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Middle to late Eocene exhumation of the Greater Himalayan Sequence in the Central Himalayas: Progressive accretion from the Indian plate

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Abstract:	In the Kali Gandaki valley (central Nepal), a ductile, high-temperature, contractional shear zone with a top-to-the-SW sense of shear, known as Kalopani Shear zone (KSZ), is located within the uppermost part of the Greater Himalayan Sequence (GHS). We mapped and investigated this shear zone in in detail, in order to unravel its age and role in the evolution of the GHS. Pseudosection modeling and inverse geothermobarometry reveal that rocks involved in the KSZ experienced pressure-temperature conditions between 0.6-0.85 GPa and 600-660°C. U-Th-Pb in-situ LA-ICP-MS and SHRIMP dating on monazite point to retrograde metamorphism related to the KSZ starting from ~ 41-30 Ma. The kinematics of the KSZ and associated erosion and/or tectonics, caused the Middle-Late Eocene exhumation of the GHS in the hanging wall of the KSZ zone at least nine million years before the activities of the High Himalayan Discontinuity, the Main Central Thrust, and the South Tibetan Detachment. Structural data, metamorphic conditions and geochronology from the KSZ, compared to those of other major tectonic discontinuities active within the GHS in the Kali Gandaki valley, indicate that shear deformation and exhumation were not synchronous but migrated downward and southward at different lower levels within the GHS. These processes caused the exhumation of the hanging-wall rocks of the activated shear zones. The main consequence of this tectonic is that exhumation was driven by an insequence shearing mechanism progressively involving new slices of the Indian crust and not solely by the coupled activity of Main Central Thrust and South Tibetan Detachment.					
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Middle to late Eocene exhumation of the Greater Himalavan 1 Sequence in the Central Himalayas: progressive accretion 2 from the Indian plate 3

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17 18

19 ABSTRACT

20 In the Kali Gandaki valley (central Nepal), a ductile, high-temperature, contractional shear zone 21 with a top-to-the-SW sense of shear, known as Kalopani Shear zone (KSZ), is located within the 22 uppermost part of the Greater Himalayan Sequence (GHS). We mapped and investigated this shear 23 zone in in detail, in order to unravel its age and role in the evolution of the GHS.

24 Pseudosection modeling and inverse geothermobarometry reveal that rocks involved in the KSZ 25 experienced pressure-temperature conditions between 0.6-0.85 GPa and 600-660°C. U-Th-Pb in-

26 situ LA-ICP-MS and SHRIMP dating on monazite point to retrograde metamorphism related to the

27 KSZ starting from ~ 41-30 Ma. The kinematics of the KSZ and associated erosion and/or tectonics,

28 caused the Middle-Late Eocene exhumation of the GHS in the hanging wall of the KSZ zone at

- 29 least nine million years before the activities of the High Himalayan Discontinuity, the Main Central
- 30 Thrust, and the South Tibetan Detachment.

31 Structural data, metamorphic conditions and geochronology from the KSZ, compared to those of 32 other major tectonic discontinuities active within the GHS in the Kali Gandaki valley, indicate that 33 shear deformation and exhumation were not synchronous but migrated downward and southward at 34 different lower levels within the GHS. These processes caused the exhumation of the hanging-wall 35 rocks of the activated shear zones. The main consequence of this tectonic is that exhumation was 36 driven by an in-sequence shearing mechanism progressively involving new slices of the Indian crust 37 and not solely by the coupled activity of Main Central Thrust and South Tibetan Detachment.

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39 Key words: Himalaya, Exhumation, Greater Himalayan Sequence, monazite geochronology, 40 pseudosections, P-T-t-D paths, Kalopani shear zone, in-sequence shearing, Kali Gandaki valley.

41

42 1. INTRODUCTION

43

44 The understanding of exhumation mechanisms of deep-seated metamorphic rocks in collisional 45 orogens has been greatly improved by the discovery of contemporaneous contractional and normal-46 sense shear zones in the same vertical section in orogenic belts. The normal sense top-to-the-NE 47 South Tibetan Detachment (STD) and the contractional top-to-the-SW Main Central Thrust (MCT), 48 bounding the crystalline core of the belt, the Greater Himalayan Sequence (GHS), in the Himalayas, to the top and to the bottom respectively, are regarded as the most classic example of a coupled 49 50 tectonic system of faults/shear zones acting contemporaneously with opposite kinematics (Burchfiel 51 et al., 1992; Hodges et al., 1992) in the time span between ~23 and 17 Ma (Godin et al., 2006). The 52 GHS, one of the major tectonic units in the Himalayan belt, is composed of medium- to high-grade 53 metamorphic rocks and exposed for nearly 2400 km along the orogen (Hodges, 2000; Yin 2006) 54 with references). This unit has been regarded as a continuous and coherent slice and attention has 55 been paid almost exclusively on the boundary shear zones/faults, especially when formulating 56 tectonic and exhumation models related to: i) channel flow (Beaumont et al., 2001; Grujic, 2006), 57 ii) wedge extrusion (Hodges et al., 1996; Grujic et al., 1996), iii) channel flow followed by 58 extrusion (Godin et al., 2006; Cottle et al. 2015 with references), iv) wedge insertion (Webb et al., 59 2007), and v) critical taper wedge (Kohn, 2008). Only in the critical taper wedge model the 60 contemporaneous activity of the MCT and STD is not required.

61 Faults or shear zones inside the GHS, such as the Kakthang thrust in Bhutan (Daniel et al., 2003), 62 the Kalopani shear zone (Nepal, Vannay and Hodges, 1996; Godin, 2003; Searle, 2010), the Modi 63 Khola shear zone (Nepal, Hodges et al., 1996), and the Nyalam thrust (Nepal, Wang et al., 2013), 64 have been interpreted as out-of-sequence thrusts (Mukherjiee et al., 2012 with references). In the 65 last few years, growing evidence of the occurrence of shear zones and metamorphic discontinuities 66 has been reported from several places within the GHS along the belt from western Nepal to Sikkim. 67 A jump in the metamorphic conditions, between the upper portion of the GHS and the lower GHS, 68 has been reported by several authors (Carosi et al., 2007, 2010; Groppo et al., 2009; Corrie and 69 Kohn, 2011; Yakymchuck and Godin, 2012; Imayama et al., 2012; Rubatto et al., 2013; Kohn et al., 70 2004; Kohn 2008; Larson et al., 2010, 2013, 2015; He et al., 2015; Montomoli et al., 2013, 2015 for 71 a review; Cottle et al., 2015; Khanal et al., 2015; Iaccarino et al., 2015; Wang et al., 2015). 72 Moreover, a regional-scale tectonic and metamorphic discontinuity, separating the upper GHS from 73 the lower GHS - called the High Himalayan Discontinuity (HHD: Montomoli et al., 2013; 2015) -74 has been recognized in the Central Himalayas (Fig. 1a). The HHD was active before the activation 75 of the MCT, since ~ 28-25 Ma, with a top-to-the-SW sense of shear. Here, we strictly follow the

definition of the HHD proposed by Montomoli et al. (2013) avoiding referring to it as a "thrust"
because it is a ductile shear zone.

78 The activation of the HHD triggered the early exhumation of the upper GHS in the Central 79 Himalayas before the classical 23-17 Ma time span for the MCT-STD coupled activity (Montomoli 80 et al., 2013; 2015). Despite an apparent partial overlap in the activity of the HHD and MCT, the 81 HHD is always older and located in a higher structural position with respect to the MCT along the 82 same section of the belt (Montomoli et al., 2015, Table 1). Iaccarino et al. (2015) reported the 83 occurrence of a tectono-metamorphic discontinuity in the Kali Gandaki section, > 1 km north of the 84 MCT at Dana village (Fig. 1) (Le Fort, 1975; Colchen et al., 1986; Vannay and Hodges, 1996). This 85 discontinuity in the Kali Gandaki section correlates with the HHD in western Nepal and was active 86 between 25 and 18 Ma (Iaccarino et al., 2015).

In order to unravel the tectonic and metamorphic history of the GHS we investigate a further ductile shear zone in the Kali Gandaki valley (Central Nepal): the Kalopani shear zone (KSZ; Vannay and Hodges, 1996) (Fig. 1b, 2), by detailed mapping, meso- and microstructural analyses, U-Th-Pb monazite dating, and pressure-temperature (P-T) pseudosection modelling. The KSZ is the structurally highest contractional top-to-the-SW shear zone up to now recognized in the GHS. According to ⁴⁰Ar/³⁹Ar cooling ages on white mica it was active before 15-13 Ma (Vannay and Hodges, 1996) and possibly also between 22.5 and 15 Ma (Godin et al., 2001).

Monazite radiometric dating in structural and metamorphic context resulted in older ages for the activity of the KSZ and for the exhumation of the uppermost part of the GHS, which cannot be explained by the most popular tectonic models proposed for the Himalaya. Therefore, we propose a different model of exhumation of the GHS that takes into account the older ages and the occurrence of three different shear zones within the GHS along the same transect.

99

100 2. GEOLOGICAL SETTING

101

102 2.1 Himalayan Units

The Himalayan mountain belt (Fig. 1a) evolved after the collision between the Asian and Indian
continental plates at ~ 55-50 Ma (Hodges, 2000; Najman et al., 2010). This collision occurred after
the break-up of Gondwana and the evolution of a long last-standing Andean-type active margin,

106 caused by the subduction of Neo-Tethys oceanic crust below the Lhasa Block, accompanied by the

- 107 intrusion of large granitoid bodies and accretion of arc terranes. The Himalayan belt is subdivided
- 108 into four main tectonic zones, separated by regional-scale tectonic discontinuities that can be
- 109 followed along the entire length of the belt (Gansser, 1964; Le Fort, 1975; Upreti, 1999; Hodges,

110 2000; Yin, 2006). In a north–south transect perpendicular to the belt in Nepal, these principal

111 tectonic zones are from south to north, the Terai, the Siwalik (Sub-Himalayan), the Lesser

112 Himalayan Sequence (LHS), the GHS and the Tethyan Sedimentary Sequence (TSS). The Terai

unit is the northern edge of the alluvial plain of the Ganges and Indus rivers (Indo-Gangetic Plain),

the foreland basin of the Himalaya with the most recent alluvial sediments (Upreti, 1999). The Sub-

115 Himalayan unit (Siwalik Group) represents the foreland basin, made up by a Tertiary molasse in a

sedimentary sequence that varies from 2 to 10 km in thickness (DeCelles et al., 1998; Upreti, 1999;

117 White et al., 2002; Szulc et al., 2006).

118 The LHS is bound at the base by the Main Boundary Thrust and at the top by the MCT, a regional

thrust sense shear zone (Fig. 1a) which separates it from the overlying GHS. Both thrusts show a

120 top-to-the-S sense of movement. Since the MCT is not a single thrust, but a thick ductile to brittle

121 shear zone, with a variable thickness (100 m up to several km: Searle et al., 2008), it is often

122 referred as the Main Central Thrust Zone (MCTZ) to identify the package of sheared rocks.

123 According to Stephenson et al. (2001) both GHS and LHS rocks are ductilely sheared by the MCT

124 activity, with the latter ductilely incorporated in the MCTZ during the shear zone activity.

125 The LHS mainly consists of lower greenschist- to lower amphibolite-facies clastic metasedimentary

126 rocks, organized according to a structurally complex system of fold-and-thrust nappes (De-Celles et

127 al., 1998; Robinson & Martin, 2014). The original sedimentary pile was 8–10 km thick, as

128 suggested by Schelling (1992) using palinspastic reconstructions. The predominant rock types are

impure quartzite and psammitic slate, phyllite and schist, with subordinate impure marble,

130 metamorphosed mafic rock and augen gneiss (Upreti, 1999; Hodges, 2000; Yin, 2006).

131 The GHS, a continuous belt of Late Proterozoic to Cambro-Ordovician medium- to high-grade

132 metasedimentary and metaigneous rocks with associated Miocene leucogranites (Le Fort, 1975;

133 Carosi et al., 1999; Upreti, 1999; Hodges, 2000; Visonà and Lombardo, 2002; Yin, 2006; Visonà et

al., 2012), represents the metamorphic core of the Himalaya, forming the central part of the belt,

and is often associated with the highest topographic relief.

136 The uppermost tectonic domain to the north is the TSS, which is tectonically separated from the

137 lower GHS by a system of normal faults and ductile shear zones (STDS) (Caby et al., 1983; Burg et

138 al., 1984; Burchfiel et al., 1992; Carosi et al., 1998, 2002; Law et al., 2004; Searle, 1999; 2010)

139 active up to 13-11 Ma in the eastern Himalaya (Kellett et al., 2009; Montomoli et al., 2015). The

140 TSS comprises a nearly continuous sequence of Palaeozoic to Eocene sediments, which were

- 141 deposited on the northern passive margin of the Indian plate (Gaetani and Garzanti, 1991). The
- 142 rocks of the TSS experienced mostly very low-grade metamorphic conditions. A higher
- 143 metamorphic grade corresponding to the greenschist facies up to the lower amphibolite facies

- 144 occurs only at the base of the sequence in the Cambro-Ordovician rocks affected by the activity of
- 145 STDS (Godin et al., 1999; Crouzet et al., 2007; Antolin et al., 2011; Dunkl et al., 2011) and in other
- sporadic localities (Montomoli et al., in press). To the north, the TSS is bounded by flysches and
- 147 ophiolites (often with a blueschist metamorphic imprint) of the Indus-Tsangpo suture zone.
- 148

149 **2.2 The Greater Himalayan Sequence**

The GHS has been classically subdivided into three litho-tectonic units (Le Fort, 1975; Colchen et
al., 1986; Vannay and Hodges, 1996; Searle and Godin, 2003; Carosi et al., 2014):

- Unit 1 is the base of the GHS consisting predominantly of clastic metasedimentary rock, such as
biotite-muscovite-garnet-kyanite gneiss, and subordinate micaschist and phyllite, calc-schist,
quartzite, and migmatitic gneiss (Hodges, 2000; Carosi et al., 2014, 2015; Iaccarino et al., 2015).
Unit 1 has been traditionally considered as a uniform crustal section with a variable thickness from
1 km to more than 20 km along strike (Le Fort, 1975). Iaccarino et al. (2015) describe the presence
of a tectono-metamorphic discontinuity active at 25-18 Ma and correlated it with the HHD of
Montomoli et al. (2015) dividing unit 1 in two sub-units.

- Unit 2. A 2-4 km thick sequence of amphibolite-facies, banded calc-silicate gneiss, paragneiss,
marble and amphibolite represents unit 2. The boundary between units 1 and 2 is parallel to the
compositional layers in both units. Its transition is gradual and highlighted by changes in mineral
composition.

163 - Unit 3. Orthogneiss, migmatite and minor marble, metapelite and calc-silicate make up unit 3 164 (Vannay and Hodges, 1996; Godin et al., 2001; Searle, 2010). The orthogneiss is Cambrian-165 Ordovician in age (Godin et al., 2001) and was intruded by a network of Miocene sills and 166 leucogranitic dykes. Isotopic Rb-Sr data indicate that the protoliths of unit 3 are entirely Cambrian-167 Ordovician in age (Pognante et al., 1990) in agreement with U-Pb zircon and monazite ages (Godin 168 et al., 2001). The uppermost part of unit 3 was affected by the Annapurna Detachment (Fig. 1b), a 169 strand of the STDS. Unit 3 includes the Largjung Formation (Colchen et al., 1986), characterized by 170 poly-deformed metapelites and marbles (Colchen et al., 1986; Vannay and Hodges, 1996). The 171 orthogneiss was affected by the ductile KSZ (Vannay and Hodges, 1996; Godin et al., 2001; Godin 172 et al., 2003; Searle, 2010; Carosi et al., 2014) (Fig. 1b). This zone is mainly characterized by highly 173 strained orthogneiss and migmatitic gneiss, with a top-to-the-S sense of shear.

The main fabric in the GHS is a pervasive transposition foliation formed during a second deformation phase (S₂; Vannay and Hodges, 1996; Carosi et al., 2010, 2014, 2015; Iaccarino et al., 2015). This fabric is often recognizable as a shear band cleavage as defined by Passchier and Trouw (2005). The GHS in the Kali Gandaki valley (Fig. 1b) shows a homoclinal attitude (Brown and 178 Nazarchuk, 1993; Vannay and Hodges, 1996). The S₂ foliation typically strikes NW-SE and dips 179 30° - 60° toward the NE. It is marked by the preferred orientation of metamorphic minerals and 180 recrystallized quartz ribbons. Kyanite, staurolite, white mica, and biotite are occasionally bent or 181 kinked along shear bands. Top-to-the-S/SW sense of shear is marked by C-S fabric, shear bands, 182 asymmetric tails around porphyroclasts, and rotated garnets within the mylonites of the lower 183 portion of the GHS affected by the deformation of the MCTZ. The elongation lineation (L₂) trends 184 NE-SW and plunges NE (20°-60°). S₁, formed during D1 deformation, is sometimes preserved as a 185 relict in D2 fold hinges (F₂) and S₂ microlithons and as internal foliation in porphyroblasts (Carosi 186 et al., 2010; Vannay and Hodges, 1996).

The GHS at the regional scale underwent at least two later folding phases, characterized by nearly orthogonal NW - SE and NE - SW trending fold axes, resulting in kilometer-scale open folds with steeply dipping axial planes. These folds, well-exposed in western Nepal, affected the tectonic boundaries (Upreti, 1999; Carosi et al., 2002, 2007; Antolin et al., 2012) and have also been described eastward in the Mt. Everest-Mt. Makalu region, Sikkim and Bhutan (Lombardo et al., 1993; Carosi et al., 1999; Schelling, 1992).

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194 **3. THE KALOPANI SHEAR ZONE**

195

196 The upper part of the GHS in the Kali Gandaki valley (Fig. 2) consists of orthogneisses (Fig. 3), 197 paragneisses, micaschists, and calsilicates (Bordet et al., 1971; Colchen et al., 1980, 1986; Brown 198 and Nazarchuk, 1993; Vannay and Hodges, 1996; Godin, 2003; Searle, 2010; Carosi et al., 2014). 199 The sequence is affected by a 20-50 m thick ductile shear zone, the KSZ (Vannay and Hodges, 200 1996; Carosi et al., 2014) (Fig. 1b, 2), which crops out ~ 1 km north of Kalopani village and can be 201 followed for at least 4-5 km to the SE, south of the village of Taglung (Figs.1b, 2). It is hosted in 202 augen gneisses, paragneisses and micaschists and strikes NW-SE moderately dipping to the NE. 203 The elongation lineation trends NE-SW and plunges 30°-40° to the NE (Fig. 2). Deflected foliation, 204 S-C-C' fabric, mica-fish and sigma-type porphyroclasts (Fig. 3) confirm the top-to-the-SW sense of 205 shear proposed by previous authors (Vannay and Hodges, 1996; Godin, 2003; Carosi et al., 2014).

Two samples from the shear zone (KL-21 and KL-19; Fig. 2) have been investigated for metamorphic evolution and geochronology of monazite. Sample KL-21 is a two mica-bearing orthogneiss (Fig. 3, 4) whereas sample KL-19 is a garnet-staurolite-bearing paragneiss (Fig. 4). Both samples show a coarse-grained spaced anastomozing foliation (S₂) outlined mainly by the dynamic recrystallization of biotite, muscovite, and quartz (Fig. 4). In both samples porphyroclasts, represented by feldspars in KL-21 and by garnet and staurolite in KL-19, are wrapped around by the 212 main foliation (Fig. 4). Garnet has pre-kinematic cores (Fig. 4a–b) that are enriched in inclusions of 213 magnetite, ilmenite, quartz and chlorite, defining an internal foliation (S_i), which is discordant with 214 the main external foliation (S_e). The garnet rims are inclusion-free. Staurolite porphyroclasts are 215 boudinaged with recrystallization of biotite between boudin necks.

216 Microstructures in both samples point to a high-temperature deformation regime. Lobate grain 217 boundaries between quartz and quartz/feldspar and pinning and window microstructures, which 218 developed between quartz and biotite crystals (Fig. 4c-d), indicate a grain boundary migration 219 mechanism for quartz recrystallization (Passchier and Trouw, 2005). Chessboard extinction in 220 quartz (Carosi et al., 2014) due to simultaneous activity of basal and prismatic slip systems or α - β 221 quartz transition indicates a T of deformation $\geq 630^{\circ}$ C (Passchier and Trouw, 2005). Myrmekites 222 abundant in feldspar porphyroclasts developed in sample KL-21 and confirm a high-temperature 223 deformation regime (Carosi et al., 2014). Main kinematic indicators at the microscale are mica fish 224 (type 1, 4 and 5 of Passchier and Trouw, 2005), C-S fabric (Fig. 4a) and rare asymmetric 225 myrmekites in feldspar. All kinematic indicators support a top-to-the-S sense of shear.

226

227 4. METAMORPHIC EVOLUTION

228 4.1 Analytical Methods

229 Mineral chemical compositions (except for monazite see below) and X-ray maps were acquired 230 using a CAMECA SX100 electron microprobe (EMP) at the Institut für Mineralogie und 231 Kristallchemie (Universität Stuttgart) equipped with five wavelength-dispersive spectrometers. For 232 chemical analyses an accelerating voltage of 15 kV and a beam current of 15 nA were used. The 233 beam spot size was 5 µm. Synthetic and natural standards were used for EMP calibration. The 234 analytical uncertainties in the method applied are reported in Massonne (2012). X-ray maps were 235 acquired by stepwise movement under an electronic beam of 50 nA and subsequent computer aided 236 evaluation. Representative garnet X-ray maps and profiles are presented in Fig. 5. Selected 237 chemical compositions of the main phases are reported in Table 1. KL-19 bulk rock composition 238 was obtained with XRF analyses of thin section chip at the Dipartimento di Scienze della Terra 239 (Università di Pisa), following the analytical protocol of Tamponi et al. (2002).

240

241 **4.2 Strategy to estimate P-T conditions**

In order to constrain the metamorphic evolution of paragneiss KL-19, a P-T pseudosection has been constructed with the software PERPLE_X (Connolly, 2005) in the MnNCKFMASHTO system and in the P-T range of 0.3-1.3 GPa and 400-800 °C, respectively (Fig. 6). The bulk rock composition used for the pseudosection is (in wt%) $SiO_2 = 67.08$, $TiO_2 = 0.60$, $Al_2O_3 = 11.23$, $F_2O_{3tot} = 15.42$, MgO = 1.76, MnO = 0.04, CaO = 0.55, Na₂O = 0.80, K₂O = 1.86, P₂O₅ = 0.09, LOI = 0.41. The rock composition is very high in iron and falls in the Fe-sand field of Herron (1988).

Since sample KL-19 contains magnetite and ilmenite as opaque minerals, the assumption of total iron as bivalent is not supported and some amount of trivalent iron must be considered. The observed modal amount of magnetite determined by point counting under reflected light yielded 5 % volume. Thus, at least ~35% of the total iron must be trivalent iron.

252 The calculations were performed with the internally consistent thermodynamic dataset of Holland 253 and Powell (1998, and updates) and a CORK EoS for H₂O. The following solid-solution models 254 were used: GlTrTsPg for amphibole, TiBio(HP) for biotite, Gt(HP) for garnet, Ctd(HP) for 255 chloritoid, Pheng(HP) for K-white mica (with a maximum paragonite content of 50% mol), St(HP) 256 for staurolite, hCrd for cordierite, Chl(HP) for chlorite, Ep(HP) for epidote, Omph(HP) for 257 clinopyroxene, Mica(M) for Na-Ca rich white mica, IlGkPy for ilmenite, Opx(HP) for 258 orthopyroxene, MtUl(A) for magnetite, melt(HP) for haplogranitic melt and feldspar models as 259 described in Massonne (2012). H₂O was considered as a pure phase.

260 Finally, in order to check the consistency of the results obtained with the P-T pseudosection, the 261 THERMOCALC average P-T (Powell and Holland, 1994) method was applied to equilibrated mineral rims (see also Vance and Mahar, 1998) and coupled with fluid-independent 262 263 geothermometers such as the Ti-in biotite thermometry of Henry et al. (2005) for syn-S₂ biotite. 264 Calculations with THERMOCALC were conducted using the 3.33 version and the internally 265 consistent dataset of Holland and Powell (1998). The activities of the mineral end-members were 266 calculated using the A-X software by Holland (http://www.esc.cam.ac.uk/research/research-267 groups/holland/ax). Since the THERMOCALC P-T estimates are dependent on the fluid 268 composition (H₂O-CO₂), they can be used to obtain information on this parameter. For sample KL-269 19, a good overlap between estimates from the pseudosection, garnet-biotite thermometry, Ti-in-270 biotite thermometry with THERMOCALC average P-T was obtained for $XH_2O = 1$ (see below).

271

272 4.3 Mineral compositions and P-T results

273

X-ray maps (Fig. 5) of garnet grains from sample KL-19 show a decrease of Mn and Ca balanced
by an increase of Mg from core to the inner rim. The outermost part of the rim shows lower Mg and
somewhat higher Ca contents. This garnet domain was corroded suggesting garnet resorption. This

277 is confirmed by a slight increase in Mn and Fe/(Fe+Mg) (i.e. Fe#, e.g. Spear, 1993; Fig. 5b). 278 Chlorite enclosed in garnet is characterized by Mg/(Mg+Fe) = XMg of 0.42 (Table 1). The 279 compositions of other phases in the matrix are relatively homogeneous. Si contents in white mica 280 vary between 3.13 to 3.08 per formula unit (p.f.u.) whereas XMg in staurolite systematically 281 decreases from core (0.15) to rim (0.12) (Table 1). Matrix biotite shows XMg and Ti (p.f.u.) of 282 0.39–0.43 and 0.12–0.14 p.f.u, respectively, which are systematically different from values of 283 biotite included in garnet (XMg = 0.50-0.56 and Ti = 0.7-0.11 p.f.u.). Plagioclase is rich in the 284 albite component with XAb (i.e. Na/(Na+Ca)) of 0.82-0.84.

285

286 According to the calculated pseudosection the observed paragenesis garnet-staurolite-biotite-white 287 mica-plagioclase-quartz-magnetite-ilmenite in sample KL-19 appears in a quite narrow P-T window 288 ranging from 0.60-0.85 GPa and 600-660°C (field labeled in bold in Fig. 6). The upper T limit is 289 represented by the appearance of aluminosilicate (kyanite or sillimanite) whereas the upper P limit 290 is determined by the formation of rutile; both phases are absent in the rock and, likely, were never 291 part of the assemblage since no relicts are preserved. Compositional isopleths (Fig. 7) of garnet and 292 matrix phases (Vance and Mahar, 1998) were used to obtain a P-T path (Fig. 8). The garnet core 293 isopleths intersect at P ~ 0.5 GPa and T ~ 550–560°C, (c. 25°C above the garnet-in curve). This 294 intersection is in a field with chlorite present and plagioclase absent (Fig. 8), in agreement with the 295 inclusion mineral assemblage in the garnet core. According to the trend of chemical zoning in 296 garnet (Fig. 5a, b; Fig. 7), the prograde evolution of KL-19 must be characterized by both 297 increasing P and T along a clockwise P-T path (see also Vance and Mahar, 1998). The peak P never 298 reached pressures of the rutile-in curve. A later stage of slight decompression from nearly 0.8 GPa 299 (as suggested by Si⁴⁺ in white mica) up to 0.68 GPa and 640°C is suggested by the trend of the 300 white mica composition, XMg in staurolite, as well as the chemical composition of the garnet rim. 301 Equilibration at 0.68 GPa and 640°C is consistent with the result of the average P-T method of 302 THERMOCALC (T = 634 \pm 28°C, P = 0.67 \pm 0.13 \Box GPa, a_(H2O)=1) applied to the garnet rim + 303 average of rims of matrix phases (Fig. 8). This stage is also supported by Ti-in-biotite thermometry 304 based on Henry et al. (2005) which returned $T = 629 \pm 15^{\circ}C$. These estimates are, within errors, in 305 agreement with previous P-T results reported by Vannay and Hodges (1996) for metapelitic and 306 garnet-bearing orthogneiss samples coming from the same structural position.

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308 5. MONAZITE U-(Th)-Pb GEOCHRONOLOGY

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310 **5.1 Monazite Texture and Chemistry**

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312 In the two samples, orthogneiss KL-21 and paragneiss KL-19, monazite was dated in textural 313 context (e.g. Williams and Jercinovic, 2002, 2012) to add time constraints to the P-T evolution of 314 the KSZ. Monazite grains, their textural position and internal features (e.g. inclusions, zoning etc.) 315 were characterized with a PHILIPS XL30 Scanning Electron Microscope at Università di Pisa. 316 Multiple point analyses were computed on selected monazite grains with a JEOL 8200 Super probe 317 at Earth Sciences Department of the University of Milan (Italy) following the analytical procedure 318 as reported in Montomoli et al. (2013). Representative analyses of monazite grains are reported in 319 Table 2.

320 Selected grains, representative of all the structural/chemical domains, were target for in situ 321 geochronology with a laser-ablation, inductively coupled plasma mass spectrometer (LA-ICP-MS) 322 using an Ar-F 193-nm excimer laser (GeoLas 102 from Micro-Las) at CNR-Istituto di Geoscienze e 323 Georisorse at Pavia. Details on the full analytical procedure are reported in Paquette and Tiepolo 324 (2007). Single analyses were performed by a one-minute acquisition of the background signal 325 followed by recording, for at least 30 s, the ablation signal of the masses related to the isotopes ²⁰²Hg, ²⁰⁴(Hg + Pb), ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb, ²³²Th, and ²³⁸U. The presence of common Pb was evaluated 326 in each analysis on the basis of the net signal of ²⁰⁴Pb (i.e. subtracted for the interference of ²⁰⁴Hg 327 and background). None of the sample revealed ²⁰⁴Pb counts above the background level. However, 328 329 the relatively high Hg signal in the gas blank does not exclude the effective presence of common Pb 330 in the analysed monazite. Laser-induced elemental fractionation and mass bias were corrected using 331 matrix-matched external monazite standard (Moacir monazite: Cruz et al., 1996; Seydoux-332 Guillaume et al., 2002a, b) and considering the values, re-calibrated for isotopic disequilibrium, 333 reported by Gasquet et al. (2010); the relative standard deviation of the analyses is mostly within 2-334 4 %. Monazite ages are plotted on the U-Th-Pb concordia (Fig. 10) as suggested by Foster et al. 335 (2000; see also Stearns et al., 2013) and interpreted according to their chemistry and textural 336 positions. Data processing and plotting was done with the software ISOPLOT (Ludwig, 2003). 337 Isotopic results and calculated ages are reported in Table 3.

A sub population of monazite crystals were analysed by ion microprobe. Portions of thin sections
were mounted in epoxy resin with a polished standard block. Backscattered electron (BSE) images
for monazite were carried out on a JEOL JSM_6610A scanning electron microscope (SEM) at the
Australian National University (ANU) in Canberra. Operating conditions for the SEM were 15
kV/60 µA and 20 mm working distance. Imaging revealed that most crystals in either sample are
homogeneous in BSE; others have small, bright cores.

Monazite was analysed for U, Th and Pb isotopes using the sensitive high resolution ion microprobe SHRIMP-II at the ANU. Instrumental conditions and data acquisition were generally as described by Williams (1998) and energy filtering was applied to remove interferences and reduce matrix effects as described in Rubatto et al. (2001). The measured ²⁰⁶Pb/²³⁸U ratio was corrected using reference monazite USGS44069 (425 Ma, Aleinikoff et al., 2007). The analyses were corrected for common Pb based on the measured ²⁰⁴Pb and ²⁰⁷Pb/²⁰⁶Pb according to the method described in Williams (1998). The analytical session had a calibration error of 2.5% (2 sigma), which was propagated to single analyses. The percent of common Pb in each analysis varied between 0.2 and 2.4% and the common Pb composition was assumed to be that predicted by the model of Stacey and Kramers (1975). Data evaluation and age calculation were done using the software Squid 1 and Isoplot/Ex (Ludwig 2003), respectively. The ion microprobe set up is not suited to accurately measure the high Th signal in monazite and thus ²⁰⁶Pb/²³⁸U and LA-ICP-MS ²⁰⁸Pb/²³²Th ages for unzoned monazite crystals indicates that any excess ²⁰⁶Pb from the decay of ²³⁰Th is below analytical uncertainty of the calculated ages.

5.2 Texture and chemistry

345 Monazite crystals identified in thin sections in both samples are 25-150 μ m in size. In orthogneiss 346 KL-21 sample, subhedral to anhedral monazite grains are found along the mylonitic foliation, both 347 in granoblastic and lepidoblastic layers. Monazite in the paragneiss KL-19 is euhedral to subhedral, 348 commonly aligned to the foliation, with equilibrium crystal boundaries with other minerals. Some 349 grains are included in garnet and one grain was found enclosed in staurolite. Other common 350 accessory minerals in both samples are zircon, apatite and sporadic xenotime. Inclusions in 351 monazite are quartz, mica, zircon and apatite in both samples. Rare tiny U-Th oxide grains are 352 enclosed in monazite of the paragneiss.

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The analysed monazites accommodate variable amounts of U and Th with a combination of cheralite and huttonite substitutions (Fig. 9a and b) as commonly observed in monazite (e.g. Spear and Pyle 2002). In KL-19, monazites included in garnet are enriched in HREE compared with matrix monazites (Fig. 9c). In the orthogneiss sample KL-21, monazite HREE composition is relatively tight and no clear monazite sub-population can be distinguished on the bases of its REE composition.

360 5.3 Results

LA-ICP-MS analyses of monazite from the two samples returned ²⁰⁸Pb/²³²Th-²⁰⁶Pb/²³⁸U concordant 361 362 dates that span from about 27 to 48 Ma (Fig. 10, Table 3). Notably, the older three dates (~ 44, 46 363 and 49 Ma) were obtained from monazite included in the garnet rim of paragneiss KL-19 (Fig. 5, 364 10), whereas 13 analyses on monazite grains along the S_2 foliation gave younger dates (~ 30-42) 365 Ma). Monazite grains along the main foliation in the orthogneiss (KL-21) provided dates in the 366 range of ~ 27-41 Ma, which are similar to those obtained from monazite grains aligned along the S_2 367 foliation in the paragneiss. A monazite core from the orthogneiss yields a concordant date at 368 502±8.8 Ma (Table 3).

Monazite in the matrix of both samples analysed by SHRIMP yield dates that cover a large time span: in metapelite KL-19 from 28 to 46 Ma and in gneiss KL-21 from 33 to 41 Ma (Fig.11, Table 4), with most data in both samples in the range 34 to 41 Ma. There is no systematic correlation between Th and U content and age. Only two analyses could be located on the texturally older core rich in Th and in either samples these core analyses yield the oldest date at ~41 and 46 Ma.

Eight monazite grains were analysed both by LA-ICP-MS and SHRIMP: 6 grains in metapelite sample KL-19 and 3 grains in gneiss Kl-21 (Table 3 and 4). Because of the small size of the monazite grains and of their zoning (Fig. 10, 11), and the different sampling volume of the instruments (LA-ICPMS crater of 10 μ m in diameter and about 8 μ m in depth, SHRIMP crater of 20 μ m in diameter and 2 μ m depth) direct comparison between the results is not straightforward (Fig. 12).

A number of monazite grains from both samples show agreement between dates obtained by the two methods. Examples are KL-19 grain 317 from sample with 206 Pb/ 238 U ages of 40.5±0.6 Ma and 40.2±0.6 Ma by SHRIMP and 40.0±0.7 and 38.6±0.7 Ma by LA-ICP-MS; KL-21 grain 212 has a SHRIMP age of 38.4±0.6 Ma and a LA-ICP-MS age of 38.6±0.7 Ma (see also KL-19 grain 201). In these cases it can thus be concluded that the monazite grains are unzoned in age and the different volumes sampled make no difference on the measured date.

386 For other monazite grains the difference in age obtained with the two techniques and thus sampling 387 volumes is significant. For example in KL-19 grains 308 and 307 three SHRIMP analyses are in the 388 range 34.4 – 36.6 Ma whereas LA-ICP-MS gives dates ranging between 30.8±0.5 and 41.3±0.7 Ma. 389 In another case from sample KL-21 grain 216 yielded SHRIMP dates of 40.7±0.6 in the Th-rich 390 core and 32.8 to 35.4 Ma in the rim, whereas LA-ICPMS dates are closer together at 36.5±0.7 and 391 37.9±0.7 Ma. Similarly, in KL-19 grain 301 the SHRIMP date is older at 41.6±0.6 than the 392 34.4±0.6 Ma date by LA-ICP-MS. These discrepancies in measured date indicate that the small 393 monazite grains are zoned in age – this age zoning correspond to chemical zoning only in some

394 grains – and the different dating methods do not equally resolve and/or mix the distinct growth395 domains.

396 In the couple of grains where core-rim textures are evident, there is a good textural correspondence 397 with older ages in cores and younger ages in rims (Fig. 12). Older monazite dates around 44-48 Ma 398 are found in the grains included in garnet or cores of monazites along the foliation testifying the 399 occurrence of older monazites reoriented and possibly partially re-equilibrated during the formation 400 of S₂ foliation. The small size of the grains and the real possibility of mixing with younger rims 401 make establishing the exact age of this older component arduous. In sample KL-19 the time span 402 for the monazite rims varies from ~34 to 42 Ma. In sample KL-21 the rim dates are from ~32 to 39 403 Ma. The two samples show consistent ages indicating a prolonged monazite crystallization and 404 recrystallization over nearly 10 Ma. Assigning the older monazite core ages to prograde 405 metamorphism, the 10 Ma span is taken to indicate the development of the S_2 foliation.

406

407 6. DISCUSSION

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409 Field observations (Fig. 2) and structural analysis at the meso- and micro-scale (Fig. 3-4) confirm 410 the occurrence of a high-temperature contractional top-to-the-S/SW shear zone in the upper part of 411 the GHS: the KSZ, localized close to the boundary between Unit 2 and Unit 3. The KSZ strikes 412 NNW-ESE and crops out for several km from Kalopani to the SE (Fig. 2). Pseudosection modeling 413 and inverse geothermobarometry (Fig. 6-8) highlighted that staurolite and garnet paragneisses (KL-414 19) involved in the shear zone record equilibration in the P-T range of 0.60-0.85 GPa and of 600-415 660°C (Fig. 8). This temperature range is in agreement with deformation temperatures suggested by 416 quartz and feldspar microstructures.

417 The correlation between structural position of monazite (inclusions in garnet rim) and chemical 418 zoning in garnet and monazite (Th-rich cores in matrix monazite) indicate that the older monazite at 419 48-41 Ma formed toward the end of prograde garnet growth, before development of the S₂ foliation. 420 In Fig. 5 the monazite at 48-41 Ma marks the changing in zoning of garnet. We attribute the 421 formation of monazite in the matrix of KL-19 garnet-staurolite-bearing paragneiss over the period 422 ~41-28 Ma to the decompression path and development of S_2 foliation during the shearing of the 423 Kalopani shear zone. Orthogneiss KL-21 does not contain garnet, and monazite ages in this sample 424 are in the range 41-32 Ma (with the exclusion of discordant analyses and an outlier at 27 Ma). One 425 single monazite core was dated at ~ 41 Ma. We thus suggest that in this sample prograde monazite, 426 was nearly completely reset during development of the S₂ foliation because it was not shielded by 427 garnet. One concordant age at 502 Ma (Fig. 10) in sample KL-21 is interpreted as the age of the428 magmatic protolith, in agreement with Godin et al. (2001).

White micas along S_2 and the outermost garnet rim mark the beginning of decreasing pressure (Fig. 8) and consequently the start of exhumation of the studied part of the GHS. The lacking of strain shadows or tails along monazite, and the equilibrium grain boundaries, along S_2 foliation reinforce the interpretation that the monazite growth occurred during the growth of other S_2 minerals.

- The initial exhumation of the uppermost part of the GHS (*i.e.* hanging wall of the KSZ) was triggered by the activity of the Kalopani contractional shear zone. Our data point to exhumation from ~41 Ma, which is the oldest record within the GHS. This event would be even older than exhumation at ~26 Ma induced by the HHD in the lower-middle part of the GHS (Montomoli et al., 2013, 2015; Iaccarino et al., 2015).
- The suggested early exhumation of the GHS is in agreement with the drastic change of sediments provenance in the Himalayan foredeep starting from Middle Eocene (Najman and Garzanti, 2000) and with the occurrence of detritus coming from crystalline rocks in the Bengal fan starting from 39 Ma (Najman et al., 2008). This testifies that, by that time, exhumation brought GHS crystalline rocks up to the surface during an early evolution of the Himalaya.
- 444

445 Ages as old as 48-44 Ma have been reported by Carosi et al., (2010) and Larson and Cottle (2015) 446 from monazite included in garnet and as isolated ages from garnet-kyanite bearing paragneisses 447 from Lower Dolpo (Western Nepal) and kyanite-bearing veins/leucosomes in the Kali Gandaki 448 valley belonging to Unit 1 of the GHS. Scattered monazite dates as old as Early Eocene (45 and 48 449 Ma) related to prograde metamorphism and a contractional shear zone (KSZ) allow to speculate a 450 metamorphic and tectonic setting related to early crustal thickening in frontal parts of the belt at that 451 time. The activity of the KSZ at c. 41-30 Ma testifies an action of contractional tectonics affecting 452 the northern margin of India, now incorporated in the main Himalayan range.

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454 **6.2. Geodynamic implications**

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The HHD in the Kali Gandaki valley with ages from ~25 to 18 Ma (monazite U-Th-Pb ages, Iaccarino et al., 2015), has been recently identified close to the base of the kyanite-bearing gneiss in Unit 1 (Fig. 1b). We propose that, at the time of activation of the HHD, both the hanging- and footwall of the KSZ (now included as hanging wall of the HHD) were exhumed (Fig. 13). Only when 460 deformation shifted to the MCT zone, the entire GHS underwent exhumation and then 461 retrogression.

- 462 The new data can be reconciled with a three stage exhumation of the GHS starting from ~ 41 Ma 463 and driven by the progressive activation of contractional top-to-the-SW shear zones (Fig. 13). He et 464 al. (2015) proposed a similar three stage exhumation in the GHS by thrusts 1, 2 and 3 progressively 465 activated towards the foreland during the Oligocene with the oldest thrust being active at ~ 26 Ma. 466 Slices of the Indian continental margin have been progressively incorporated in the orogen. 467 However, following the model proposed by of He et al. (2015), we argue that a difference in the 468 timing of prograde metamorphism, or at least a part of it, is expected for the three slices. A major 469 difference is however in the timing of exhumation, which is progressively younger toward the 470 foreland and is triggered by three major ductile contractional shear zones occurring within the GHS 471 (Fig. 13). A consequence of this observation is that GHS underwent underthrusting below the Asian 472 plate and progressive metamorphism and after some million years from the collision, slices of 473 Indian crust were exhumed progressively, starting from the upper one.
- The incorporation 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). Subsequently, additional slices of the LHS were incorporated in the crustal wedge recording progressively lower P-T values and activating a duplexing mechanism (Robinson and Martin, 2014).
- 479 Exhumation starting from ~ 41 Ma in shear zones at the higher level of the GHS with respect to the 480 MCT does not support previous exhumation models in which the exhumation is mainly driven by 481 the coupled activities of the STDS and MCT at 23-17 Ma with opposite kinematics. Such models 482 are: rigid and ductile extrusion, channel flow, channel flow followed by extrusion and wedge 483 insertion (see Montomoli et al., 2013 for an overview of the models). The activity of the STD 484 and/or erosion and kinematic thinning of the GHS (or combination of these) could explain the 485 exhumation process based on the activity of contractional shear zones. Even if in principle an older 486 channel flow could be localized in the uppermost part of the GHS, as already pointed out by 487 Montomoli et al. (2013; see also He et al., 2015) there is not enough thickness of the GHS above 488 the HHD to generate a "large scale" channel flow (as the models require a 10-20 km thick GHS; 489 Beaumont et al., 2001) and even less space is available for the relatively thin hanging-wall of the 490 KSZ delimitated to the North by the Annapurna Detachment (the local strand of the STDS in the 491 Kali Gandaki; Searle, 2010).
- 492

493 Prograde metamorphism at this stage was limited to the lower GHS, which continued to be 494 underthrust beneath the HHD. The Bura Buri leucogranite intruded at 23-24 Ma across the STD and 495 locked the contact between GHS and TSS (Carosi et al., 2013) in western and central (?) Nepal. The 496 intrusion of the Mugu granite or similar granitic bodies occurred later at ~ 19 Ma (Harrison et al., 497 1999).

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), the MCT zone became active resulting in the overall exhumation of the GHS. At this stage, the metamorphism was shifted to the Lesser Himalayan Sequence becoming involved in the deformation propagating to the South (Mottram et al., 2014).

In this framework, the P-T-t paths of the slices of the GHS, delimited by the top-to-the-SW shear zones, are of similar shape. However, 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, 2015). The timing of exhumation shows a difference of several million years between the hanging-wall and footwall of the HHD (*e.g.* 508 5-6 Ma, Montomoli et al., 2013, 2015).

509 The diachronous activation of contractional top-to-the-S and SW shear zones within the GHS, while 510 it experienced an overall underthrusting, explains the relatively low peak P recorded by the 511 hanging-wall compared to that of the footwall rocks (Carosi et al., 2010). The difference in pressure 512 (at peak temperature) from literature data is estimated to be at least 0.2-0.3 GPa (Kohn, 2008; 513 Montomoli et al., 2013, 2015). In this framework older ages (up to ~ 25 Ma) are found in the upper 514 portion of the GHS as already pointed out by previous workers (Kohn et al. 2005; Corrie and Kohn 515 2011; Kohn 2008, 2014, 2016; Montomoli et al., 2013; Ambrose et al. 2015; Wang et al., 2015). A 516 similar mechanism of propagation of shear zones toward the foreland has been proposed by 517 Ambrose et al. (2015) who combined monazite geochronology and pseudosection modeling to 518 identify the sequence of activation of shear zones. They propose the occurrence of several "cryptic" 519 shear zones and "ductile" thrust sheets progressively activated at 24-18 Ma in the mid crust (GHS) 520 of Eastern Nepal. Ambrose et al. (2015) in sequence-thrusting model implies that external ductile 521 "duplexes" in the mid crust underwent still prograde metamorphism when the hanging-wall was 522 exhumed, as also proposed by Montomoli et al. (2013). Crustal slices are progressively 523 incorporated from the footwall in the southward propagating orogenic wedge. However the 524 available data from the timing of prograde metamorphism in the lower part of the GHS point to a 525 prograde metamorphism of the kyanite-bearing gneiss at 43-36 Ma in the Kali Gandaki valley 526 (Carosi et al., 2015; Iaccarino et al., 2015) before the activation of the propagation of shear zones at

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527 24-18 Ma, and consequent exhumation of the hanging-wall and prograde metamorphism in the528 footwall, as proposed by Ambrose et al. (2015) and Larson et al. (2015).

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530 **6.3 Folded Isograds in the GHS**

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532 Occurrence of Barrovian index minerals such as garnet, staurolite and kyanite both in the upper and 533 in the lower part of the GHS (i.e. in the MCT zone) has been often regarded as an evidence of large-534 et al., 2008; Searle, 2010). Geochronological data on staurolite-bearing paragneiss (sample KL-19) 535 localized in the uppermost portion of the GHS offer the opportunity to check if Barrovian 536 metamorphism is contemporaneous in the upper and in the lower portions of the GHS. Barrovian 537 index minerals, e.g. garnet, can grow during different P-T trajectories (related to different tectonic 538 settings) and record different stages of metamorphism during their growth (e.g. Spear et al., 1990; 539 Caddick and Kohn, 2013). In addition, bulk rock compositions play an important role in the 540 development of Barrovian index minerals (e.g. Spear 1993). Therefore we prefer to compare if 541 during the same time span rocks from the upper and lower GHS recorded the same prograde, 542 decompressional and/or retrograde paths.

543 In the upper part of the GHS in the study area, monazite geochronology is compatible with a 544 retrograde path at 41-30 Ma (samples KL-21 and KL-19, this work). In the lower part of the GHS 545 garnet and kyanite show prograde growth from (at least) 43-36 Ma and a retrograde one at 25-18 546 Ma (samples K-28a and c in Carosi et al., 2015 and Iaccarino et al., 2015 respectively). The 547 Barrovian minerals thus grew in different periods of time. Moreover, retrograde segments of the P-548 T paths are shifted by several million years from the upper to the lower part of the GHS (see also 549 Kohn, 2014). This finding does not support the hypothesis of folded Barrovian isograds or passively 550 folded isograds by the southward motion of the hot-channel made of partially molten rocks (Searle 551 and Szulc, 2005; Jessup et al., 2008; Searle, 2010). Moreover, according to this work and Iaccarino 552 et al. (2015) Barrovian minerals in the upper and lower part of the GHS were not part of the same 553 tectonic units because the GHS has been effectively subdivided in three tectonic units bounded by 554 the KSZ, HHD and MCT.

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Another aspect that is worth considering is the age of the main foliation in the GHS. According to the channel-flow model the foliation should be developed at the same time all over the GHS during the horizontal motion along the hot-channel between 23 and 17 Ma (Grujic, 2006). Our new age data on the development of the foliation in the sheared uppermost part of the GHS at 41-30 Ma, is older with respect to the age of the foliation in the HHD (25-18 Ma) and in the MCT zone (younger than 17-18 Ma). Similar differences in age between upper and lower GHS have been reported by

562 Imayama et al. (2012) and Rubatto et al. (2013) in Sikkim and Wang et al. (2015) in Central Nepal.

563 This timing does not support the hypothesis of a foliation developed in the same time span in a

tectonic unit being as thick as 10-20 km as requested by the channel flow model (Beaumont et al.,

565 2001; Grujic, 2006).

566

567 **7. CONCLUSIONS**

The kinematics of ductile shear zones, P-T paths and monazite U-Th-Pb ages recorded within the GHS highlight that exhumation occurred at ~ 41-30 Ma and did not affect the entire GHS at the same time. The high-temperature KSZ in the upper part of the GHS triggered the earlier exhumation of this sequence.

572 Taking into consideration recently published age data on the activity of the HHD and MCT, it is 573 evident that the exhumation process, firstly localized in the hanging-wall of the uppermost shear 574 zone shifted downwards and resulted in progressively larger portions of the GHS being exhumed. 575 When deformation was finally localized along the MCT, the entire GHS underwent exhumation. It 576 is noteworthy that three different GHS slices (or sub-units) separated by the KSZ, HHD and MCT 577 underwent diachronous metamorphism reaching peak T and P at different times and showing 578 younger ages of exhumation progressively moving structurally downward in the orogenic pile (Fig. 579 13).

580 Middle – Late Eocene exhumation of the upper part of the GHS cannot be explained by the 581 contemporaneous activity of MCT and STD, which occurred later, and by previously published 582 exhumation models such as the extrusion, wedge insertion, channel flow and channel flow followed 583 by extrusion models. A model that takes into account the occurrence of tectonic and metamorphic 584 discontinuities in the upper GHS, which progressively shifted to the lower part of the GHS and later 585 into the LHS, is able to explain the newly obtained data.

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975

976 **Figure captions**

977 Figure 1. (a) Simplified geological map of the Central Himalaya (modified after Ambrose et al., 978 2015). The study area is indicated by the dotted box. (b) Geological sketch map of the Kali Gandaki 979 valley with location of the Kalopani Shear Zone, the samples in this study (KL-19, KL-21) and 980 samples of the K28 series of Carosi et al. (2015) and Iaccarino et al. (2015). Stereographic 981 projection of the main foliation planes (S₂) and object lineation (Lext) are shown in the insert in the 982 upper right. 1 Quartzite (LHS); 2: Kyanite gneiss (GHS); 3: Calcsilicate and marble (GHS); 4: 983 Metapelite (GHS); 5: Orthogneiss (GHS); 6: Tethyan Sedimentary Sequences (TSS); 7: Alluvial 984 debris; 8: South Tibetan Detachment; 9: Minor normal fault; 10: Kalopani shear zone; 11: High 985 Himalayan Discontinuity according to Iaccarino et al. (2015) and Main Central Thrust close to 986 Dana village (according to Colchen et al. 1986; Vannay and Hodges 1996 and Carosi et al. 2014); 987 12: Main foliation; 13: object lineation; 14: location of samples quoted in the text.

988 **Figure 2.** Detailed geological map of the Kalopani Shear Zone.

Figure 3. Orthogneiss of Unit 3 of the GHS sheared by the Kalopani Shear Zone and position of the
sample KL-21. Asymmetric fabric points to a top-to-the S–SW sense of shear.

Figure 4. Microscopic features of Kalopani Shear Zone samples: (a) paragneiss KL-19, with top-tothe-S shearing; (b) Garnet and staurolite crystals in KL-19. Note the internal foliation in garnet (S_i);
(c) general view of KL-21 sample, showing Grain Boundary Migration in quartz; (d) pinning
microstructures in quartz of KL-21.

Figure 5 Representative X-ray maps for Mg, Ca, Mn and Fe in garnet. The line C-R refers to the
core-rim profile in (b), the scale bar is 750 µm. In the Mg map the ellipse indicates the monazite
(Mnz 334) included in garnet; (b) Core to rim normalized profiles through garnet.

Figure 6. P-T pseudosection for paragneiss KL-19. The observed equilibrium assemblage is
highlighted. Minerals abbreviation after Whitney and Evans (2010) except for fluid phase, white
mica and silicate melt indicated by V, Wm and L, respectively.

Figure 7. Details of isopleth contouring for: (a) XCa (i.e. Ca/(Ca+Mg+Mn+Fe)) in garnet (Grt); (b)

1002 XMg (i.e. Mg/(Ca+Mg+Mn+Fe)) in garnet; (c) Si^{4+} (p.f.u.) in white mica; (d) XMg in staurolite; (e)

1003 Na/Na+Ca (i.e. XAb) in the plagioclase feldspar and (f) modal amount of garnet (Vol% Grt) in

1004 100% solids.

Figure 8. Sketch of the P-T path for the sheared paragneiss (sample KL-19), based on
pseudosection calculation, THERMOCALC average PT (AvePT), and Ti-in biotite thermometry.
Abbreviations as in Fig. 6.

Figure 9. (a) Chemistry of monazite in the system 2REEPO₄–CaTh(PO₄)₂–2ThSiO₄, after Linthout

(2007); (b) Plot of cheralite and huttonite exchange vectors; (c) Heavy Rare Earth Elements (HREE
and Y) versus Light Rare Earth Elements (LREE) plot of monazite.

Figure 10. U-Th-Pb concordia diagrams for KL-21 and KL-19 monazite analysed by LA-ICP-MS.
Only data with <10% of discordance are shown. Quoted errors are at 2σ level.

Figure 11 Conventional Concordia plot (left) for U-Pb SHRIMP analyses of monazite and representative BSE image (right) of dated monazite crystal from paragneiss KL-19. White numbers in the BSE image indicate ²⁰⁶Pb/²³⁸U ages and absolute errors (±1 sigma) whereas green numbers indicate LA-ICP-MS ages.

Figure 12. Cumulative histogram and probability curve of LA–ICP–MS and SHRIMP ²⁰⁶Pb/²³⁸U
 ages differentiated by methods, sample and textural position.

1019 Figure 13. Sketch of the evolution of the GHS by progressive activation of top-to-the-SW shear 1020 zones from the uppermost part to the lower part. The kinematic path of particles in the hanging wall 1021 and footwall of the detected ductile shear zones in the GHS is shown by squares with different 1022 colors. At ~ 41-30 Ma the hanging wall of the KSZ was exhuming whereas the footwall was still 1023 undergoing prograde metamorphism. At 26-24 Ma, following the activation of the HHD, the GHS1 1024 and 2 in the hanging wall of the HHS started exhumation whereas rocks in the footwall of the HHD 1025 were still buried. At 17-12 Ma the activation of the MCT caused the exhumation of all sub-units of 1026 the GHS (GHS 1, 2 3) and the LHS was incorporated in the belt. GHS1, 2, 3: tectonic sub-units of 1027 the Greater Himalayan Sequence (GHS); TSS: Tethyan Sedimentary Sequence; Grey areas: 1028 leucogranites emplaced in the time span 19-24 Ma (Bertoldi et al., 211; Carosi et al., 2013); KSZ: 1029 Kalopani Shear Zone; HHD: High Himalayan Discontinuity (Montomoli et al., 2013, 2015; 1030 Iaccarino et al., 2015); MCT: Main Central Thrust; LHS: Lesser Himalayan Sequence. Not to scale.

1031

1032 List of tables

- 1033 Table 1. Representative EMP analyses (in wt%) of minerals in the paragneiss sample KL-19
- 1034 (formulae were calculated on the following basis: garnet = 24 O, 8 cations; staurolite = 46 O; micas
- 1035 = 11 O; chlorite = 28 O; feldspar = 8 O; spinel = 4 O, 3 cations; ilmenite = 3 O).
- 1036 Table 2. Representative EMP analyses of monazite (recalculated on the basis of 4 O) from the dated
- 1037 samples (KL-19 and KL-21).
- 1038 Table 3. Summary of monazite LA-ICP-MS isotopic results for sample KL-19 and KL-21.
- 1039 Table 4. SHRIMP U-Th-Pb analyses of monazite in samples KL-21 and KL-19.

















1 ChlWmPlMagPgQzRtV 2 ChlWmPIIImMagPgQzRtV 3 ChlEpWmPIIImMagPgQzRtV 4 ChIEpWmPIMagCpxPgQzRtV 5 ChlWmPIIImMagCpxPgQzV 6 ChlWmPIIImMagCpxPgQzV 7 ChIEpWmMagCpxPgQzRtHemV 8 ChlWmCpxPgLwsQzRtHemV 9 ChIEpWmCpxPgLwsQzRtHemV 10 ChlWmCdlCpxPgQzRtHemV 11 ChlWmCdlMagCpxPgQzRtHemV 12 ChlWmCdlMagCpxPgQzRtV 13 ChlEpWmCdlMagCpxPgQzRtV 14 ChlWmCdlMagCpxGrtPgQzRtV 15 ChlEpWmMagGrtCpxPgQzRtV 16 ChlWmlImMagGrtPgBtQzRtV 17 ChlWmlImMagGrtCpxPgBtoQzV 18 ChlWmlImMagCpxPgBtQzV 19 ChlEpWmlImMagPgBtQzV 20 ChIEpWmIImMagGrtPgBtQzV 21 ChlWmPllImMagGrtPgBtQzV 22 ChlWmPIIImMagQzV 23 ChlWmPIIImMagBtQzV 24 ChlWmPIIImMagPgBtQzV 25 ChIStPIIImMagPgBtQzV 26 ChIStPIIImMagBtQzV 27 ChIStPIIImMagGrtBtQzV 28 ChIStPIIImMagGrtPgBtQzV 29 StCrdPIIImMagGrtBtSilQzV 30 ChIStIImMagGrtPgBtQzV 31 StPIIImMagGrtPgBtQzV 32 StllmMagGrtPgBtQzV 33 WmStPIIImMagGrtPgBtQzV 34 WmllmMagGrtPgBtQzV 35 WmllmMagGrtPgBtQzRtV

37 ChlWmMagGrtCpxPgBtQzRtV 38 WmMagGrtCpxPgBtQzRtV 39 LWmMagGrtPgBtQzRtV 40 LWmMagGrtCpxPgBtQzRt 41 LWmPIMagGrtPgBtQzRt 42 LWmMagGrtPgBtKyQzRt 43 LPIMagGrtPgBtQzRtV 44 LWmPIMagGrtBtKyQzRtV 45 WmStPIIImMagGrtBtKyQzV 46 LWmPIIImMagGrtBtKyQz 47 LPIIImMagGrtBtSilQz 48 LPIIImMagGrtBtSilQzV 49 LPIMagGrtSilQzV 50 PIMagGrtBtSilQzV 51 CrdPIMagGrtBtSilQzV 52 LCrdPIMagGrtBtSilQzV 53 CrdPIIImBtSilQzV L 54 LCrdPIMagBtSilQzV 55 LCrdPIMagGrtBtQzV 56 LOpxCrdPIMagGrtBtQz 57 LCrdPlKfsMagGrtBtQz 58 LCrdPIMagGrtSilQz 59 LMagGrtBtSilQz 60 LPIMagGrtBtSilQzRt 61 LPIKfsMagGrtBtSilQzRt 62 LKfsMagGrtBtSilQzRt 63 LPIKfsMagGrtBtKyQzRt 64 LPIKfsMagGrtBtKyQzRt 65 LWmPIKfsMagGrtKyQzRt















Minerals:	Grt	Grt	Grt	St	St	Bt	Bt	Ms	Ms	PI	PI	Opaque	llm
	core	middle	rim	core	rim	in Grt	matrix						
8:0	35 41	25.09	35 32	27 40	27.58	26 50	35 62	45 41	46 20	co c7	64.06	0.00	0.00
510 ₂	0.02	35.98	0.00	0.63	0.66	36.50	2 44	0.60	0.51	63.67	64.26	0.09	48.57
	20.85	0.01	20.98	53 77	55 34	10.00	17 47	33.22	32 74	22.08	22.02	0.32	0.00
$\Lambda_{12}O_3$	0.03	0.01	0.00	0.05	0.05	10.00				22.00	22.03	0.12	0.02
EeO	38.03	38.41	38.79	14.75	13.33	18.07	22.84	2.91	3.18	0.02	0.03	94.12	50.93
MnO	0.67	0 15	0.17	0.00	0.01	0.03	0.00	0.00	0.01	0.02	0.00	0.02	0.01
MaQ	1.93	3.12	3.33	1.40	0.98	12 19	8.39	0.73	0.87	0.00	0.00	0.00	0.19
ZnO		0.12		0.58	0.59	12110				0.00	0.00	0.04	0.02
CaO	2.72	1.91	1.40	0.01	0.01	0.00	0.10	0.00	0.02	3.81	0.00	0.03	0.00
Na ₂ O	0.00	0.00	0.01	0.00	0.00	0.39	0.37	1.52	1.40	9.99	3.53		
<u>-</u> К ₂ О				0.00	0.01	8.78	8.77	9.3	9.41	0.06	10.21		
BaO						0.06	0.05	0.11	0.11	0.00	0.05		
Tot.	99.66	100.64	100.00	98.59	98.56	95.86	96.05	93.80	94.45	99.63	100.11	94.74	99.78
Si	5.804	5.806	5.746	7.333	7.347	2.730	2.732	3.094	3.129	2.826	2.837	0.000	0.00
™AI	0.196	0.194	0.254	0.667	0.653	1.270	1.268	0.906	0.871	1.155	1.146		0.00
Ti	0.002	0.001	0.000	0.127	0.132	0.065	0.141	0.031	0.026			0.003	0.95
۷IAI	3.832	3.810	3.770	16.290	16.723	0.376	0.311	1.762	1.742			0.014	0.00
Cr	0.004	0.001	0.000	0.010	0.010							0.004	0.00
Fe ³⁺	0.166	0.189	0.230			0.000	0.000	0.000	0.000	0.001	0.001	1.981	
Fe ²⁺	5.048	4.994	5.049	3.302	2.969	1.130	1.465	0.166	0.180			0.994	1.10
Mn	0.093	0.021	0.023	0.001	0.001	0.002	0.000	0.000	0.001			0.001	0.00
Mg	0.471	0.750	0.244	0.560	0.390	1.359	0.959	0.075	0.088	0.000	0.000	0.000	0.00
Zn				0.114	0.115							0.001	0.00
Ca	0.478	0.330	0.808	0.002	0.002	0.000	0.004	0.000	0.002	0.181	0.167	0.001	0.00
Na	0.000	0.000	0.003	0.001	0.000	0.056	0.055	0.201	0.184	0.860	0.874		
К				0.000	0.003	0.838	0.858	0.809	0.813	0.004	0.003		
Ва						0.002	0.003	0.003	0.003	0.000	0.000		

Sample:	KL-21	KL-21	KL-21	KL-21	KL-21	KL-21	KI-19	KI-19	KI-19	KI-19	KI-19	KI-19
Grain:	Mnz217	Mnz216	Mnz216	Mnz240	Mnz240	Mnz226	Mnz 334	Mnz 334	Mnz326	Mnz330	Mnz317	Mnz317
*T. P.:	mic.	Sp	Sp	Sp	Sp	mic.	in Grt	in Grt	in Grt	Sp	Sp	Sp
**S.P:	core	core	rim	core	rim	core	rim	rim	rim	rim	core	rim
wt%												
P_2O_5	31.46	30.24	31.37	30.07	29.31	31.19	32.08	31.29	31.21	32.29	32.46	33.02
SiO ₂	1.17	0.74	0.96	0.63	1.40	1.15	0.23	0.34	0.19	0.07	0.25	0.19
ThO ₂	8.97	9.80	6.89	9.67	9.82	9.67	4.42	5.56	4.30	5.50	5.25	5.01
UO ₂	0.49	0.58	0.42	0.76	0.65	0.48	0.40	0.37	0.42	0.82	0.51	0.85
La_2O_3	11.75	11.44	12.64	11.84	11.53	11.42	14.36	13.73	13.46	14.41	13.79	14.16
Ce_2O_3	27.40	26.19	28.11	26.58	26.87	26.15	30.49	29.24	29.41	29.49	28.71	29.48
Pr_2O_3	3.07	2.71	3.07	3.00	3.05	2.96	3.12	3.18	3.25	3.24	3.29	3.34
Nd_2O_3	10.37	10.42	10.98	10.29	10.54	10.12	11.25	11.24	11.33	11.35	11.03	11.11
Sm_2O_3	2.23	2.24	2.21	2.13	2.33	2.16	1.91	1.97	2.16	2.06	2.11	2.10
Eu_2O_3	0.31	0.20	0.14	0.30	0.18	0.34	0.49	0.43	0.53	0.53	0.66	0.65
Gd_2O_3	1.67	1.42	1.73	1.69	1.64	1.64	1.16	1.32	1.52	1.20	1.42	1.28
Tb_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dy ₂ O ₅	0.66	0.65	0.60	0.60	0.83	0.67	0.25	0.07	0.29	0.09	0.64	0.01
Er_2O_3	0.11	0.01	0.05	0.02	0.19	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Yb ₂ O ₃	0.00	0.00	0.11	0.02	0.01	0.00	0.01	0.00	0.00	0.04	0.00	0.00
Y_2O_3	2.15	2.12	2.22	1.95	2.33	2.23	0.80	1.07	1.60	0.27	2.05	0.29
CaO	1.10	1.57	0.77	1.72	1.08	1.31	0.89	1.05	0.99	1.32	1.02	1.22
Tot.	102.91	100.34	102.28	101.27	101.76	101.50	101.85	100.85	100.65	102.69	103.19	102.70
element												
Р	0.992	0.988	0.996	0.982	0.957	0.994	1.020	1.010	1.010	1.022	1.017	1.032
Si	0.044	0.029	0.036	0.024	0.054	0.043	0.008	0.013	0.007	0.002	0.009	0.007
Th	0.076	0.086	0.059	0.085	0.086	0.083	0.038	0.048	0.037	0.047	0.044	0.042
U	0.004	0.005	0.003	0.007	0.006	0.004	0.003	0.003	0.004	0.007	0.004	0.007
La	0.161	0.163	0.175	0.168	0.164	0.159	0.199	0.193	0.190	0.199	0.188	0.193
Ce	0.374	0.370	0.386	0.375	0.380	0.360	0.419	0.408	0.412	0.404	0.389	0.399
Pr	0.042	0.038	0.042	0.042	0.043	0.041	0.043	0.044	0.045	0.044	0.044	0.045
Nd	0.138	0.144	0.147	0.142	0.145	0.136	0.151	0.153	0.155	0.152	0.146	0.147
Sm	0.029	0.030	0.029	0.028	0.031	0.028	0.025	0.026	0.028	0.027	0.027	0.027
Eu	0.004	0.003	0.002	0.004	0.002	0.004	0.006	0.006	0.007	0.007	0.008	0.008
Gd	0.021	0.018	0.022	0.022	0.021	0.020	0.014	0.017	0.019	0.015	0.017	0.016
Tb	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Dy	0.008	0.008	0.007	0.007	0.010	0.008	0.003	0.001	0.004	0.001	0.008	0.000
Er	0.001	0.000	0.001	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Yb	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Y	0.043	0.044	0.044	0.040	0.048	0.045	0.016	0.022	0.033	0.005	0.040	0.006
Са	0.044	0.065	0.031	0.071	0.044	0.053	0.036	0.043	0.040	0.053	0.041	0.048
Cat. Sum	1.98	1.99	1.98	2.00	1.99	1.98	1.98	1.99	1.99	1.98	1.98	1.98

* T.P. = Textural position of the grain, mic. = microlithon, Sp = main foliation;

**S.P. = EMP Spot Position

Sample	Mnz	Spot	Textural	Analysis	Isotope ratios						Apparent ages (Ma)						% Th-Pb disc.*
number	number	location	Position	number	²⁰⁶ Pb/ ²³⁸ U	1s % (Prop)	²⁰⁷ Pb/ ²³⁵ U	1s % (Prop	208Pb/232Th	1s % (Prop)	²⁰⁶ Pb/ ²³⁸ U	1s abs	²⁰⁷ Pb/ ²³⁵ U	1s abs	²⁰⁸ Pb/ ²³² Th	1s abs	
KL-21	Mnz 240	core	main foliation.	JI04a006	0.08102	0.14%	0.70437	2.36%	0.02514	0.05%	502.2	8.8	541.4	18.2	501.9	9.9	0%
KL-21	Mnz 239	core	main foliation	JI04a007	0.00636	0.01%	0.05281	0.22%	0.00194	0.00%	40.9	0.8	52.3	2.2	39.2	0.7	4%
KL-21	Mnz 237	core	in microlithon	JI04a008	0.00684	0.01%	0.08716	0.39%	0.00177	0.00%	43.9	0.9	84.9	3.7	35.7	0.7	19%
KL-21	Mnz 226	rim	main foliation	JI04a009	0.00849	0.02%	0.06370	0.49%	0.00187	0.00%	54.5	1.3	62.7	4.8	37.8	0.9	31%
KL-21	Mnz 226	rim	main foliation	JI04a010	0.00637	0.01%	0.05415	0.28%	0.00198	0.00%	40.9	0.8	53.5	2.8	40.0	0.9	2%
KL-21	Mnz 228	rim	in microlithon	JI04a011	0.00670	0.01%	0.05764	0.32%	0.00158	0.00%	43.0	0.9	56.9	3.1	31.9	0.6	26%
KL-21	Mnz 229	rim	main foliation	JI04a012	0.00532	0.01%	0.04358	0.16%	0.00175	0.00%	34.2	0.6	43.3	1.6	35.3	0.7	-3%
KL-21	Mnz 229	rim	main foliation	JI04a013	0.00568	0.01%	0.04721	0.22%	0.00178	0.00%	36.5	0.7	46.8	2.1	35.9	0.7	2%
KL-21	Mnz 242	core	in microlithon	JI04a014	0.00495	0.01%	0.03895	0.15%	0.00145	0.00%	31.8	0.6	38.8	1.5	29.3	0.6	8%
KL-21	Mnz 217	rim	in microlithon	JI04a015	0.00574	0.01%	0.04549	0.21%	0.00180	0.00%	36.9	0.7	45.2	2.1	36.3	0.7	1%
KL-21	Mnz 216	rim	main foliation	JI04a016	0.00568	0.01%	0.04702	0.19%	0.00178	0.00%	36.5	0.7	46.7	1.9	35.9	0.7	2%
KL-21	Mnz 216	rim	main foliation	JI04a017	0.00590	0.01%	0.04796	0.17%	0.00187	0.00%	37.9	0.7	47.6	1.7	37.8	0.7	0%
KL-21	Mnz 218	rim	main foliation	JI04a020	0.00490	0.01%	0.04404	0.21%	0.00152	0.00%	31.5	0.6	43.8	2.1	30.7	0.6	3%
KL-21	Mnz 212	rim	main foliation	JI04a021	0.00601	0.01%	0.04699	0.20%	0.00187	0.00%	38.6	0.7	46.6	2.0	37.8	0.7	2%
KL-21	Mnz 209	rim	main foliation	JI04a022	0.00626	0.01%	0.05054	0.19%	0.00184	0.00%	40.2	0.7	50.1	1.9	37.2	0.7	8%
KL-21	Mnz 208	rim	main foliation	JI04a024	0.00538	0.01%	0.04364	0.23%	0.00166	0.00%	34.6	0.7	43.4	2.3	33.5	0.7	3%
KL-21	Mnz 206	core	in microlithon	JI04a026	0.00571	0.01%	0.04803	0.22%	0.00175	0.00%	36.7	0.7	47.6	2.1	35.3	0.7	4%
KL-21	Mnz 204	rim	in microlithon	JI04a027	0.00417	0.01%	0.04341	0.19%	0.00129	0.00%	26.8	0.5	43.1	1.9	26.1	0.6	3%
KL-21	Mnz 203	rim	in microlithon	JI04a028	0.01072	0.02%	0.08327	0.41%	0.00182	0.00%	68.7	1.3	81.2	4.0	36.8	0.7	47%
KL-21	Mnz 201	rim	main foliation	JI04a029	0.00613	0.01%	0.05576	0.24%	0.00188	0.00%	39.4	0.8	55.1	2.4	38.0	0.7	4%
KL-21	Mnz 201	rim	main foliation	JI04a030	0.00613	0.01%	0.04533	0.16%	0.00187	0.00%	39.4	0.7	45.0	1.6	37.8	0.7	4%
KL-19	Mnz 301	rim	in staurolite	JI04b006	0.00533	0.01%	0.04270	0.14%	0.00186	0.00%	34.3	0.6	42.5	1.4	37.6	0.5	-9.6%
KL-19	Mnz 304	rim	main foliation	JI04b009	0.00582	0.01%	0.04524	0.13%	0.00183	0.00%	37.4	0.6	44.9	1.2	37.0	0.5	1.2%
KL-19	Mnz 306	core	in microlithon	JI04b010	0.00588	0.01%	0.05253	0.12%	0.00179	0.00%	37.8	0.7	52.0	1.2	36.1	0.5	4.4%
KL-19	Mnz 307	rim	In magnetite	JI04b011	0.00479	0.01%	0.03086	0.10%	0.00151	0.00%	30.8	0.5	30.9	1.0	30.5	0.4	1.0%
KL-19	Mnz 308	rim	main foliation	JI04b012	0.00637	0.01%	0.04944	0.15%	0.00195	0.00%	40.9	0.7	49.0	1.4	39.4	0.7	3.8%
KL-19	Mnz 308	rim	main foliation	JI04b013	0.00643	0.01%	0.04187	0.11%	0.00202	0.00%	41.3	0.7	41.6	1.1	40.8	0.7	1.3%
KL-19	Mnz 311	rim	main foliation	JI04b015	0.00564	0.01%	0.03922	0.11%	0.00173	0.00%	36.3	0.6	39.1	1.1	34.9	0.5	3.6%
KL-19	Mnz 311	rim	main foliation	JI04b016	0.00571	0.01%	0.04748	0.15%	0.00175	0.00%	36.7	0.6	47.1	1.5	35.3	0.5	3.7%
KL-19	Mnz 313	rim	in microlithon	JI04b017	0.00576	0.01%	0.04163	0.10%	0.00181	0.00%	37.0	0.6	41.4	1.0	36.6	0.5	1.3%
KL-19	Mnz 317	rim	main foliation	JI04b018	0.00623	0.01%	0.04728	0.11%	0.00205	0.00%	40.0	0.7	46.9	1.1	41.4	0.7	-3.4%
KL-19	Mnz 317	rim	main foliation	JI04b019	0.00601	0.01%	0.04784	0.12%	0.00194	0.00%	38.6	0.7	47.4	1.2	39.2	0.7	-1.4%
KL-19	Mnz 319	rim	main foliation	JI04b020	0.00648	0.01%	0.05056	0.14%	0.00205	0.00%	41.6	0.7	50.1	1.4	41.4	0.7	0.6%
KL-19	Mnz 319	rim	main foliation	JI04b021	0.00642	0.01%	0.05122	0.15%	0.00204	0.00%	41.3	0.7	50.7	1.5	41.2	0.7	0.2%
KL-19	Mnz 322	rim	main foliation	JI04b023	0.00467	0.01%	0.03758	0.11%	0.00153	0.00%	30.0	0.5	37.5	1.1	30.9	0.5	-2.9%
KL-19	Mnz 330	rim	main foliation	JI04b025	0.00464	0.01%	0.03634	0.12%	0.00145	0.00%	29.8	0.6	36.2	1.2	29.3	0.4	1.9%
KL-19	Mnz 334	rim	in garnet	JI04b027	0.00681	0.01%	0.05160	0.18%	0.00216	0.00%	43.8	0.8	51.1	1.8	43.6	0.7	0.3%
KL-19	Mnz 334	core	in garnet	JI04b028	0.00708	0.01%	0.05196	0.17%	0.00221	0.00%	45.5	0.8	51.4	1.7	44.6	0.7	1.9%
KL-19	Mnz 334	rim	in garnet	JI04b029	0.00754	0.02%	0.05575	0.29%	0.00241	0.00%	48.4	1.0	55.1	2.9	48.7	0.9	-0.5%
KL-19	Mnz 332	core	main foliation	JI04b030	0.00537	0.01%	0.04173	0.14%	0.00166	0.00%	34.5	0.6	41.5	1.4	33.5	0.5	2.9%

* Prop = propagated error

** % Th-Pb disc. = % of Th-Pb discordance

Spot Name	% Pbc	U (ppm)	Th (ppm)	²³² Th/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	1 sigma %	²⁰⁶ Pb/ ²³⁸ U	1 sigma %	errcorr	²⁰⁷ Pb-corrected ²⁰⁶ Pb/ ²³⁸ U	1 sigma	²⁰⁷ Pb-corrected ²⁰⁶ Pb/ ²³⁸ U age	1 sigma Zoning	
KL19-312.1	2.43	3582	19644	5.7	0.011162	42.8	0.0027128	2.13	0.05	0.002770	0.000045	17.8	0.3 unzoned	
KL19-312.2	0.84	3340	21237	6.6	0.031580	9.6	0.0048082	1.62	0.17	0.004802	0.000074	30.9	0.5 unzoned	
KL21-216.1	1.96	1920	33047	17.8	0.022079	28.7	0.0050137	1.88	0.07	0.005107	0.000083	32.8	0.5 rim	
KL19-308.1	1.80	4179	26781	6.6	0.037137	8.7	0.0053770	1.55	0.18	0.005354	0.000081	34.4	0.5 rim	
KL21-216.2	1.08	2847	49706	18.0	0.026413	14.7	0.0054342	1.62	0.11	0.005513	0.000086	35.4	0.6 rim	
KL19-307	1.03	2701	17622	6.7	0.034664	10.5	0.0055063	1.60	0.15	0.005514	0.000084	35.4	0.5 unzoned	
KL19-308.3	0.90	3694	21494	6.0	0.036107	12.5	0.0056928	1.62	0.13	0.005698	0.000084	36.6	0.5 rim	
KL21-212	1.39	2536	44690	18.2	0.035865	14.2	0.0059520	1.66	0.12	0.005975	0.000091	38.4	0.6 unzoned	
KL21-4	0.80	2052	27504	13.8	0.028114	23.6	0.0059299	1.87	0.08	0.006023	0.000098	38.7	0.6 unzoned	
KL21-201.1	2.09	3703	62310	17.4	0.015617	59.3	0.0059001	1.93	0.03	0.006106	0.000096	39.2	0.6 unzoned	
KL19-317.2	0.64	4701	34309	7.5	0.025332	20.8	0.0061216	1.64	0.08	0.006252	0.000094	40.2	0.6 rim	
KL19-317.1	1.09	4044	31074	7.9	0.033934	11.4	0.0062471	1.64	0.14	0.006306	0.000100	40.5	0.6 rim	
KL21-216.3	1.06	3555	61072	17.8	0.037972	13.7	0.0063039	1.71	0.12	0.006329	0.000101	40.7	0.6 core	
KL19-301	1.18	3501	76746	22.6	0.038289	13.3	0.0064700	1.66	0.12	0.006502	0.000100	41.8	0.6 rim	
KL19-330	0.77	3883	25415	6.8	0.036640	11.2	0.0065488	1.57	0.14	0.006601	0.000099	42.4	0.6 unzoned	
KL19-308.2	0.21	3706	24947	7.0	0.043585	7.3	0.0070936	1.53	0.21	0.007115	0.000107	45.7	0.7 core	

Pbc : common lead