SH)
Main Frontal Thrust (MFT)
North Himalayan Dome (NHD)
Higher Himalayan Leucogranite (HHL)
Ama Drime Massif
Mountain peak
City, village

Figure 3

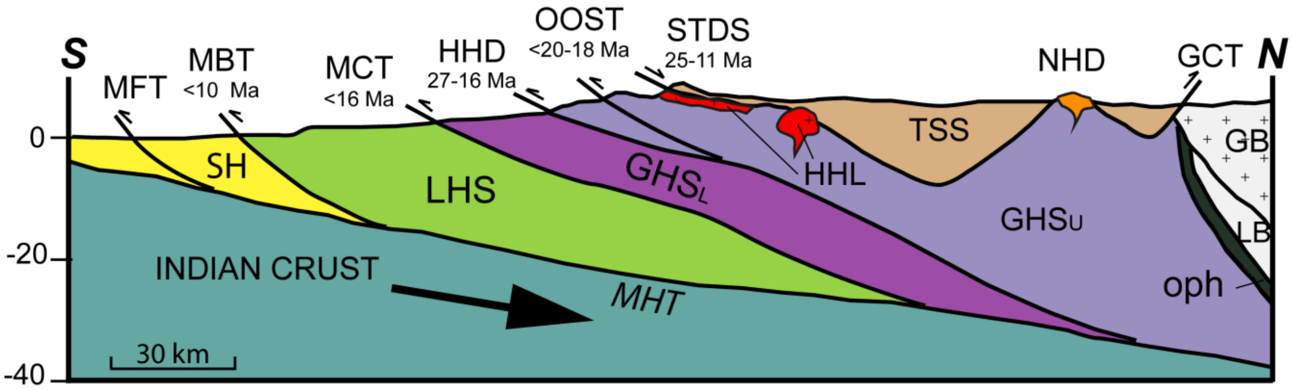
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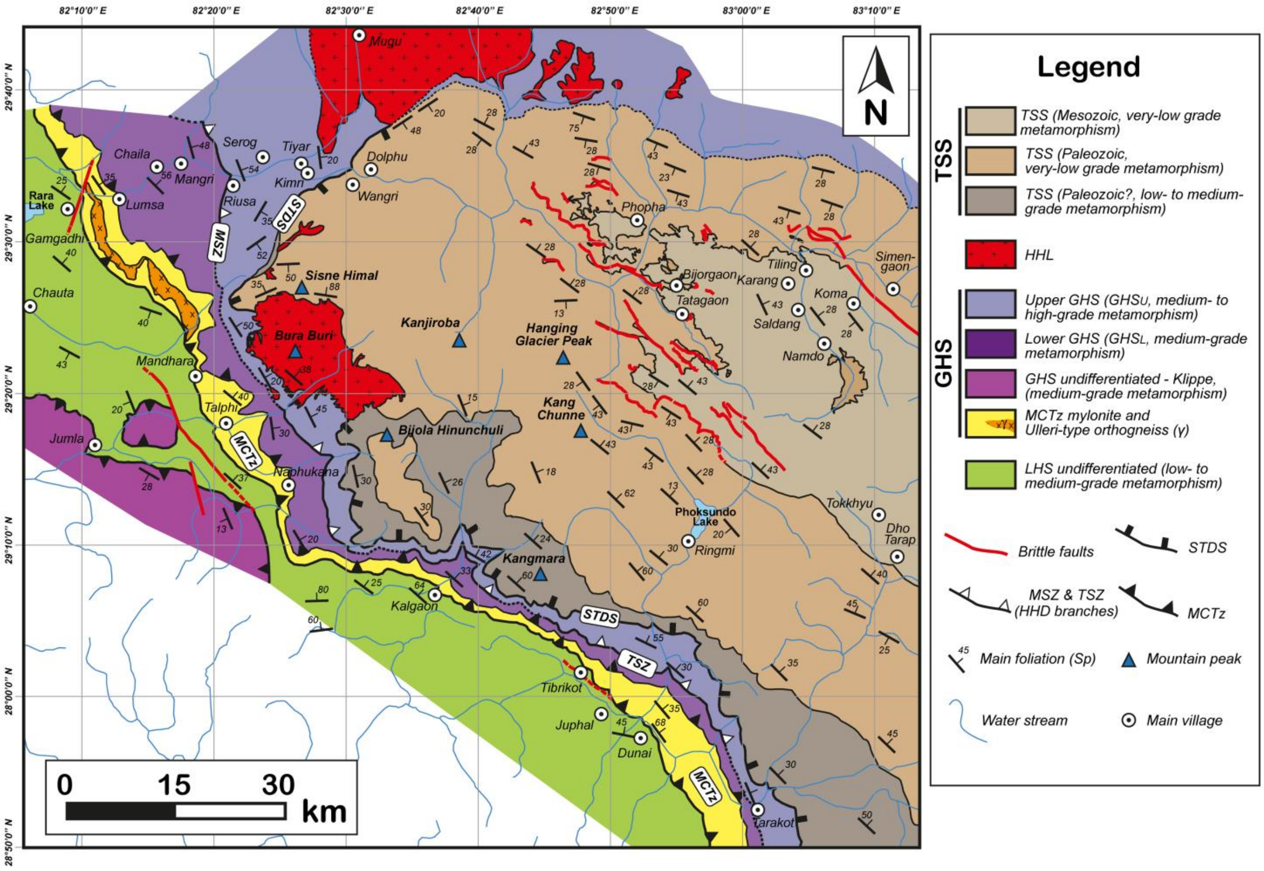
Figure 4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Mangri
Serog
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Kimri
Dolphu
Wangri
Riusa
Lumsa
Rara Lake
Gamgadhi
Chauta
Mandhara
Talphi
Jumla
Naphukana
Sisne Himal
Bura Buri
Kanjiroba
Hanging Glacier Peak
Kang Chunne
Bijola Hinunchuli
Kangmara
Kalgaon
Tibrikot
Juphal
Dunai
Tarakot
Phopha
Bijorgaon
Tatagaon
Karang
Tiling
Koma
Saldang
Namdo
Simen-gaon
Phoksundo Lake
Ringmi
Tokkhyu
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TSS
TSS (Mesozoic, very-low grade metamorphism)
TSS (Paleozoic, very-low grade metamorphism)
TSS (Paleozoic?, low- to medium-grade metamorphism)
HHL
GHS
Upper GHS (GHSU, medium- to high-grade metamorphism)
Lower GHS (GHSL, medium-grade metamorphism)
GHS undifferentiated - Klippe, (medium-grade metamorphism)
MCTz mylonite and Ulleri-type orthogneiss (γ)
LHS undifferentiated (low- to medium-grade metamorphism)
Brittle faults
STDS
MSZ & TSZ (HHD branches)
MCTz
Main foliation (Sp)
Mountain peak
Water stream
Main village

Figure 5

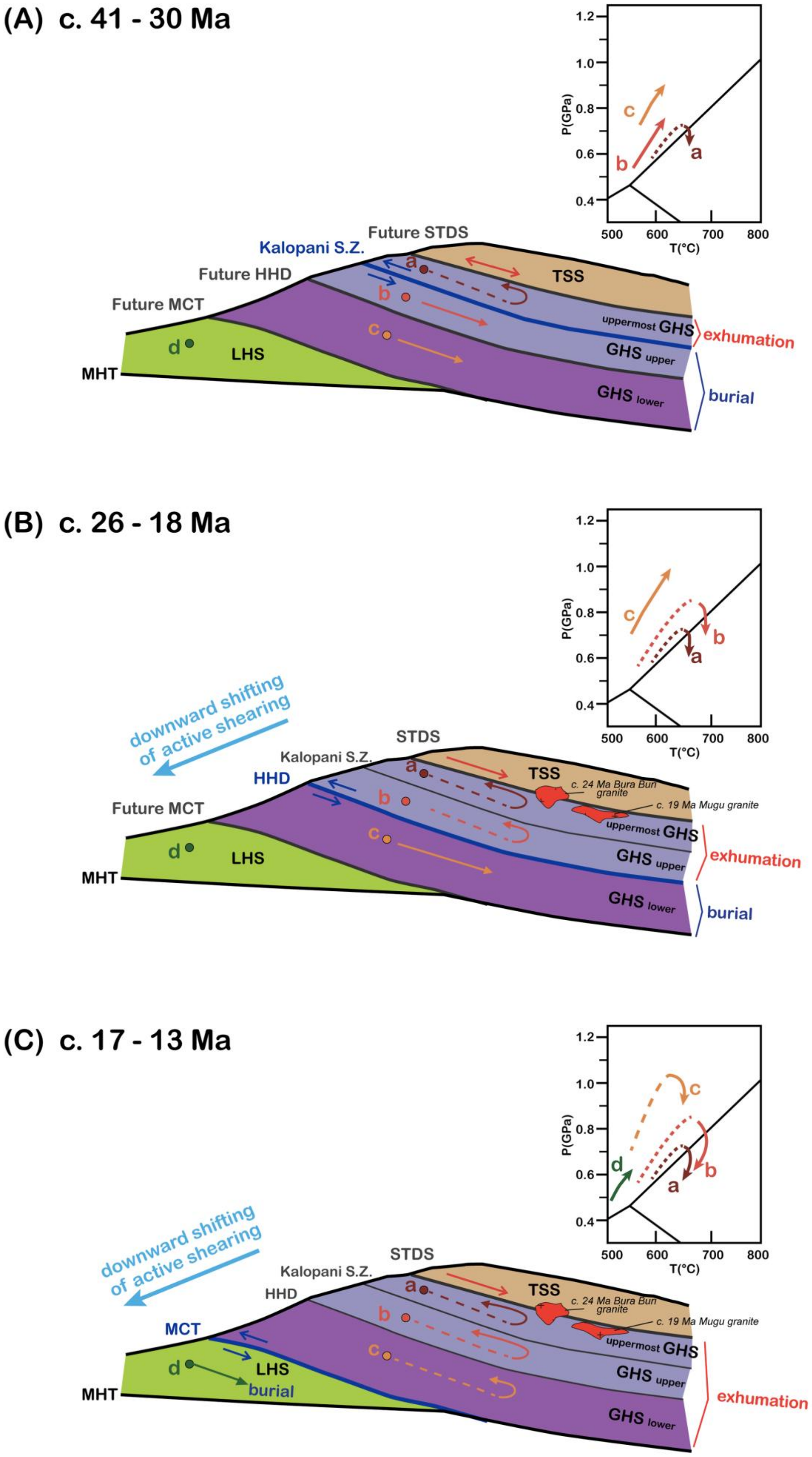
(A) c. 41 - 30 Ma
1.2
1.0
0.8
0.6
0.4
P(GPa)
500
600
700
800
T(°C)
a
b
c
Future STDS
Kalopani S.Z.
Future HHD
Future MCT
MHT
TSS
uppermost GHS
GHS upper
GHS lower
LHS
d
exhumation
burial
(B) c. 26 - 18 Ma
downward shifting of active shearing
STDS
Kalopani S.Z.
HHD
c. 24 Ma Bura Buri granite
c. 19 Ma Mugu granite
(C) c. 17 - 13 Ma
MCT
burial

Figure 6