Records of Himalayan Metamorphism and Contractional Tectonics in the central Himalayas (Darondi Khola, Nepal)

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Abstract

The Himalayan orogen exposes a range of metamorphosed assemblages, from low-grade Indian shelf sediments of the Tethyan Formation to eclogite and ultra-high pressure rocks documented near the suture zone between the Indian craton and Asian subcontinent. Barrovian-grade pelites and mafic protoliths are exposed in the Himalayan core and include the Greater Himalayan Crystallines and Lesser Himalayan Formations. These units are separated by the Main Central Thrust (MCT). This fault system accommodated a significant amount of India-Asia convergence and is the focus of several models that explore ideas about the development of the range and collisional belts in general. These units provide critical information regarding the mechanisms of heat transfer within collisional belts. Garnets collected across the MCT record their growth history through changes in chemistry. These chemical changes can be extracted and modeled using a variety of thermodynamic approaches. This paper reviews the geological framework of the Himalayas with a focus on the protolith of its metamorphosed assemblages. It describes and applies particular thermobarometric techniques to decipher the metamorphic history of several garnet-bearing rocks collected across the MCT in central Nepal. Comparisons are made between the results of previously-reported conventional rim P-T conditions and P-T paths extracted using the Gibb's method to isopleth thermobarometry and high-resolution P-T path modeling using the same data and assemblages. Predictions of the paths on garnet zoning are also presented for the high-resolution P-T path modeling and Gibb's method using the program TheriaG. Although the approaches yield different absolute conditions and P-T path shapes, all are consistent with the

development of the MCT shear zone due to imbrication of distinct rock packages. Greater Himalayan Crystalline garnets experienced higher-grade conditions that make extracting its P-T conditions and paths a challenge. Lesser Himalayan garnets appear to behave as closed systems and are ideally suited for thermodynamic approaches.

1 Introduction

Nineteenth-century geologists studying the Himalayas perceived an anomalous geologic relationship that appeared to contradict two commonly accepted principles: the oldest rocks in a sedimentary succession are found at the base of the pile, and metamorphosed strata are older than unmetamorphosed. The Main Central Thrust (MCT), located at the base of the Himalayan break in slope, places lower-grade Lesser Himalayan Formation (LHF) metasediments beneath high-grade gneisses of the Greater Himalayan Crystallines (GHC) (Figure 1 and Figure 2). Exploration of the Himal Pradesh region in northern India surprised the pioneering geologists (Medicott, 1864; Oldham, 1883; Middlemiss, 1887) who saw the highest-grade, and thus supposedly oldest rocks, form the tallest peaks:

> "Now the belief which is at present so rapidly gaining ground that metamorphic strata are presumably older than unmetamorphosed strata makes one at first glance assume the strong probability in favor of the inner schistose series [Greater Himalayan Crystallines] being of much greater age than the outer zone of formations [Lesser Himalaya]. But no sooner has this a priori probability obtained a firm hold of the mind than a rude shock is given to it by the discovery that at every point round the schistose area the Outer formations appear to dip towards and under the schistose series at steep angles (50°-60°), whilst the schistose series itself is disposed apparently…upon the top of the Outer Formations, and culminating in a capping of gneissose rock on the summit of Kalogarhi mountain, the highest point in the neighborhood (Middlemiss, 1887)."

The recognition of widespread thrusting within the Himalaya was largely based on the observations (von Loczy, 1907; Pilgrim & West, 1928; Auden, 1937; Heim and Gansser, 1939) and the orogen's "inverted metamorphism," an increase in metamorphic intensity towards higher structural levels, appeared resolved by invoking compressional/contractional tectonics and the thrusting of the GHC unit on top of the LHF. However, future studies indicated that the kyanite isograd remained unbroken across the MCT, and its footwall is characterized by an inverted geotherm (Figure 3) (Ray, 1947; Gansser, 1964; LeFort, 1975; Pêcher, 1989; England et al., 1992). The idea of Himalayan inverted metamorphism reemerged but was relocated to the MCT footwall.

Inverted metamorphic gradients suggest the presence of wholly overturned strata or heat sources that counteract the influence of the asthenosphere (e.g., England & Molnar, 1993; Jamieson et al., 1996; Grasemann & Vannay, 1999; Kidder et al., 2013). The cause of the phenomenon has implications for establishing mechanisms of heat transfer within collisional belts and the role of heat sources, such as shear heating in fault zones, heat advection by magmas, radiogenic heating, and asthenospheric input. Inverted metamorphism has long been associated with areas of extensive thrust faulting, where heat is thought to flow from a hot upper plate to a colder lower plate (Ernst, 1973; Graham & England, 1976; Spear et al., 1995). Some models of Himalayan orogenesis link the apparently anomalous geothermal gradient spatially and temporally with motion along the MCT, whereas others suggest a juxtaposition of previously

metamorphosed sequences (Searle & Rex, 1989; Harrison et al., 1999; Hodges, 2000; Dasgupta et al., 2004; Larson et al., 2015).

The MCT has accommodated a significant amount of Indo-Asian convergence (e.g., Schelling & Arita, 1991; Yin & Harrison, 2000; Yin, 2006; Tobgay et al., 2012; Roberts et al., 2020), but other large-scale structures, including crustal-scale strike-slip faults to the north, active thrusts to the south, and the Main Himalayan Thrust (MHT) decollement compete for strain accommodation (Figure 2). The MCT has long been thought to be presently quiescent (Ye et al., 1981; Ni & Barazangi, 1984; Schelling & Arita, 1991; England et al., 1992). However, some earthquakes, like the 2015 Nepal (Gorkha) and 1991 Uttarkashi (Garhwal) events, challenge the notion, as their epicenters and epicenters of their aftershocks are modeled to zones within the LHF (Thakur & Kumar, 1994; Jain & Chander, 1995; Kayal, 1996; Gupta et al., 2015; Bai et al., 2016; Catlos et al., 2020). The MCT has also been linked to the generation of numerous geologic elements that characterize the Himalayan range, including hanging wall anatectic granitoids and crustal-scale extension found in association with the GHC (e.g., Burg et al., 1984; Valdiya, 1988; Burchfiel et al., 1992; Harrison et al., 1997; Kawakami et al., 2019).

Studies of the MCT hanging wall indicate the unit has discontinuities possibly related to internal structures (e.g., western Nepal, Carosi et al., 2010; Montomoli et al., 2013; Braden et al., 2017; central Nepal, Cottle et al., 2015; Wang et al., 2013; 2016; Rapa et al., 2018; Larson et al., 2015; Sikkim, Chakraborty et al., 2019; NW India, Iaccarino et al., 2020; Benetti et al., 2021; see discussions in Mukherjee et al., 2012; Larson et al., 2013; Montomoli et al., 2015). The nature of these cryptic discontinuities is unclear and could be due to unmapped faults or shear zones or inheritance of pre-existing basement structures (e.g., Cottle et al., 2015). Their presence enhances the complexity of the Himalayan orogenic system as their activity could have significantly disrupted geotherms within the GHC core during its exhumation. This is a scenario that is not accounted for in the channel flow model for the extrusion of the Himalayan core (e.g., Benetti et al., 2021; Maiti & Mandal, 2021). Understanding when Himalayan fault systems were active is critical for deciphering the processes involved during convergence.

The metamorphic history of the Himalayas has been the focus of sustained attention for almost seventy-five years (e.g., Ray, 1947). Garnet-bearing assemblages have long been using to test hypotheses proposed for the origin of MCT inverted metamorphism, understand the slip history of the MCT and the dynamics of Himalayan convergence. The focus includes generating the peak pressure-temperature (P-T) conditions and paths that rocks followed as they were metamorphosed during Indo-Asia collision (e.g., Brunel and Kienast, 1986; Hodges et al., 1988; Hodges and Silverberg, 1988; Hubbard, 1989; Inger and Harris, 1992; Hodges et al., 1993; Metcalfe, 1993; Pognante and Benna, 1993; Kaneko, 1995; Macfarlane, 1995; Coleman, 1996; Vannay and Hodges, 1996; Vannay and Grasemann, 1998; Manickavasagam et al., 1999; Catlos et al., 2001; Kohn et al., 2001; Kohn, 2008; Phukon et al., 2019; Waters, 2019; Iaccarino et al., 2020; Catlos et al., 2018; 2020).

As a universal outcome, models for the development of the Himalayas predict the P-T paths that rocks follow as they track the conditions they experienced during displacement. Common approaches to generate Himalayan P-T paths have included connecting peak metamorphic conditions of individual rocks, inferring from mineral assemblages, pseudosections, or Gibbs method thermodynamic modeling. Some rocks yield problematic P-T estimates based on (1) a lack of evidence of phases in equilibrium among phases, (2) the application of barometers to inappropriate (uncalibrated) mineral compositions, and (3)

calculated conditions that appear at odds to observed mineral assemblages and structural data (e.g., Kohn & Spear, 2000; Kohn, 2008). P-T paths and absolute peak P-T conditions may not be diagnostic of tectonic processes involved (e.g., Gervais & Brown, 2011). Low-resolution P-T paths can be limited in their ability to test ideas regarding lithospheric response to perturbations, including motion within fault zones. However, this type of information can be used to supplement other data, such as the timing of deformation or strain recorded in microstructures (see Kohn, 2016; Rolfo et al., 2014).

This paper has two goals. The first is to review the geological framework of the Himalayas with a focus on the protolith of its metamorphosed assemblages. The second is to describe and apply particular thermobarometric approaches to decipher the metamorphic history of garnet-bearing rocks collected from the central portion of the range across the MCT using data published in the literature (Darondi Khola, Figure 3, Figure 4, Figure 5) (Kohn et al., 2001). A range of approaches are available to obtain P-T and time garnet growth (P-T-t data) (see review by Waters, 2019). The Darondi Khola case study compares conventional and isopleth thermobarometry in terms of their outcomes and insights and presents new P-T paths from metamorphosed garnet-bearing rocks using previously collected data. Garnet-bearing pelitic assemblages exposed in units across the Himalayas contain information regarding their history that can be extracted and applied to test models developed to decipher the crustal response during orogeny.

2 Geological Background

The Himalayan arc extends ~2400 km from Nanga Parbat (8138 m) in the west to Namche Barwa (7756 m) in the east (e.g., Le Fort, 1996) (Figure 1 and Figure 2). This region includes the independent kingdoms of Nepal and Bhutan and parts of Pakistan, India, and China. The orogen forms a sharp transition between the average ~5 km-high, arid Tibetan plateau and the warmer, wetter Indian lowlands and is comprised of roughly parallel, crustal-scale fault systems that bound distinctive lithologic units along strike (DiPietro & Pogue, 2004; Yin, 2006). These units have Indian affinity and experienced variable degrees of metamorphism before their assembly with Asia.

2.1 Geological framework before collision

The Indian subcontinent initiates rifting from other continents and fragments associated with Gondwana during the Early Cretaceous (140-130 Ma, e.g., Scotese et al., 1988; Jadoul et al., 1998; Hu et al., 2010). Evidence for Early Cretaceous rift- and plume-related alkaline and basaltic volcanism exists within the LHF, which extends the entire length of the Himalayas, and is the oldest stratigraphically lowest unit (e.g., Sakai et al., 2013; Bhandari et al., 2019). The LHF is considered the MCT footwall and Main Boundary Thrust (MBT) sheet (Figure 1 and Figure 2) (Dey et al., 2020). It is mainly comprised of Paleoproterozoic Gondwana-associated sediments that experienced deposition and granite intrusion centered around 1800 Ma (e.g., Trivedi et al., 1984; Tripathi & Singh, 1987; Parrish & Hodges, 1996; Miller et al., 2000; DeCelles et al., 2004; Kohn et al., 2010; Martin et al., 2011; McKenzie et al., 2011; Long et al., 2011; Sakai et al., 2013; Khanal et al., 2014; Mandal et al., 2016). The depositional environment is a passive-margin, shallow-water coastal, fluvial, volcanoclastic (e.g., Parrish & Hodges, 1996; Ahmad et al., 1999; Martin et al., 2011; Sakai et al., 2013; Bhandari et al., 2019). However, the lower section of the LHF may have formed in a continental arc on the northern margin of the Indian plate (Kohn et al., 2010; Mandal et al., 2016). In some locations, rift-related alkaline

trachytic lava and pillow-bearing volcanic rocks are interbedded with pebble conglomerates and black shales, and signatures of significant asthenosphere upwelling are evident using geochemical proxies (e.g., Ahmad et al., 1999; Larson et al., 2019; Bhandari et al., 2019).

The stratigraphic classification of the Proterozoic succession of Lesser Himalaya is yet to be defined following the Code of Stratigraphic Nomenclature, and orogen-scale correlations along strike are hindered by uncertainties (Myrow et al., 2006; Long et al., 2011; Mandal et al., 2016; Dey et al., 2020). Sedimentation was long-lasting, but a lack of fossiliferous assemblages makes correlating specific units problematic (Upreti, 1999; Martin et al., 2011; Long et al., 2011). Detrital zircon geochronology and stable isotopic analysis of suitable assemblages assist in this regard (e.g., Long et al., 2011; Martin et al., 2011; Sakai et al., 2013). A series of augen gneisses (the Melung Salleri or Phaplu Augen Gneiss of eastern Nepal and NW India, the Ulleri of central Nepal, or Chainpurplay in western Nepal) distinguish different levels of the MCT shear zone and LHF stratigraphy (Figure 3, Figure 4, Figure 5) (Kohn et al., 2010; Dyck et al., 2019; Jharendra & Paudyal, 2019). These gneisses have ages from 2.2 Ga to 900 Ma (e.g., Le Fort & Rai, 1999; DeCelles et al., 2000; Catlos et al., 2002; Kohn et al., 2010) and define the base of the MCT shear zone in some interpretations. A Permian-Cambrian unconformity is recognized in NW India, Nepal, and Bhutan (e.g., Bhargava et al., 2011; Martin et al., 2011; Long et al., 2011). Some have related its presence and Cambro-Ordovician granites found in GHC and LHF units to a pre-Tertiary orogeny (Gehrels et al., 2003; 2006; Cawood et al., 2007; Bhargava et al., 2011).

The GHC protolith is a clastic sedimentary sequence intruded by Cambro-Ordovician granitoids (e.g., Trivedi et al., 1984; Bhargava & Bassi, 1994; Parrish & Hodges, 1996; Upreti & Le Fort, 1999; DeCelles et al., 2004; Dyck et al., 2019). The depositional age is bracketed between the age of the youngest detrital zircons (~800-600 Ma) and granite intrusions (~500-460 Ma) (Ahmad et al., 2000; DeCelles et al., 2000; DeCelles et al., 2004; Martin et al., 2005; Dyck et al., 2019). Whole-rock Nd isotopes distinguish GHC [εNd(0) -19 to -12, average -16] from LHF affinities [εNd(0) -20 to -26, average -21.5] (Robinson et al., 2001; Martin et al., 2005). The GHC detrital zircons may have originated from the East African portion of the Pan-African orogeny (Arabian-Nubian Shield), uplifted during the Neoproterozoic (DeCelles et al., 2000; 2004), or from the late Mesoproterozoic terranes of Western Australia and East Antarctica (Circum-East Antarctic Orogen, Upreti & Yoshida, 2005; Yoshida & Upreti, 2006). The GHC has been modeled as unconformably deposited on the LHF (Parrish & Hodges, 1996) or tectonically juxtaposed (Upreti & Le Fort, 1999; DeCelles et al., 2000). The similarity in Cambrian ages between the LHF and GHC suggest they may be part of a shared depositional environment, with the LHF as proximal and the GHC as distal (Brookfield, 1993; Parish & Hodges, 1996; Corfield & Searle, 2000; Myrow et al., 2003; Myrow et al., 2006; Long et al., 2011). Alternatively, the GHC may have been a distinct basement unit separating the LHF from the Tethyan metasediments (Saxena, 1971; Aharon et al., 1987) or an exotic terrane involved in a pre-Himalayan collision (DeCelles et al., 2000; Gehrels et al., 2003).

Tethyan sedimentary and metasedimentary rocks are bounded to the north by the Indus Yarlung-Tsangpo suture zone (also Yarlung Zangbo Ophiolite Zone, Liu et al. 2010) (Gansser, 1964; Dewey & Bird, 1970; Burg et al., 1984; Yin et al., 1994; Quidelleur et al., 1997; Zhang et al., 2004; Yin, 2006; Zyabrev et al., 2008), and to the south by the GHC or South Tibetan Detachment System (STDS) (Figure 1 and Figure 2) (e.g., Makovsky & Klemperer, 1996; Wu et al., 1998; Searle, 2010; Long et al., 2017; Montomoli et al., 2017; Hughes et al., 2018; Kellett et

al., 2018; Long et al., 2019). The Great Counter Thrust (or the Renbu-Zedong Thrust or Himalayan Backthrust) is mapped south of the zone also works to accommodate crustal shortening (Yin et al., 1999; Yin, 2006; Aikman et al., 2008). The Tethyan unit has long been considered as a contiguous stratigraphic cover of the GHC (Bodenhausen et al., 1964; Bordet et al., 1971; Stöcklin, 1980; Garzanti & Pagni Frette, 1991; Brookfield, 1993; Liu & Einsele, 1994; Fuchs & Linner, 1995; Vannay & Steck, 1995; Garzanti, 1999; Dyck et al., 2019), and the suture zone marks the geological boundary separating rocks of Indian and Asian affinity (e.g., Gansser, 1981; Yin & Harrison, 2000). In NW India, the Tethyan Formation may be in thrust contact with the LHF (Webb et al., 2007). The Tethyan Formation consists of Paleoproterozoic to Eocene Indian shelf sediments (marine, fossiliferous strata) interbedded with Paleozoic and Mesozoic volcanic assemblages (Bassoullet et al., 1980; Brookfield, 1993; Yin, 2006; Bhargava & Singh, 2020). The unit has been divided into four sequences: a Proterozoic to Devonian pre-rift, a Carboniferous–Lower Jurassic rift and post-rift, Jurassic–Cretaceous passive continental margin sequence, and an uppermost Cretaceous–Eocene syn-collision sequence (Liu & Einsele, 1994; Garzanti, 1999; Yin, 2006). Tethyan Formation lithostratigraphy changes both along and perpendicular to the Himalayan orogeny (Brookfield, 1993; Yin, 2006). In some locations, the unit has undergone pre-Himalaya low-grade to greenschist facies metamorphism (e.g., Crouzet et al., 2007; Dunkl et al., 2011; Montomoli et al., 2017) and the latest Cretaceous to Paleocene sequence of the formation records the obduction of ophiolitic material (Allègre et al., 1984; Burg et al., 1987; Willems et al., 1996; Gnos et al., 1997; Makovsky et al., 1999; Aitchison et al., 2000; Ding et al., 2005).

2.2 Timing of major metamorphic events and fault systems

2.2.1 Collision and metamorphism in the Tethyan Formation

The Indian subcontinent moves over 60° latitude north towards Asia during the mid-Mesozoic to Eocene, closing the ancient Neo-Tethyan Ocean (e.g., Burg, 2011). The Early Cretaceous (140-130 Ma) is often cited as the time when the Indian subcontinent initiates rifting from other continents and fragments associated with Gondwana (e.g., Scotese et al., 1988; Jadoul et al., 1998; Hu et al., 2010). Remnants of Neo-Tethyan ophiolites are present across the Himalayas and provide information regarding the timing and processes involved during Indo-Asia collision and the nature of Neo-Tethyan ocean crust and upper mantle (e.g., Hébert et al., 2012; Hu et al., 2016; Catlos et al., 2019). Based on data from these ophiolites, a Late Cretaceous intra-oceanic arc has been suggested to be present within the Neo-Tethyan Ocean near the paleo-equator (e.g., Reuber, 1986; Abrajevitch et al., 2005; Metcalfe, 2009; Dai et al., 2011; Siddiqui et al., 2012; Siddiqui et al., 2017) or ~30°N (Zhu et al., 2013). The arc is recorded by the Samail (Oman), Zagros (Iran), Chagai–Raskoh (western Pakistan, southern Iran, eastern Afghanistan), Kandahar and Kohistan–Ladakh, Dazhuqu, and Zhongba arcs (Brookfield and Reynolds, 1981; Bhutani et al., 2004; Abrajevitch et al., 2005; Dai et al., 2011; Siddiqui et al., 2012; Baxter et al., 2016). Paleogeographic reconstructions of Lawver et al. (2018) restrict the location of the intra-oceanic arc to the south of the Lhasa Terrane, although others suggest the Lhasa Terrane had already accreted onto other Tibetan-related continental fragments by the Late Jurassic-Early Cretaceous (Rolland, 2002; Kapp et al., 2003, 2007; Guynn et al., 2006; Zhu et al., 2013). Alternatively, the Lhasa Terrane accreted just before the final collisional event in the Paleocene (54.9±2.3 Ma and 40.0±3.3 Ma; Yang et al., 2015; 61 Ma and ~53-48 Ma; Yuan et al., 2020). Multiple arcs, besides the Lhasa Terrane, may also have been present (e.g., Zyabrev et al., 2008). The oldest portion of the Neo-Tethyan domain is Late Triassic to Late Cretaceous (Sinha-

Roy, 1982; Şengör and Atayman, 2009; Cao et al., 2018) and is sometimes termed the Ceno-Tethyan Ocean (Metcalfe, 1999; Matsuoka et al., 2002; Wakita and Metcalfe, 2005). The Yarlung-Tsangpo suture zone itself is mapped as the zone of the closure of the Ceno-Tethyan Ocean (e.g., Metcalfe, 1999; 2009; 2013).

The timing of initial collision varies along strike of the range but is often cited as during the Paleocene (Patriat & Achache, 1984; Klootwijk et al., 1992; Rowley, 1996; Yin & Harrison, 2000; Najman et al., 2001, 2002, 2003; Zhu et al., 2005; Ding et al., 2005; Yang et al., 2015; Hu et al., 2016). Much younger constraints are also suggested (e.g., Eocene/Oligocene boundary, Aitchison et al., 2007) and a division between a soft (Paleocene) and hard collision (25-20 Ma, van Hinsbergen et al. 2012; see review in Parsons et al., 2020). In the hard scenario of Indo-Asia collision, the Tethyan unit represents the northern extension of the Indian subcontinent (Brookfield, 1993; Yin & Harrison, 2000; Myrow et al., 2003, Hughes et al., 2005; Myrow et al., 2009; Myrow et al., 2015; Hughes, 2016). Others suggest the Tethyan formation may have been an independent terrane in the Mesozoic (DeCelles et al., 2000; see review in Yuan et al., 2020). Parsons et al. (2020) note that little progress has been made to resolve the differences between models of Indo-Asia collision. Gehrels et al. (2003) indicates that ascertaining the relative contributions of early Paleozoic versus Tertiary tectonism poses a significant challenge in understanding the Himalayan orogen. To understand which model is relevant requires understanding the metamorphic and timing history of fault systems that were active during collision. The Great Counter Thrust, which bounds the upper portion of the Tethyan Formation along much of its strike (Figure 1), is significantly younger than the Paleocene ages of Indo-Asia collision. This structure shows activity primarily during the Miocene (20-13 Ma) across the western and central Himalayas (see review in Yin, 2006).

Compilations regarding the Tethyan Formation's metamorphic history collected along strike suggest the Tethyan sequences have experienced multiple (4-5) deformation events, although the timing of these episodes is poorly constrained (Aikman et al., 2008; Dunkl et al., 2011). Studies focusing on the low-grade history reveal Early Cretaceous pre-collisional metamorphism (e.g., Crouzet et al., 2007; Dunkl et al., 2011). Eocene greenschist to amphibolite facies metamorphism is recorded in portions of the unit and record conditions likely related to the onset of collision (580-600°C, 5-8 kbar) (Dunkl et al., 2011; Catlos et al., 2020). Paleocene radiometric ages related to collision are found in the Spongtang ophiolite (Figure 1) (64.3±0.8 Ma and 42.4±0.5 Ma, zircon U-Pb ages, Catlos et al., 2019) and in a Tethyan Formation garnet (50.3±0.6 Ma; Catlos et al., 2020). The collisional event is also recorded by eclogite, high-pressure (HP) and ultra-high pressure (UHP) rocks documented within the Tethyan Formation near the suture zone (e.g., Guillot et al., 2008; Laskowski et al., 2016). In some locations, HP assemblages record multiple metamorphic stages (e.g., Chen et al., 2021). Oligo-Miocene anchi- to epizonal metamorphism and alteration are related to crustal shortening during this time, whereas rocks at the base of the unit record Miocene STDS motion and gneiss dome exhumation (e.g., Dunkl et al., 2011). Oligocene- to Miocene-age contact metamorphism marks the onset of the intrusion of some North Himalayan granitic bodies and gneiss domes (e.g., Guillot et al., 1995, 1999; Liu et al., 2016; Gao et al., 2016; Lihter et al., 2020). The onset of the north-dipping STDS and its associated imbrications (Figure 1) is often constrained to the Miocene (Carosi et al., 1998, 1999a, 1999b; Searle, 1999; Sachan et al., 2010; Iaccarino et al., 2017; Long et al., 2017; Montomoli et al., 2017; Kellett et al., 2018; Iaccarino et al., 2020). However, at some locations, the GHC shows a transitional relationship with limestone of the Tethys sediments and metamorphic grade remains unchanged across the STDS with stratigraphy and lithology

excluding a distinct fault boundary (e.g., Bordet et al., 1975; Stöcklin, 1980; Fuchs et al., 1988; Schneider & Masch, 1993; Vannay & Steck, 1995; Cooper et al., 2012; Long et al., 2017). Long et al. (2019) suggest that extensional motion associated with the STDS in Bhutan occurs both within the GHC and Tethyan units.

2.2.2 The GHC Eohimalayan and Neohimalayan events

The GHC is mainly comprised kyanite- to sillimanite- grade gneisses intruded by High Himalayan leucogranites in structurally higher levels (e.g., Upreti, 1999; Searle et al., 2006; Sachan et al., 2010; Wu et al., 2020). The GHC is generally divided into different units, although the assemblages that comprise its sections differ along strike (Le Fort, 1975; Myrow et al., 2003; Yin, 2006). In central Nepal (Guillot, 1999), the upper Formation III consists of augen orthogneisses, whereas the middle Formation II are calc-silicate gneisses and marbles, and the basal Formation I are kyanite- and sillimanite-bearing metapelites, gneisses, and metagreywackes with abundant quartzite. The division of the package into three units mirrors the nomenclature ~250 km east (Lombardo et al., 1993; Pognante & Benna, 1993; Carosi et al., 1999a), although the assemblages differ from that of central Nepal. In eastern Nepal, the upper Black Gneiss is comprised of biotite-sillimanite paragneisses with metaconglomerates and quartzite layers. The middle Namche Migmatite Orthogneiss contains granite-granodiorite sillimanite-bearing orthogneisses. The Barun Gneiss at the base is a migmatized paragneiss with minor metabasites, calc-silicate rocks, and marbles. In the Garhwal Himalaya, the Vaikrita Group is the analog to the GHC (e.g., Ahmad et al., 2000). Early observations, the unit's complex metamorphic history, and possibility of out-of-sequence thrusting at higher levels led Stöcklin (1980) to doubt the assumption of a three-tiered, laterally-continuous, tectonostratigraphic framework. More recent thermobarometric data and P-T-t paths from garnet-bearing assemblages from the GHC unit indicate the unit itself has discontinuities related to internal structures that overlap in age with MCT motion (Carosi et al., 2010; Montomoli et al., 2013; Wang et al., 2013; Larson et al., 2015; Montomoli et al., 2015; Carosi et al., 2016; Wang et al., 2016; Braden et al., 2017; Rapa et al., 2018; Chakraborty et al., 2019; Benetti et al., 2021).

A Tertiary history involving two metamorphic episodes has been proposed for the GHC (see Pêcher & Le Fort, 1986; Metcalfe, 1993; Pognante & Benna, 1993; Wiesmayr & Grasemann, 2002; Carosi et al., 1999b; Lombardo & Rolfo, 2000; Hodges, 2000; Wiesmayr & Grasemann, 2002; Cottle et al., 2009; Kohn, 2014; Robyr & Lanari, 2020). The first stage (Eocene-Oligocene) of Barrovian-type metamorphism, termed the Eohimalayan event, corresponds to the nappe's burial beneath Asia and is best preserved near the base of the unit (e.g., Pêcher, 1989; Hodges et al., 1994; Wiesmayr & Grasemann, 2002). During this stage, the base of the unit reached garnet-grade conditions (550-750□C and at least 8-10 kbar, e.g., Pognante & Benna, 1993; Hodges et al., 1994). Thrusting may have been accommodated by a fault system considered a proto-STDS that reactivated as a normal fault during the second stage in the Miocene (e.g., Vannay & Hodges, 1996; Wiesmayr & Grasemann, 2002; DiPietro & Pogue, 2004). The locations where this scenario has been proposed show mylonitic contractional fabrics overprinted by extensional structures and include the Himachal Pradesh, NW India (Vannay & Grasemann, 1998), Zanskar, NW India (Patel et al., 1993), and the Kali Gandaki, central Nepal (Vannay & Hodges, 1996). Note that even earlier events may have preceded Himalayan orogenesis and can be challenging to distinguish from Cenozoic tectonics (see Gehrels et al., 2003).

The Eohimalayan event occurred between 50-35 Ma coincides with a dramatic decrease in convergence rate between India and Asia from ~15 to ~4 cm/yr (Copley et al., 2010). During the Miocene Neohimalayan event, the base of the GHC experienced 550-600□C and the top records lower pressures and/or temperatures (3-7 kbar, 575-850□C) (e.g., Hodges et al., 1994; Simpson et al., 2000; Daniel et al., 2003). The Neohimalayan event has been associated with MCT slip and with the development of Miocene-age High Himalayan leucogranites found in close association with STDS (Pêcher, 1989; Harris et al., 1993; Metcalfe, 1993; Hopkinson et al., 2017; Liu et al., 2018; Yang et al., 2019; Wu et al. 2020).

The duration and onset of MCT movement varies along strike and is often attributed sometime during the Miocene. To time fault activity, monazite [(Ce, La,Th)PO4] is often targeted, a mineral that appears in these rocks at garnet grades and is ideal for timing metamorphism (e.g., Catlos, 2013). In western Bhutan, the duration of MCT displacement is bracketed by monazite ages between 20.8±1.1 and 15.0±2.4 Ma (Togbay et al., 2012). However, in eastern Bhutan, prograde metamorphism and deformation is reported to have been underway along the structure by c. 23 Ma (Daniel et al., 2003). Monazite ages from the lower portions of the GHC in western Nepal yield younger ages timed to fault motion at 17-13 Ma (Montomoli et al., 2013). Depth profiling of unpolished monazite indicate that the MCT hanging wall was deforming in central Nepal between 24-22 Ma (Harrison et al., 1995). The 22 Ma age is also attributed to MCT activity in central Nepal (Hodges et al., 1996; Coleman & Hodges, 1998)

In NW India (Garhwal region), the MCT shear zone is thought to be active from 20 Ma to 5 Ma (Iaccarino et al., 2020) or even younger to 1 Ma (Catlos et al., 2007; 2020). Mukhopadhyay et al. (2017) suggest activity on the MCT itself in the Sikkim region occurred in pulses over an extended period of time from 26 to 11 Ma. Monazite grains from the MCT shear zone in the Sikkim indicate the structure was active at c. 22 Ma, 14-15 Ma, and 12-10 Ma (Catlos et al., 2007) and from 21-13 Ma (Mottram et al., 2014). Younger ages are attributed to structures south of the GHC-LHF contact, and are often found at lower structural levels within the shear zone elsewhere. For example, Figure 5 shows the distribution of in situ secondary ion mass spectrometry (SIMS) Th-Pb monazite and muscovite $^{40}Ar/^{39}Ar$ total gas ages along the Darondi Khola (Catlos et al., 2001). The oldest early Miocene monazite ages are found in upper LHF units (21.7±1.2 Ma to 21.1±0.8 Ma), but they decrease towards lower structural levels to 7.6±0.2 Ma to 6.9±0.5 Ma. In Arun valley of eastern Nepal Himalayas, Oligocene activity within the upper portions of the MCT shear zone has been reported (~31 Ma, Groppo et al., 2010). Late Eocene to Oligocene monazite ages have been found in GHC samples from central Nepal (37.6±3.8 Ma to 30.4±0.5 Ma, Catlos et al., 2001; see also Gibson et al., 2016 for the same transect) and NW India (37.9±0.9 Ma to 34.3±0.8 Ma, Catlos et al., 2007). The Oligocene ages are consistent with the events related to the Eohimalayan time frame of Himalayan orogenesis and may not be related to activity along the MCT.

Distinguishing between the Eohimalayan and Neohimalayan events is challenging, and the Eohimalayan event may only be recorded in GHC and Tethyan units in particular locations (Aikman et al., 2008; Stickroth et al., 2019). North-east verging folds of the Tethys Formation may have developed during the Eohimalayan event (e.g., Godin et al. 1999a, 1999b), whereas these and others reported in the GHC (Bhargava & Bassi, 1994; Carosi et al., 1999b) may be the result of gravity sliding along the STDS (e.g., Burchfiel et al., 1992; Hodges et al., 1996; Vannay & Hodges, 1996; Searle, 2010). Large-scale folding that aligns preexisting isograds into an apparent inverted metamorphic position was attributed as a significant factor in the metamorphic

history of the GHC (Searle & Rex, 1989). In a petrochronology study of GHC monazite-bearing assemblages, Gibson et al. (2016) suggest that Eocene-Oligocene monazite ages represent prograde burial, which was followed by Miocene retrograde metamorphism and Miocene-Pliocene exhumation. Wu et al. (2020) suggest the High Himalayan leucogranites can be classified as Eohimalayan (46-25 Ma), Neohimalayan (25-14 Ma), and post-Himalayan (<14 Ma) based on their relationship with particular detachment systems, ages, and compositions. Some North Himalayan granites that intrude Indian shelf sediments are similar in age to their post-Himalayan stage (Harrison et al., 1997; 1998; Lee et al., 2004; Zhang et al., 2004).

2.2.3. Metamorphism in the LHF

At their base, the GHC is thrust over Middle Proterozoic phyllites, metaquartzites, and mylonitic augen gneisses of LHF along the broad-scale 8-12 km thick MCT shear zone (Le Fort, 1975; Gansser, 1981; Arita, 1983; Brunel & Kienast, 1986; Pêcher, 1989; Searle & Rex, 1989; England et al., 1992; Schelling, 1992; Le Fort, 1996; Henry et al., 1997; Harrison et al., 1998; Kohn et al., 2004; Bollinger et al., 2006; Carosi et al., 2013; Parsons et al., 2016; Martin, 2017a,b; Mukhopadhyay et al., 2017; Yin & Harrison, 2000; Catlos et al., 2001; Catlos et al., 2018; 2020). The onset of MCT activity occurred during the early Miocene (Pêcher, 1991; Vannay et al., 2004; Yin, 2006), at a time when Indo-Asia convergence slows (>40% between 20-10 Ma, Molnar and Stock, 2009) and had a significant impact on the extrusion of the GHC orogenic wedge (Maiti et al., 2020). The MCT fault system plays a central role in many models for the evolution of the Himalayas (e.g., Le Fort, 1975; Searle & Rex, 1989; England et al., 1992; Henry et al., 1997; Harrison et al., 1998; Bollinger et al., 2006; Kohn, 2008; Carosi et al., 2013; Beaumont et al., 2001; 2004; Jamieson et al., 2004; 2006; Searle et al., 2006; Long & McQuarrie, 2010; Wang et al., 2013; Cottle et al., 2015).

Lack of an apparent break in metamorphic grade between the GHC and LHF makes the placement of the boundaries of the MCT shear zone difficult to discern. Definitions of the structure center around age, metamorphic history, rheology, and role as separating units of different depositional environments (see Martin, 2017a). As the GHC and LHF evolved in different depositional environments, geochemical and geochronological evidence aids in its placement (e.g., Parrish & Hodges, 1996; Ahmad et al., 2000; Martin, 2017a,b; Khanal et al., 2014). The original Pêcher (1989) MCT definition involved three criteria in identifying the MCT in the field: (1) the boundary between hanging wall gneisses and upper carbonate-rich formations of the Lesser Himalaya, (2) where Lesser Himalaya shear fabric (L-S) is replaced by the flattening fabric of the Greater Himalayan Crystallines, and (3) where the rotational deformation that increases progressively through the Lesser Himalaya reaches a maximum. In central Nepal, Arita (1983) places two thrusts (MCT-I and MCT-II) on each side of the MCT shear zone. The MCT-II corresponds to that described by Pêcher (1989), whereas the MCT-I separates a mylonitic augen gneiss from other Lesser Himalaya metasedimentary rocks. The MCT-I correlates to the Ramgarh Thrust, which accommodates the Ramgarh Thrust sheet within the LHF duplex (DeCelles et al., 2001; Robinson et al., 2003; Pearson & DeCelles, 2005; Robinson et al., 2006; Matin and Mukul, 2010; Khanal et al., 2014; Mandal et al., 2015). Some researchers do not recognize the MCT-I anywhere in the Nepal Himalaya (see Upreti, 1999). Along the Dudh Kosi-Everest transect, the MCT corresponds to the contact between the GHC gneisses and the upper LHF pelitic schists, whereas the MCT-I separates the mylonitic Phaplu augen gneiss from low-grade Lesser Himalaya metasedimentary rocks. Along the Bhagirathi River, Garhwal region, the Vaikrita Thrust (=MCT) and Munsiari Thrust (=MCT-I) bound the MCT shear zone,

but no equivalent to the Phaplu augen gneiss is exposed (e.g., Valdiya, 1980; Pêcher, 1991; Metcalfe, 1993; Searle et al., 1993; Ahmad et al., 2000; Singh & Thakur, 2001).

The MCT footwall is characterized and defined by inverted metamorphism, where metamorphic grade increases toward structurally shallower levels (e.g., Ray, 1947; Pêcher, 1989; Larson et al., 2015; Chakraborty et al., 2016; Searle et al., 2008; Iaccarino et al., 2020). Understanding the origin this phenomenon has implications for establishing the role of various crustal heat sources and mechanisms of heat transfer within collisional belts (e.g., radiogenic, asthenospheric input, shear heating, addition of melts) (e.g., England et al., 1992) and is facilitated by obtaining metamorphic P-T conditions and paths from shear zone garnet-bearing assemblages (Stäubli, 1989; Metcalfe, 1993; Kaneko, 1995; Vannay & Hodges, 1996; Vannay & Grasemann, 1998; Manickavasagam et al., 1999; Kohn et al., 2001; Catlos et al., 2001; Imayama et al., 2010; Corrie et al., 2010; Larson et al., 2013; Anczkiewicz et al., 2014; Kohn, 2014; Mottram et al., 2014; Mukhopadhyay et al., 2017; Catlos et al., 2018; Waters, 2019; Catlos et al., 2020).

The MCT has also been considered to be an expression of the Main Himalayan Thrust (MHT) (Bollinger et al., 2004; Mahajan et al., 2010), a pervasive décollement that separates the downgoing Indian plate from the Himalayan orogenic wedge (Figure 2) (Bilham et al., 1997; Nelson et al., 1996; Subedi et al., 2018; Zhao et al., 1993). Other surface expressions of the MHT include the MBT and Main Frontal Thrust (MFT) (Figure 1 and Figure 2). The STDS may be a local phenomenon, occurring when the Tethys dissociated from the GHC and slid along N-dipping planes due to gravity following uplift (e.g., Pêcher & Le Fort, 1986; Fuchs, 1987), although some models for channel flow connect this fault system to the MHT (e.g., Beaumont et al., 2001; 2004; Jamieson et al., 2004; 2006). The MHT is one of the largest and fastest slipping continental megathrusts on Earth (e.g., Duputel et al., 2016; Rajendran et al., 2017; Searle et al., 2017). Understanding its geometry, history, and fault systems that splay into the structure has implications for assessing and predicting the initiation, propagation, and termination of major event Himalayan earthquakes (e.g., Wang et al., 2017). The topography of the MHT is uncertain (e.g., Caldwell et al., 2013; Denolle et al., 2015; Elliott et al., 2016; Hazarika et al., 2017; Hubbard, 2016; Nábělek et al., 2009; Whipple et al., 2016; Wang et al., 2017; Zhou et al., 2019), due in part to the lack of recognition that fault systems within the LHF duplex or MCT shear zone have the potential to accommodate present-day slip (Catlos et al., 2020). The LHF duplex has long been known to be a ~50-km-wide seismogenic zone of predominately moderate earthquakes (Bai et al., 2016; Cattin & Avouac, 2000; Khattri & Tyagi, 1983; Mahajan et al., 2010). Bai et al. (2016) suggest that a thrust system within the LHF is the most seismically active region in the Himalayas and accommodates most of its elastic strain accumulation. Alternatively, the shallower events are explained by a segmented MHT that includes a ramp (He et al., 2018; Hubbard, 2016; Pandey et al., 1995).

2.2.4 The MBT and MFT

South of the MCT, the MBT separates the Lesser Himalaya from Neogene molasse, the Siwalik Formation (Figure 1) (Valdiya, 1992; Meigs et al., 1995; Mukul, 2000; Thakur et al., 2010; Goswami & Deopa, 2017; Dhamodharan et al., 2020). South of the MBT, the MFT is the boundary between the Siwalik Formation and the northern Indo-Gangetic Plains (e.g., Mugnier et al., 1999; Mukul et al., 2007; Burgess et al., 2012; Bollinger et al., 2014). The MBT has few timing constraints, but is primarily thought to have been initiated during the Late Miocene (13-10 Ma, Meigs et al., 1995; Chirouze et al., 2012; Patra & Saha, 2019), although it may have been

active since 5 Ma in Nepal (DeCelles et al. 2020). The Siwalik formation overall is a 7-10 km-thick succession of dominantly fluvial sedimentary rocks located along the entire length of the Himalaya from the Potwar plateau to the Brahmaputra in the east, likely due to the evolution of the Ganga river system (Bora and Shukla, 2005; Sanyal & Sinha, 2010; Khan et al., 2019; Dhamodharan et al., 2020). The Siwalik unit itself is divided into several sectors due to lineaments related to normal faulting in the Indian basement that reactivated as thrust faults during Himalayan collision (Raiverman et al., 1983; Dubey, 1997; Sanyal & Sinha, 2010). The Siwalik formation records key information regarding Himalaya erosional history, paleoclimate, transitions in paleobotany, and exhumation rates (e.g., Quade et al., 1989, 1995; Acharya, 1994; Najman et al., 2009; Sanyal & Sinha, 2010; Najman et al., 2017; Ghosh et al., 2018; Khan et al., 2019). In some locations, the MBT has nearby active steep faults that show normal or strike-slip senses of motion as they accommodate a critical taper (Mugnier et al., 1994; Patra & Saha, 2019). The MFT cuts Siwalik strata in places and is often manifested as growing anticlines (Yeats et al., 1992; Powers et al., 1998; Srivastava et al., 2018). These crustal-scale faults sole into the MHT (Figure 2) (Zhao et al., 1993; Nelson et al., 1996).

3. Models for the extrusion of the Himalayan core

The MCT fault system has long played a central role in models for the evolution of the Himalaya. Initial models presume that activity along the MCT only occurred during the Early Miocene (Figure 6) (Le Fort, 1975; Searle & Rex, 1989; Hubbard, 1996; England et al., 1992; Hodges et al., 1993; Harris & Massey, 1994). LeFort (1975) conceived that the inverted metamorphism in the LHF footwall was caused by the transfer of thermal energy due to large-scale underthrusting of the LHF beneath the GHC (the “Hot-Iron model” Figure 6A). In this scenario, fluids released from the MCT footwall migrate through the hanging wall and flux a leucogranite belt. The alternative was proposed by Hubbard (1996), in which the inverted mineral isograds result from ductile shearing a pre-existing zone of right-way-up metamorphism (Figure 6B). Searle and Rex (1989) delegated a significant role to STDS and suggested that the present-day distribution of metamorphic facies and leucogranite bodies are caused by overprinting earlier isograds during MCT-related anatexis and folding (Figure 6C). Fluids released from the MCT footwall assist with the formation of leucogranite. The STDS has appeared prominently in almost every model since. Hodges et al. (1993) proposed that the wedge GHC extruded via synchronous STDS and MCT movement (Figure 6D), and Harris & Massey (1994) suggested extensional collapse led to rapid GHC exhumation and decompression melting of kyanite-bearing schists that led to melts emplaced near the STDS (Figure 6E).

As more data became available, more numerical solutions and quantitative models appeared (Figure 7). Molnar and England (1990) matched P-T conditions obtained by Hubbard (1996) by solving a one-dimensional time-dependent heat equation for an inclined fault (Figure 7A). The model derived thermal energy from three sources: (1) radioactive nuclides, (2) the asthenosphere, and (3) frictional heating along the MCT, and suggested that shear stresses >100 MPa can account for peak T< 600°C at the MCT and contributes ~13°C/km to the inverted geotherm. Huerta et al. (1998) introduced the idea that MCT inverted metamorphism was caused by accretion and erosion acting on a crust enriched with radiogenic elements (Figure 7B). The presence of post-Miocene mineral crystallization ages in the LHF and MCT shear zone led Harrison et al. (1998) to model footwall inverted metamorphism as the accretion of tectonic slivers of the LHF to the hanging wall (Figure 7, Figure 8A). This model was one of the first to suggest the concept of critical taper as an important control in developing inverted

metamorphism and the geometry of the fold-and-thrust belt. In this scenario, anatexis is linked to shear heating on along the MHT. This model is also the first in a series that suggested the Himalaya is an outcome of stacked thrust systems within and below the GHC (Figure 8) (e.g., Kohn, 2008; Corrie & Kohn, 2011; Cottle et al., 2015; Catlos et al., 2020).

Large-scale imaging of the Himalayan and Tibet crust led Nelson et al. (1996) to advocate that thrusting within the Himalaya results from anatexis (Figure 7D). The Tibetan middle crust is assumed to be partially molten today, and the region between the MCT and STDS is earlier extruded equivalent. This model is the foundation of others that suggest the GHC is the result of gravity-driven lateral mid-crustal flow (Gruijic et al., 1996; Beaumont et al., 2001; Jamieson et al., 2006; Searle, 2010; Webb et al., 2011; Cottle et al., 2015). Channel flow was initially conceived as a Neohimalayan event, with the extrusion of the GHC due to synchronous MCT and STDS activity with focused erosion along the topographic front (e.g., Beaumont et al., 2001; 2004; Jamieson et al., 2004; 2006; Robinson et al., 2006; Searle et al., 2006; Long & McQuarrie, 2010; Wang et al., 2013; Cottle et al., 2015). This model can be combined with the scenario where LHF footwall slivers are accreted to the hanging wall as GHC channel flow progressed (Figure 8B). LHF footwall inverted metamorphism may also be an outcome of channel flow experienced by the GHC (Daniel et al. 2003; Searle et al., 2008).

Channel flow has also been invoked to model the inverted metamorphic sequence within the MCT footwall, where discrete fault systems within the LHF and the MCT or other faults within the GHC are active during the Miocene (Imayama et al., 2010; Goswami-Banerjee et al., 2014). The alternative to channel flow is the critical taper model, where the GHC is exhumed through a series of stacked thrust systems within and below the GHC (Figure 8A) (Kohn, 2008; Corrie & Kohn, 2011). Critical taper has also been applied to explain thrusting with fault systems associated with the MFT (Mukul et al., 2007; Hirschmiller et al., 2013). In addition, the recognition that in NW India, the LHF and Tethyan Formation appear in thrust contact suggests that the GHC may have acted as a tectonic wedge (Figure 8C and D) (Webb et al., 2007; Webb et al., 2011; Cottle et al., 2015). One outcome of these models has been a wholesale re-distribution and re-defining of the MCT from a fault system that separates the GHC and LHF to one in which portions of the GHC are involved in large-scale thrust movement (Searle et al., 2008; Carosi et al., 2018). The inverted metamorphic sequence is redelegated from the LHF and MCT footwall to lower levels of the GHC (Figures 8E and F). Thermal heating along faults within the GHC may have played a role in accommodating wedge extrusion and developing inverted metamorphism (e.g., Goscombe et al., 2006; Searle et al., 2008). Figure 8G shows a scenario in which the MCT shear zone develops due to imbrication and activity is accommodated by fault systems within the GHC (Carosi et al., 2016). GHC structures include the Kalopani shear zone (KSZ) at 41-30 Ma (Eohimalayan time frame) and High Himalayan Discontinuity (HHD) at 26-24 Ma (Neohimalayan).

Although lines of evidence exist that the LHF inverted metamorphism involved multiple episodes of post-Miocene imbrication and deformation with the MCT shear zone or LHF duplex (e.g., Figure 5) (Caddick et al., 2007; Catlos et al., 2001; Kohn et al., 2001; Groppo et al., 2009; 2010; Herman et al., 2010; Mosca et al., 2012; Montomoli et al., 2013; Mottram et al., 2014; Carosi et al., 2016; Braden et al., 2018; Catlos et al., 2018; Montemagni et al., 2018; Catlos et al., 2020; Montemagni et al., 2020), the idea of tectonic inversion of a coherent rock package that experienced a single Barrovian Neohimalayan-related metamorphic event remains (Hubbard, 1996; Martin et al., 2010; Gaidies et al., 2015). Multiple episodes of ductile overthrusting of the

GHC over the LHF are proposed as an explanation (Goscombe & Hand, 2000), as well as post and tectonic overpressure that changed fundamental rock properties (Thakur et al., 2015; model of Schmalholz & Podladchikov, 2013). The originally-proposed "hot iron" model in which the primary heat source for inverted metamorphism is GHC thermal energy transferred as Miocene MCT emplacement occurred (England & Molnar, 1993) has an alternative end-member, where no contribution of dissipative to downward conductive heating from the GHC is required (Stephenson et al., 2000).

The Himalaya is often framed as a large-hot orogen that may have grown by distributed extrusion (channel flow) or discrete thrusting (critical taper) (Beaumont et al., 2006; Jamieson & Beaumont, 2013; Mukherjee, 2013; Iaccarino et al., 2020; review in Wang et al., 2013). In fact, both scenarios may be relevant to the Himalayan core, depending on the location within the range and the time frame of metamorphism (Larson et al., 2010; Mukherjee, 2013; Cottle et al., 2015). The Himalaya may indeed represent a scenario in which the two 'end-member models apply and are not mutually exclusive (Beaumont & Jamieson, 2010; Larson et al., 2010, 2013; Corrie et al., 2012; Jamieson & Beaumont 2013; Cottle et al., 2015). Evaluating models for GHC extrusion requires understanding of the P-T-t paths of its rocks as they experienced the transition from convergence and subduction to their final exhumation (e.g., Catlos et al., 2001; Caddick et al., 2007; Kohn, 2008; Corrie et al., 2010; Goswami-Banerjee et al., 2014; Catlos et al., 2018, 2020).

Kohn (2008) presents particle paths predicted by end-member critical taper and channel flow models in the end-member models. Channel flow predicts the GHC experienced isothermal exhumation, and the LHF experiences isobaric heating. Critical taper predictions imply isobaric cooling for GHC rocks and "hair-pin" LHF P-T paths (Kohn, 2008). The metamorphic field gradients predicted by the models also differ. Complicating this scenario is the observation that P-T conditions from garnet-bearing assemblages collected from the MCT hanging wall indicate the unit has cryptic discontinuities related to unmapped faults, shear zones, or inheritance of pre-existing basement structures (see discussions in Mukherjee et al., 2012; Larson et al., 2013; Montomoli et al., 2015; Cottle et al., 2015; Carosi et al., 2016). Understanding when these possible fault systems, termed High Himalayan discontinuities (HHD), were active is critical for deciphering the processes involved during convergence. Their age may similar to activity along the MCT (28-18 Ma; e.g., Carosi et al., 2010; Montomoli et al., 2013, Larson et al., 2015; Montomoli et al., 2015; Carosi et al., 2016; Carosi et al., 2018; Benetti et al., 2021). This is a scenario that is not accounted for in the channel flow model (e.g., Benetti et al., 2021; Maiti & Mandal, 2021).

4 Himalayan Metamorphism and Contractional Tectonics (Darondi Khola, Central Nepal)

As indicated in the previous sections, garnet-bearing assemblages are valuable recorders of compressional/contractional metamorphism and help constrain models for the Himalaya's uplift history. P-T data from garnet-bearing Himalayan assemblages can be generated using several approaches (see review in Waters, 2019). This section compares conditions generated using conventional thermobarometers and the Gibb's method (Kohn et al., 2001) to those obtained using isochemical phase diagrams, isopleth thermobarometry, and the garnet zoning method (e.g., de Capitani & Petrakakis, 2010; Moynihan & Pattison, 2013; Catlos et al., 2018; 2020). The approaches were applied to the same samples and data from rocks collected from the GHC and LHF units along the Darondi Khola in central Nepal (Figure 3, Figure 4, Figure 5). The TheriaG model of Gaides et al. (2008) is also used to predict garnet zoning based on Gibb's P-T

paths for some samples. The reason for any discrepancies in the P-T paths and conditions within the context of equilibrium thermodynamics is evaluated, and the impact of the results on models for Himalayan orogenesis is explored. Regardless of calibrations used, the P-T conditions and paths coupled with previously-reported timing constraints from Darondi Khola assemblages suggest the MCT shear zone developed during pulses of movement that resulted in progressive transfer of rock packages as the MCT shear zone developed (Catlos et al., 2001; Kohn et al., 2001).

4.1 Methods, samples, and assumptions

4.1.1 Samples

Kohn et al. (2001) report rim P-T conditions from eighteen garnet-bearing assemblages exposed along the Darondi Khola and divides LHF samples into lowermost (n=3), lower to mid (n=6), and upper MCT zones (n=4) (Figure 4 and Figure 5, Table 1). Five GHC rocks were also analyzed. We use the definition of the MCT shear zone following this nomenclature, but also note that based on the placement of the Phaplu and Ulleri augen gneisses, others would allocate all of these samples squarely in the GHC unit (e.g., Searle et al., 2008).

Mineral assemblages, X-ray element maps, and compositional transects were made across garnets and are reported in Kohn et al. (2001). Petrographic images of some samples are shown in Figure 9. All samples contain garnet and prograde quartz, muscovite, biotite, and ilmenite. All are metamorphosed pelites, except DH38, which is a metabasite and contains hornblende and plagioclase. All lower LHF rocks contain prograde chlorite and plagioclase, but DH75A and DH75B also have retrograde chlorite (Figure 9). The upper LHF and GHC rocks do not have chlorite (DH38, DH60, DH61, DH63, DH66, DH67) or contain only retrograde chlorite (DH57, DH58, DH71). All samples, except upper LHF rock DH57, contain plagioclase. Most plagioclase show core-rim zoning with higher-Ca cores and lower-Ca rims, expected if garnet grew in a closed chemical system (Spear et al., 1990). Samples DH26, DH75A, and DH75B have plagioclase with relict albite cores overgrown by an oligoclase mantle that is either unzoned or slightly zoned to lower Ca towards its rim. The mantle was assumed to be metamorphic and reflects garnet growth and uptake of Ca. Sample DH57 has both staurolite and kyanite, whereas DH63 has staurolite. Other rocks for this study do not show any of these index minerals. No chloritoid or carbonate minerals are reported in the samples. All samples appear syntectonic and the presence of strain shadows are common. As seen in Figure 9, micas and quartz appear deflected around the garnet porphyroblasts. Some garnets are inclusion free, however, middle LHF sample DH30 has quartz inclusions in the center of the garnet that appear thinner and elongated compared to the larger, anhedral grains in its outer-rim region. GHC samples DH61, DH63, and DH67 have inclusion filled cores and inclusion free outer rims. Inclusions of ilmenite and quartz in middle LHF samples DH51 and DH75B are aligned in relatively straight tracks into the rock matrix, consistent with syntectonic growth.

Figure 10 shows garnet compositional transects for LHF samples in which high-resolution P-T paths (DH17, DH19, DH22, DH23, DH26, DH75B) were obtained and Figure 11 shows compositional transects across garnets in two GHC samples (DH61 and DH66). LHF samples show typical prograde bell-shaped profiles in Mn, with no evidence of retrogression at the rims. The garnets all show a smooth decrease in grossular and increase in pyrope and almandine from core to rim. GHC garnets, however, show evidence of retrogression with sharp increases in Mn contents at the rim. These garnets also show significant fluctuations in grossular,

pyrope, and almandine from core to rim. GHC samples are not ideal candidates for high-resolution P-T path modeling because their zoning profiles suggests modification of prograde garnet compositions after growth, open-system behavior, and the potential of major changes in rock bulk composition after growth. These situations are assumed not to occur when modeling and developing high-resolution P-T paths.

4.1.2 Conventional thermobarometry and Gibbs method P-T paths

The garnet-biotite thermometer calibrated by Ferry and Spear (1978) with the Berman (1990) Ca-in garnet solution model and the garnet-muscovite-biotite-plagioclase barometer of Hoisch (1990) were applied to the assemblages with pelitic bulk compositions (Kohn et al., 2001). Sample DH38 is a metabasite, so the garnet-hornblende thermometer of Graham and Powell (1984) and the garnet amphibolite barometer of Kohn & Spear (1990) were used. Results are summarized in Table 1. The conditions are internally consistent, and Kohn et al. (2001) emphasize that different calibrations would change estimated P and T by ±25°C and ±0.5–1 kbar and would not alter overall trends. The conditions were estimated using minimum garnet Mn contents. Note that these garnet compositions are the same used for the estimating the garnet rim conditions using isopleth thermobarometry as described in the next section (Table 2; polygons in Figure 12, Figure 13, Figure 14, Figure 15, Figure 16, Figure 17).

The Gibb's method to generate the P-T paths from zoned garnets and their co-existing matrix mineral assemblages is outlined in Spear & Selverstone (1983), Spear (1986, 1993), Spear et al. (1984), and Spear & Rumple (1986). P-T paths were only generated from LHF rocks with pelitic bulk compositions (DH16, DH17, DH22, DH23, DH26, DH75A, and DH75B) that preserved prograde compositional zoning best. The rocks were modeled with the observed solid assemblage garnet + biotite + chlorite + muscovite + plagioclase + quartz in the MnNCKFMASH system. Compositional changes were derived from garnet and plagioclase compositional zoning produced as the garnet grew. Garnet core and rim conditions were selected for samples DH17, DH19, DH22, and DH26, whereas an intermediate point was also included for samples DH23, DH75A, and DH75B. This intermediate garnet composition was used to better account for nonlinearity in the garnet zoning pattern. In the case of DH23 and DH75B, its inclusion results in hair-pin P-T paths (Figure 13A, Figure 14C, and Figure 17). A pure H2O fluid at lithostatic pressure was assumed to have been present. Kohn et al. (2001) emphasize that activity models would not significantly affect the trends of retrieved P-T paths.

The P-T results obtained using conventional and Gibb's method show an inverted metamorphic signature in the LHF, with P-T conditions increasing up section from near the garnet isograd at 520±25°C and 5.0±1.0 kbar (DH16) to 640±25°C and 11.5±2 kbar (samples DH57 and DH58) just below the mapped MCT. GHC rocks were collected near the mapped MCT (Figure 4 and Figure 5) and record the highest P-T conditions (660-715°C and 7.6-11.5 kbar). Samples DH17, DH19, and DH75A have P-T paths consistent with burial (increasing in both P and T), whereas those from DH22 and DH26 yield exhumation paths (decreasing P with increasing T). P-T paths from DH75B and DH23 are "hair-pin" and are interpreted as recording both burial and exhumation during imbrication of the MCT shear zone. Monazite inclusions in DH75B garnets range from 11.1±0.7 Ma to 7.6±0.2 Ma (Th-Pb secondary ion mass spectrometry, SIMS, ±1□) and were interpreted as constraining Late Miocene reactivation of the MCT shear zone (Figure 5). These Late Miocene monazite inclusions in garnet are also found in other samples along the transect as well as young (Pliocene-Late Miocene) $^{40}Ar/^{39}Ar$ muscovite total gas ages (Catlos et al., 2001; Kohn et al., 2001).

4.1.3 Isopleth core thermobarometry

The approach to obtain isopleth P-T conditions and paths is the same as that outlined in Catlos et al. (2018, 2020) and Etzel et al. (2019). Bulk rock compositions were obtained from rock chips of the DH samples using inductively coupled plasma spectrometry (ICP) at Activation Laboratories (Canada) (Table 3 and Table 4). No modifications in these compositions were made for the approach. Samples DH22 and DH23 were collected nearby, and the same bulk composition is used for both rocks. Compositions vary from low SiO_2 (~45 wt % samples DH17, DH22, and DH23) to higher SiO_2 (69-76 wt% DH26, DH75A). In general, upper LHF and GHC rocks have mid to high SiO_2 contents (56-80 wt%). Their molar values are used as direct input for the effective bulk composition needed to create the isochemical phase diagrams using the software package Theriak-Domino (de Capitani and Brown, 1987; de Capitani and Petrakakis, 2010) (Figure 12, Figure 13, Figure 14, Figure 15, Figure 16, Figure 17). The Holland and Powell (1998 with updates to solution models through 2010) thermodynamic dataset and appropriate mixing models in the system $MnO\text{-}Na_2O\text{-}CaO\text{-}K_2O\text{-}FeO\text{-}MgO\text{-}Al_2O_3\text{-}SiO_2\text{-}H_2O\text{-}TiO_2$ were used. The specific solid solution models used are the same as in Catlos et al. (2018). H2O saturation is assumed for these samples (i.e., H2O (100) in Theriak Domino), as is appropriate for these assemblages. Fe^{3+} was not estimated but did not significantly affect results.

For samples where compositional data were available from the garnet's central section, isopleths of ±0.01-0.02 mole fraction spessartine, almandine, pyrope, grossular, and ±0.01-0.02 Mg-# (Mg/Fe+Mg), are plotted on the phase diagram as grey-shaded bars. Their intersection corresponds with our closest approximation of garnet core P-T conditions as indicated by a polygon. Although isopleth intersections occurred over small regions, the uncertainty in the conditions is likely approaching that of conventional methods (i.e., ±25°C and ±1 kbar). Overlapping garnet core isopleths are only found for LHF samples DH17, DH19, DH22, DH23, DH26, DH75A, DH75B, DH58, and GHC sample DH61 (Figures12, Figure 13, Figure 14, Figure 15, Figure 16). The core was defined as the portion of the garnet with the highest Mn content and is the best approximation of the chemical system when garnet began growth. In all cases, the intersections are located in mineral stability fields consistent with their assemblages (feldspar + garnet + biotite + phengite + ilmenite ± rutile ± chlorite + quartz + H2O) and anticipated conditions. Core metamorphic conditions increase up section over a north-south distance of ~5 km from a low of 4-4.5 kbar and 520-540°C in lower LHF samples DH17 and DH19 to 6.8-7.5 kbar and 540-550°C in middle LHF samples DH75A and DH75B (Table 2). Upper LHF sample DH58 collected directly beneath the MCT yields overlapping core isopleths at ~550°C and 6.0 kbar. Core isopleths for GHC sample DH61 overlap at ~7 kbar and 580°C, similar to those from some LHF rocks (Table 2).

The garnet-in reaction line and garnet growth contours (volume 0.5% increments) are overlaid on each isochemical phase diagram (Figure 12, Figure 13, Figure 14, Figure 15, Figure 16). The topology of the diagrams and the location of the garnet core suggest that garnet appears in all samples through chlorite dehydration. Only samples DH75A and DH75B yield core P-T conditions that overlap the garnet-in reaction line (Figure 14). The other samples yield overlapping isopleths on or near the 0.5% (DH17, Figure 12A), 1% (DH19, DH61, DH58, Figure 12C, Figure 15A and Figure 15C), and 1.5-2% volume contours (DH22 and DH23, Figures 12E and Figure 13A). The results suggest that the true core was missed during the analysis of these garnets. The lack of retrograde zoning in the LHF samples suggests that the effect of diffusional

homogenization is minimal (Figure 10), although this process likely modified GHC DH61 garnet compositions (Figure 11B).

4.1.4 High-resolution and Gibb's P-T path modeling

For samples DH17, DH19, DH22, DH23, DH26, DH75A, and DH75B, the garnet's core isopleth P-T conditions can be directly compared to those obtained using the Gibb's approach (Figure 17). Sample DH26 yields the same pressure using both methods (~6.5 kbar), but the thermal conditions are lower using the Gibb's method by 50°C. Sample DH23 yields the same thermal conditions using both approaches (~525°C), but the isopleth barometry suggests the sample experienced lower pressures by ~2 kbar (5.1 kbar compared to 7.0 kbar). In all other samples, isopleth thermobarometry results in the samples recording lower P (from 0.5 kbar to 1.7 kbar, samples DH75A and DH75B) and higher T (from 10°C to 50°C, samples DH75A and DH75B) compared to than those generated by the Gibb's method. The discrepancies of 10°C and 0.5 kbar are within the stated uncertainties of both methods (Kohn, 1993), but those approaching 50°C and 1.5 kbar are significant differences that would influence understanding their depth of exhumation and metamorphic reaction history. For example, in sample DH26, the Gibb's core P-T condition shows similar P, but the low Gibb's T starting conditions lie in a region where chlorite, not garnet, is stable (Figure 13C).

High-resolution P-T paths (Moynihan and Pattison, 2013) were generated for lower LHF samples where garnet transect data were available, suggested prograde conditions, and minimal modification since growth. In generating the high-resolution P-T paths, zoning profiles are smoothed using a Savitzky-Golay function to minimize the impact of missing analyses due to inclusions or cracks (Figure 10). The Matlab script starts with the bulk composition and initial smoothed core garnet composition and calls Theriak-Domino to calculate an isochemical phase diagram. A Matlab optimization function searches the P-T grid for the smallest misfit between a modeled garnet composition and the smoothed composition. It then calculates the portion of the bulk composition sequestered in the first step of garnet growth. Sequestered components are subtracted from the bulk composition to estimate an effective bulk composition for the next step of growth. A new diagram is calculated from the effective bulk composition, and the process is repeated for all steps along the garnet zoning profile from core to rim. Each step yields an estimate of the P-T conditions of incremental garnet growth, culminating in a P-T path. This data is available in the repository.

Two independently estimated high-resolution P-T paths can be obtained from a rim-to-rim compositional transect across the garnet using the garnet zoning method. The expectation is that the P-T paths from the same garnet should record similar trajectories, and was the case for samples DH17, DH19, and DH23 (Figures 12A and C, Figure 13A). The starting and endpoints may differ due to the proximity of the initial condition near the garnet core and the extent of garnet rim preservation. In addition, garnet zoning can be predicted by the high-resolution P-T path and is indicated as a bolder grey line in Figure 10. The high-resolution P-T paths reproduce the original garnet zoning to ±0.01 mole fraction in most cases and for most compositions, which is expected if the garnet behaved in a closed system and had no significant changes in bulk rock composition as it grew.

As with the core conditions, the shapes of the high-resolution P-T paths for samples DH17, DH19, DH22, DH23, DH75A, and DH75B can be directly compared to those obtained using the Gibb's approach (Figure 17). The length of the high-resolution and Gibb's P-T paths are

similar (ranges from 14°C to 52°C) but do not show the same trajectories. For example, instead of hair-pin trajectories (increase in P followed a P decrease as T increases) predicted by DH23 and DH75B Gibb's P-T paths, their high resolution P-T paths suggest that these rocks only experience an increase in P as T increased. The Gibb's P-T path in sample DH17 shows an increase in P, but the high-resolution P-T path from the same rock using the same data decreases in P as T increases. Minor fluctuations in P in the high-resolution P-T paths (±10-50 bars) in sample DH19 and near the core of sample DH22 are likely due to small compositional changes as the program seeks the best fit and should not be interpreted tectonically. DH19 shows an overall similar P-T path shape as the one reported using the Gibb's approach, but the conditions are different with the high-resolution P-T path showing much lower P (by ~2 kbar) and higher T (by ~50°C). The high-resolution P-T paths from samples DH22 and DH23 are similar in that they show minor increases in P as T increased, but the Gibb's P-T path from sample DH22 suggests decompression, a result not observed with this sample. A P-T path from sample DH26 could not be generated due to a lack of garnet zoning data, but core and rim isopleth conditions suggest it could have followed the decompression path as T increased. A decrease in P as T increased is the same trajectory suggested by the Gibb's P-T path but at higher T conditions.

To gauge how well Gibb's P-T paths reproduce garnet zoning, the Gibb's P-T path was used as input in the program TheriaG (Gaides et al., 2008) using the bulk composition indicated in Table 3. The time of garnet growth over the P-T path is regularly spaced over durations of 5 m.y., 10 m.y., and 15 m.y. Modeling parameters are available in supplementary files. In each case, the predicted Gibb's P-T path was identical and would predict garnet zoning inconsistent with what is observed in the sample (Figure 10). Results may change if different size classes than those used were selected (10 μm successive shells in 2000 □m garnet radius), if garnet growth did not occur over regular space durations, or if the selected exhumation path was different. Using the chosen parameters, the Gibb's P-T path predictions for samples DH17, DH19, and DH22 show similar trends with the garnet zoning but significantly different compositions (Figure 10). The Gibb's P-T paths predictions for those samples that produced hair-pin P-T paths (DH75B and DH23) resulted in significantly different garnet zoning and compositions and did not replicate observed garnet compositions.

4.1.5 Isopleth rim thermobarometry

Garnet rim isopleth conditions were estimated using the same garnet compositions used to generate conventional P-T conditions. Rim isopleths also include those from the sample's average composition of matrix plagioclase (±0.01 mole fraction Ca), chlorite, and biotite [±0.01 Mg-number, Mg#= Mg/(Mg+Fe)], when available. The last effective bulk composition generated by the high-resolution P-T paths was used for LHF samples DH17, DH19, DH22, DH23, and DH75B. For other LHF samples where garnet transect data is not available and for the GHC rocks, the bulk composition was used (DH26, DH75A, DH58, DH60, DH61, DH63, DH66, DH67) (Table 3 and Table 4). Only three GHC samples (DH61, DH63, and DH66) yield overlapping garnet compositional isopleths (Figure 15D, Figure 16A and B), and those from upper LHF sample DH58 did not overlap.

The extent of overlap of garnet rim with matrix mineral compositions varies for the GHC and LHF rocks. Garnet rim isopleths for GHC sample DH61 rim overlapped with all matrix mineral compositions, but DH66 show no overlap of the garnet rim with any of the matrix mineral compositions. The garnet rim isopleths for GHC sample DH63 overlapped with ±0.01 Mg-number chlorite, but not with the biotite or plagioclase compositions. As seen with some

844 footwall samples, the overlaps for the GHC assemblages are located far from the garnet-in
845 reaction line as seen by the garnet growth contours (>1.5 vol%) (Figure 15 and Figure 16). The
846 garnet rim isopleths for LHF samples DH17, DH19, DH22, DH23, and DH75B overlap with
847 Mg# biotite, but not plagioclase. No matrix mineral isopleths overlap with the garnet rim
848 isopleths for samples DH26 and DH75A within the compositional ranges applied here (±0.01
849 mole fraction Ca and Mg#).

850 For samples where garnet and matrix mineral isopleths overlap, conditions are consistent
851 with their mineral assemblages and are similar to the garnet core assemblages (feldspar + garnet
852 + biotite + phengite + ilmenite ± rutile ± chlorite + quartz + H2O). As with the core conditions,
853 the rim P-T conditions increase up section over a north-south distance of ~5 km from a low of
854 4.5-4.8 kbar and 550-560°C in lower LHF samples DH17 and DH19 to 5.5-8.8 kbar and 560-
855 590°C in middle LHF samples (Table 2). Although garnet compositional data is not available for
856 Upper LHF sample DH51, its mineral assemblage of coexisting staurolite and kyanite allows for
857 an approximation of rock conditions using only its bulk rock composition and observations
858 conditions where these mineral coexist (Figure 15E), which appears at ~7.0 kbar and ~650°C.
859 Rim isopleths for GHC samples DH60, DH61, and DH66 yield similar P of ~7 kbar, but T
860 ranges from 550-600°C. GHC sample DH63 yields the highest P-T isopleth conditions of ~10.5
861 kbar and 650°C.

862 Comparisons are made between the conventional rim P-T conditions and isopleth rim
863 conditions. As seen in Figure 17B, the lower LHF samples yield higher T (by 25-30°C) and
864 lower P (by 1.4-2.3 kbar). All middle LHF samples (Figure 17D and F) overlap in P conditions
865 within uncertainty, but the isopleth T for samples DH22 and DH26 is higher than the
866 conventional results by 5-85°C, depending on how uncertainty is applied. For GHC sample
867 DH61, the approaches yield similar T conditions, but P differ by 1-2 kbar, depending on
868 uncertainty (Figure 17F). The opposite observation is seen with GHC sample DH66, where P is
869 similar, but the isopleth conditions suggest significantly lower T (Figure 17F). Some overlap is
870 seen with GHC sample DH63, but the conventional results suggest higher P-T than the isopleth
871 results.

872 **5 Discussion**

873 Using the same samples and data, Darondi Khola MCT footwall P-T paths using the
874 Gibb's method and high-resolution garnet modeling do not yield the same conditions or shapes
875 (Figure 17), even within the estimated uncertainties of the Gibb's method (e.g., Kohn, 1993). In
876 addition, the lowest-grade footwall samples record higher T and lower P isopleth rim P-T
877 conditions than those generated using conventional thermometers and barometers. Conventional
878 garnet rim P-T conditions and isopleth thermobarometry for GHC samples yield absolute
879 conditions that differ, although overlap exists within uncertainty (±25°C and ±1kbar). An
880 important check on the feasibility of the P-T conditions generated using any approach is if the
881 results seem geologically reasonable and consistent with mineral assemblages (e.g., Moynihan
882 and Pattison, 2013; Kelly et al., 2015; Catlos et al., 2018; Etzel et al., 2019; Craddock Affinati et
883 al., 2020). However, this is the case with all conditions reported for the Darondi Khola samples,
884 regardless of approach.

885 Several assumptions underlie many P-T estimates generated using thermodynamic
886 modeling. For all thermobarometric methods applied here, a critical assumption is that the
887 minerals in a sample experienced equilibrium, which can never be proven for any rock system

(e.g., Spear & Peacock, 1989; Lanari & Duesterhoeft, 2019). The samples are also assumed to have experienced closed system behavior, and the original compositions of the mineral phases and the bulk rock have not changed significantly since metamorphism (e.g., Lanari and Engi, 2017). LHF assemblages appear to have preserved their original garnet compositions, as shown by their prograde zoning profiles (Figure 10). Garnets with preserved divalent cation zoning based on previously reported thermal conditions of generally <600°C (e.g., Carlson, 1989, Spear, 1993; Carlson 2002), consistent with the results shown here. GHC samples show fluctuations in garnet compositions from core to rim and have evidence of diffusional modification by an increase of Mn at the rims (Figure 11).

Multiple sources of error are inherent in conventional P-T conditions and include uncertainty in the accuracy of end-member reactions, electron microprobe analyses, calibration errors, variations in activity models, and compositional heterogeneity (e.g., Kohn & Spear, 1991). The precise uncertainty with approaches that involve isochemical phase diagrams is likewise challenging to determine due to the same factors incorporated into their creation as well as uncertainty associated with the thermodynamic properties inherent in the choice of internally consistent database (e.g., molar enthalpy of formation, molar entropy, molar volume, heat capacity, bulk modulus, Landau parameters, and Margules parameters, e.g., White et al., 2014; Lanari & Duesterhoeft, 2019). The error suggested by the grid created due to overlapping mineral compositional isopleths likely underestimates the actual uncertainty in the identified conditions. Applying a standard values of uncertainty (±25°C and ±1 kbar) to the overlapping isopleth conditions as those used for conventional results appears appropriate, and is commonly reported (e.g., Spear & Peacock, 1989; Kohn, 1993; Kohn et al., 2001).

Ultimately, each approach to generating P-T conditions discussed here transforms the sample into a model representing the true rock and mineral assemblage but restricts its behavior as if it was in a closed system that experienced particular boundary conditions. Confidence in conventional and Gibb's P-T paths increases when conditions agree with minerals assemblages and if the P-T paths reproduce broad-scale trends in garnet zoning from core to rim. Samples collected from the same outcrop or nearby should yield similar P-T conditions and paths. Although Kohn et al. (2001) only report one Gibb's P-T path per sample, the expectation is that multiple paths collected from the same garnet or multiple garnets in the same rock would agree in terms of shapes and conditions. The high-resolution P-T path approach and the garnet isopleth thermobarometry use these same criteria to evaluate the estimated result's appropriateness. However, they have two additional values in critically evaluating results. First, a user can gauge the extent of overlapping mineral isopleths in P-T space. Second, a user can identify how well the high-resolution P-T paths predict the trends and values of garnet compositional zoning (Figure 10). A significant value of the high-resolution P-T path and isopleth approaches is that a user can detect when systems stray from the equilibrium and closed system assumptions.

These samples illustrate that not all garnets are suitable candidates for high-resolution P-T path modeling and isopleth thermobarometry. Garnets with significant changes in composition over short distances from core to the rim and those affected by diffusion cannot be modeled. Garnets in samples that experienced significant changes in bulk composition or multiple deformation episodes resulting in modification of composition are also unable to be modeled. Not all field areas are ideal candidates, and the GHC samples show that they often fail assumptions required for isopleth thermobarometry and high-resolution P-T path modeling. For example, overlapping garnet core isopleths were only found for one GHC sample DH61, and this

was located far from the garnet-in reaction line (Figure 15C). In fact, the intersections for all samples, except DH75A and DH75B, are far from the garnet-in reaction line (>1 vol%), although all overlap mineral stability fields consistent with rock assemblages. The compositional core may not coincide with the geometric garnet center (e.g., Spear & Daniel, 1998), shown for most samples. Overlapping garnet compositional rim isopleths were found for three GHC samples (DH61, DH63, DH66), but only GHC sample DH61 appears ideal as garnet rim isopleths also intersect those of the matrix minerals (±0.01 mole fraction Ca in anorthite and ±0.01 Mg# chlorite and biotite). Confidence in isopleth conditions increases when matrix mineral compositions overlap the garnet rim conditions, as these mineral compositions are independent.

The high-resolution P-T paths should be considered approximations of how a garnet with a specific type of compositional zoning would behave in a closed system of a known bulk composition as it evolves during increasing T. Rocks are open systems, but LHF garnet-bearing assemblages appear as if they approach an ideal scenario of a closed system. This appearance of equilibrium is shown by overlapping isopleths of compositions from the garnet core and from those of the garnet rim with matrix minerals. In addition, predictions of garnet zoning made by the high-resolution P-T paths closely match the original garnet for these samples (Figure 10). Multiple paths from the same sample yield similar conditions and shapes. The inability to reproduce garnet zoning using Gibb's P-T path trajectories using TheriaG modeling suggests these paths may not be relevant to the samples using the applied parameters.

Regardless of calibrations used, the P-T conditions and paths along with previously-reported timing constraints, are consistent with an imbrication model that suggest the MCT shear zone developed as rock packages within the LHF were progressively transferred (Catlos et al., 2001; Kohn et al., 2001). For example, Figure 18 shows P-T path predictions for one such imbrication model described in Catlos et al. (2018) and (2020). In this model, thermobarometric histories are calculated using a two-dimensional finite-difference solution to the diffusion-advection equation. Samples within the LHF travel along the MCT at a 5 km/Ma speed rate from 25 to 18 Ma (Figure 18A). The hanging wall speed rate is 10 km/Ma, and topography progressively accumulates until a maximum height of 3.5 km. The increase in topography is required to accommodate the pressure changes recorded by the garnets while matching their thermal histories. Once the topography is achieved at 18 Ma, a period of cessation is applied to the MCT between 18 and 15 Ma, and topography is reduced at a rate of 1.5 km/Ma. The model returns to activity within the MCT shear zone with the activation of the MCT footwall slivers from 8 to 2 Ma (Figure 18B). P-T changes recorded by the footwall garnets are the direct result of thermal advection combined with alterations in topography. Changes in the timing of fault motion would affect the model outcomes. However, the model's current constraints and boundary conditions appear to match the observed high-resolution P-T paths. For example, the P-T diagram in Figure 18 C-E are model predictions for samples that experienced imbrication in the MCT footwall. High-resolution P-T paths are also plotted in these panels from samples collected from the LHF along the Darondi (Figure 18C) and Marsyangdi (Figure 18D) rivers in central Nepal and from along the Bhagirathi River in NW India (Figure 18E). For most samples, the P-T paths match the model predictions remarkably well. P-T paths for sample DH75B (Panel 18C) suggests the possibility of very high exhumation rates (>12mm/year) within the MCT shear zone since the Pliocene, which is a scenario predicted by this imbrication model.

6 Conclusions

This paper reviews the geological framework of the Himalayas and describes and applies particular thermobarometric approaches to decipher the metamorphic history of garnet-bearing rocks collected across the MCT along the Darondi Khola in central Nepal using previously reported data (Kohn et al., 2001). A comparison is made between the results of conventional and isopleth thermobarometry for all samples and high-resolution and Gibb's P-T paths for MCT footwall rocks only. A significant value of the high-resolution P-T path and isopleth approaches is that a user can detect when systems stray from the equilibrium assumption. Confidence in conditions exists when minerals assemblages predicted by thermodynamic modeling appear consistent with the actual rock and when the P-T paths reproduce broad-scale trends in garnet zoning from core to rim. The expectation is that multiple paths collected from the same garnet or multiple garnets in the same rock would agree in terms of shapes and conditions and that samples collected from the same outcrop or nearby should record similar P-T conditions and paths. Using isopleth thermobarometry, a user can gauge the extent of overlapping mineral compositions and where the overlap occurs with respect to the garnet-in reaction line and garnet volume % growth contours. MCT footwall garnet compositions predicted by Gibb's P-T paths using the software package TheriaG fail to reproduce the original garnet zoning. However, high-resolution P-T paths reproduce the original garnet zoning to ±0.01 mole fraction in most cases and for most compositions, expected if the garnet behaved in a closed system and had no significant changes in bulk rock composition as it grew. Although the assumption of equilibrium has long been known can never be proven for any rock system (e.g., Spear & Peacock, 1989), isopleth thermobarometry and high-resolution P-T path modeling applied to garnet-grade Himalayan MCT footwall assemblages show they appear to behave as if they evolved in a closed system that experienced particular P-T path trajectories. Ultimately, the P-T conditions and paths generated for rocks across the MCT along the Darondi Khola, regardless of calibrations used, are consistent with the imbrication model that suggest the MCT shear zone developed as rock packages within the LHF were progressively transferred (Catlos et al., 2001; Kohn et al., 2001).

Figure Captions

Figure 1. Geological map of the Himalayas after Yin (2006). See Figure 2 for a cross-section through central Nepal and Figure 3, Figure 4, and Figure 5 for the sample transect taken across the MCT shear zone along the Darondi Khola.

Figure 2. Generalized cross-section through the Himalayas in central Nepal after DeCelles (2015) and Robinson et al. (2006). See additional cross-sections in the range in DeCelles et al. (2020).

Figure 3. Generalized geological map of the Annapurna-Manaslu-Ganesh region of central Nepal after Colchen et al. (1980). Isograds are dashed and labeled: bt= biotite, grt= garnet; ky= kyanite; sta= staurolite; sil= sillimanite; pyx= pyroxene, carbonate lithologies. STDS? = the presence of the South Tibetan Detachment is debated; MCT= Main Central Thrust; MCT-I?= the presence of Arita's (1983) thrust at the base of the MCT shear zone is debated.

Figure 4. Sample location map from rocks collected along the Darondi Khola. The contour interval is 500 ft. See Figure 3 for the location of this transect on the geological map of the Himalayas. Samples are indicated by "DH#" in the text. Isograds are dashed and labeled (grt= garnet; stau= staurolite). See Figure 5 for a cross-section along A-A'.

Figure 5. Cross-section across the Darondi Khola section showing available muscovite $^{40}Ar/^{39}Ar$ and Th-Pb ages after Catlos et al. (2001). See Figure 4 for line of section.

Figure 6. Cross-sections of early models of Himalayan inverted metamorphism and leucogranite formation. (A) The "hot-iron" model of LeFort 1975. (B) Juxtaposing right-way-up metamorphic isograds after Hubbard (1996). (C) A combination of models in panels (A) and (B) after Searle and Rex (1989). Wedge extrusion models after (D) Hodges et al. (1993) and (E) Harris & Massey (1994).

Figure 7. Cross-sections of early kinematic models of Himalayan inverted metamorphism and leucogranite formation. (A) After Molnar and England (1990). (B) After Huerta et al. (1998). (C) After Harrison et al. (1989). (D) After Nelson et al. (1996).

Figure 8. (A) An illustration of the critical taper model. (B) Schematic of channel flow and wedge extrusion. (C) A combination of critical taper and tectonic wedging of the GHC. A "*" indicates an incipient fault. (D) Illustration of GHC tectonic wedging after Webb et al. (2011). Panels (E) and (F) show the final geometry of the range, which has affected the position and definition of the MCT. Panels (A), (B), (C), and (E) are after Cottle et al. (2015), and panel (F) is after Searle et al. (2008).

Figure 9. Selected petrographic (plane polarized light) images of samples along the Darondi Khola showing the relationship of the garnet porphyroblasts and rock textures. Garnets are outlined using bold lines. Pressure shadows and inclusion trails are indicates by lighter and dashed lines, respectively. Mineral abbreviations after Whitney and Evans (2010). Panels are labeled with sample number. The scale bar for each image is 200 □m. See Figure 4 and 5 for sample locations.

Figure 10. Compositional transects across garnets in lower LHF samples (A) DH17 and (B) DH19, and middle LHF samples (C) DH22, (D) DH23, and (E) DH75B. Distance is in analytical points, and the spacing between the points is ~20□m. The larger black squares are the raw electron microprobe data, whereas the smaller black squares near the EPMA data points are the smoothed data used for input into the model to generate the high-resolution P-T paths. The high-resolution P-T paths predict garnet zoning, which is shown by the bold gray lines. TheriaG was used to predict the garnet zoning for the Gibb's P-T paths, and these are also indicated.

Figure 11. Compositional transects across garnets in GHC samples DH66 (two transects) in (A) spessartine, (C) grossular, (E) pyrope, and (G) almandine. Panels (B), (D), (F), and (H) are compositional transects in spessartine, grossular, pyrope, and almandine, respectively, across a garnet in sample DH61. Distance from the garnet core is in analytical points, and the spacing between the points is ~20□m.

Figure 12. Isochemical phase diagrams from lower LHF samples DH17 (A) garnet core and (B) garnet rim, DH19 (C) core and D (rim), and mid-LHF sample DH22 (E) core and (F) rim. See Figures 4 and 5 for sample locations. Garnet-in reaction line (+Grt) and garnet growth contours (volume 0.5% increments) are overlaid on each diagram. Each core diagram was created using the rock bulk compositions reported in Table 3 and the software program Theriak-Domino. Some mineral stability fields are labeled using abbreviations after de Capitani and Petrakakis (2010) and include quartz and H2O. For the core diagrams, isopleths of ±0.01-0.02 mole fraction spessartine (XMn), grossular (XCa), pyrope (XMg), almandine (XFe), and ±0.01-0.02 Mg-number (Mg/Fe+Mg, Mg#) of the compositional data point selected from the garnet's highest Mn content are overlain (Kohn et al., 2001). They intersect as indicated by the polygon and labeled as "T-D core." High-resolution P-T paths (DH17, n=2; DH19, n=2; DH22, n=1) were generated from garnet core-to-rim transects after the approach of Moynihan & Pattison (2013).

These are compared to the P-T paths obtained using the Gibb's method for the samples using the same data by Kohn et al. (2001). The starting point of the Gibb's P-T paths is labeled with "Gibb's core." Isochemical phase diagrams for the garnet rim were created using the final effective bulk composition generated by Theriak-Domino. In this case, isopleths for the garnet compositions reported for garnet rims are overlain on the diagram, as well as matrix mineral compositions isopleths for An-content for plagioclase, Mg-number for biotite and chlorite, (Mg/Fe+Mg, Mg#-bt and Mg#-chl) (Kohn et al. 2001), when available. They intersect as indicated by the polygon and labeled as "T-D rim." These are compared to the rim P-T conditions (GB-GBMP conditions) for the samples using the same data and conventional thermobarometric approaches by Kohn et al. (2001).

Figure 13. Isochemical phase diagrams from middle LHF samples DH23 (A) garnet core and (B) rim and DH26 (C) core and (D) rim. See Figures 4 and 5 for sample locations. Detailed caption is the same as in Figure 12. High-resolution P-T paths for sample DH23 were generated from two garnet core-to-rim transects after the approach of Moynihan & Pattison (2013). These are compared to the P-T paths obtained using the Gibb's method for the samples using the same data by Kohn et al. (2001). No data was available for the garnet transect for sample DH26, so a high-resolution P-T path was not created. In this case, the rock bulk composition (Table 3) was used for both core and rim panels.

Figure 14. Isochemical phase diagrams from middle LHF samples DH75A (A) garnet core and (B) rim and DH75B (C) core and (D) rim. See Figures 4 and 5 for sample locations. Detailed caption is the same as in Figure 12. High-resolution P-T paths for sample DH75B were generated from garnet core-to-rim transects after the approach of Moynihan & Pattison (2013). These are compared to the P-T paths obtained using the Gibb's method for the samples using the same data by Kohn et al. (2001). The Gibb's path was also reported for sample DH75A. The starting point of the Gibb's P-T paths is labeled with "Gibb's core." The isochemical phase diagram for the garnet rim in sample DH75B was created using the final effective bulk composition generated by Theriak-Domino. In this case, isopleths for the garnet compositions reported for garnet rims are overlain on the diagram, as well as matrix mineral compositions isopleths for ±0.01 An-content for plagioclase (Kohn et al. 2001). Intersecting isopleths are indicated by the polygon and labeled as "T-D rim." No data was available for the garnet transect for sample DH75A, so a high-resolution P-T path was not created, and the rock bulk composition (Table 3) was used for both core and rim panels. In the rim panels, data are compared to the conventional P-T conditions for the samples (grey polygon) using the same data reported by Kohn et al. (2001).

Figure 15. Isochemical phase diagrams from upper LHF samples DH58 (A) garnet core and (B) rim and (E) DH51 showing the mineral reactions only. The figure also includes isochemical phase diagrams from GHC sample DH61 (C) core and (D) rim, and DH60 (F) garnet rim data only. See Figures 4 and 5 for sample locations. Garnet-in reaction line (+Grt) and garnet growth contours (volume 0.5% increments) are overlaid on each diagram. Each diagram was created using the rock bulk compositions reported in Table 3 and the software program Theriak-Domino. Detailed caption is the same as in Figure 12. All labeled stability fields include quartz and H2O, except in panel (B), where the quartz-out reaction line is noted. The isopleths did not intersect in panels (B) and (F) but did in panel (D), as indicated by the polygon labeled as "T-D rim." In the rim panels, data are compared to the rim P-T conditions for the samples (labeled polygon) using the same data and conventional thermobarometric approaches by Kohn et al. (2001). No mineral data is available for sample DH51, so the isochemical phase diagram in panel (E) shows only

reaction lines with staurolite, sillimanite, garnet, and kyanite reaction lines in bold. This sample has co-existing kyanite and staurolite, so the shaded area indicates the field where both of these minerals are stable.

Figure 16. Isochemical phase diagrams from GHC samples (A) DH63, (B) DH66, and (C) DH67. See Figures 4 and 5 for sample locations. Garnet-in reaction line (+Grt) and garnet growth contours (volume 0.5% increments) are overlaid on each diagram. Each diagram was created using the rock bulk compositions reported in Table 3 and the software program Theriak-Domino. Some mineral stability fields are labeled using abbreviations after de Capitani and Petrakakis (2010). All labeled stability fields include quartz and H2O. For each diagram, isopleths of ±0.01-0.02 mole fraction spessartine (XMn), grossular (XCa), pyrope (XMg), almandine (XFe), and ±0.01-0.02 Mg-number (Mg/Fe+Mg, Mg#) of the compositional data point selected from the garnet's rim are overlain (Kohn et al., 2001). Isopleths of An-content for matrix plagioclase (A) and Mg# for matrix chlorite are also overlaid on the diagrams in panels (A) and (C), respectively. Mineral isopleths intersect in panels (A) and (B) as indicated by the polygon and labeled as "T-D rim." These isopleths did not intersect in panel (C). In each panel, data are compared to the rim P-T conditions for the samples (grey polygon) using the same data and conventional thermobarometric approaches by Kohn et al. (2001).

Figure 17. Summary of the P-T conditions and paths reported in Figures 12-16. In panels (A), (C), and (E), Gibb's P-T paths are shown as bold arrows and high-resolution P-T paths are labeled with core and rim points. In panels (B), (D), and (F), rim data generated using isopleth (white polygons) and conventional thermobarometry (grey polygons) are compared. Uncertainty scales in T (±25°C) and P (±1 kbar) are shown as insets in each panel.

Figure 18. (A) Thermal-kinematic model cross-section after Catlos et al. (2018) showing the MCT (dark line) and MBT (white line) from 25 to 8 Ma. The MCT and MBT sole into the MHT at depth. Isothermal sections in degree increments are indicated by the scale bar. The isotherms show the thermal situation at 18 Ma after MCT slip. Example sample trajectories on the diagram are represented by arrows with dots at the initial and heads at the final position. The MCT is active from 25 to 18 Ma, whereas slip transfers to the MBT from 15 to 8 Ma. (B) The model cross-section of the reactivation of the MCT shear zone from 8 to 2 Ma. Both the MCT and MCT-I sole into the MHT at depth. This panel represents the thermal situation at 6 Ma right before the development of MCT shear zone inverted metamorphism. Example sample trajectories are shown. (C) P-T diagram showing the trajectories of the model predictions for samples panels A and B and high-resolution P-T paths for the Darondi Khola samples. Sample DH75B is identified. Panels (D) and (E) show the same model predictions but high-resolution P-T paths from the Marsyangdi River (Catlos et al., 2018) and Bhagirathi River transects (Catlos et al., 2020).

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Data Availability Statement

Supplementary data used in the paper will be made available in the Texas Data Repository, a platform for publishing and sharing datasets, and is included here for review purposes only.

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Table 1. Conventional P-T data from samples collected along the Darondi Khola.

Sample[a]	Gibbs Core P (±1kbar)	Gibbs Core T (±25°C)	Gibbs Rim P (± 1kbar)	Gibbs Rim T (±25°C)	Conv. Rim P (kbar, ±1σ)	Conv. Rim T (°C, ±1σ)
			Lower LHF			
DH16	-[b]	-	-	-	5.0±1.0	520±25
DH17	6.0	510	7.0	525	6.8±1.0	525±15
DH19	5.5	475	6.0	525	6.2±0.5	527±12
			Middle LHF			
DH22	6.0	498	5.0	525	5.2±1.0	520±25
DH23	7.0	525	7.3	575	7.2±2.0	540±35
DH26	6.5	500	5.5	520	5.5±1.0	524±25
DH30	-	-	-	-	8.5±2.0	570±20
DH75A	8.5	530	9.0	560	8.5±2.0	570±20
DH75B	8.0	500	8.0	560	8.5±2.0	570±20
			Upper LHF			
DH38	-	-	-	-	8.2±1.0	578±20
DH57	-	-	-	-	11.5±2.0	640±25
DH58	-	-	-	-	11.5±2.0	640±25
DH71	-	-	-	-	11.5±1.0	640±20
			GHC			
DH60	-	-	-	-	10.5±1.0	652±10
DH61	-	-	-	-	9.1±2.0	625±12
DH63	-	-	-	-	11.5±1.5	705±25
DH66	-	-	-	-	7.6±1.0	660±12
DH67	-	-	-	-	10.2±2.0	715±5

[a] See Figure 3 for samples location. Conditions estimated from Kohn et al. (2001).

[b] "-" not reported.

Table 2. P-T data generated from samples collected along the Darondi Khola using garnet isopleth thermobarometry.

Sample[a]	Isopleth Core P (±1kbar)	Isopleth Core T (±25°C)	Isopleth Rim P (±1kbar)	Isopleth Rim T (±25°C)
		Lower LHF		
DH17	4.5	540	4.5	560
DH19	4.0	520	4.8	550
		Middle LHF		
DH22	4.8	540	6.0	580
DH23	5.1	525	6.0	580
DH26	6.5	550	5.5	560
DH75A	6.8	540	6.5	580
DH75B	7.5	550	8.8	590
		Upper LHF		
DH51	-[b]	-	7.0	650
DH58	6.0	550	-	-
		GHC		
DH60	-	-	7.5	570
DH61	7.0	580	7.5	600
DH63	-	-	10.5	650
DH66			7.5	550

[a] See Figure 3 for sample locations.
[b] "-" not reported.

Table 3. Bulk rock compositions (wt%) from lower and middle LHF samples.

Analyte/Sample [a]	DH17	DH19	DH22/23	DH26	DH30	DH75A	DH75B
SiO_2	45.39	66.04	45.22	76.04	50.89	70.24	68.75
Al_2O_3	27.31	16.36	28.09	11.79	27.80	12.79	8.16
Fe_2O_3(T)	9.18	7.12	6.37	3.52	6.11	4.98	3.78
MnO	0.10	0.17	0.20	0.05	0.02	0.02	0.02
MgO	2.81	1.88	1.50	1.24	2.03	1.78	1.52
CaO	0.30	0.44	0.51	0.58	0.20	0.39	0.46
Na_2O	1.07	0.45	1.57	3.54	1.44	1.14	1.51
K_2O	7.72	5.14	7.26	1.22	6.12	2.97	1.99
TiO_2	0.86	0.52	0.86	0.40	0.79	0.49	0.35
P_2O_5	0.11	0.16	0.13	0.11	0.14	0.09	0.07
LOI	n.m.	2.15	n.m.	2.26	5.21	4.89	n.m.
Total	94.8	100.4	91.7	100.7	100.7	99.8	86.6

[a] See Figure 3 for sample locations.

2412 **Table 4.** Bulk rock compositions (wt%) from upper LHF and GHC samples.

Analyte/Sample [a]	DH51	DH58B	DH60	DH61	DH63	DH66	DH67
	LHF samples				GHC samples		
SiO_2	66.13	55.66	71.51	55.47	69.01	68.35	79.92
Al_2O_3	15.14	23.82	12.62	19.54	13.88	10.47	9.01
Fe_2O_3(T)	5.29	4.48	5.80	7.76	6.69	5.44	3.57
MnO	0.03	0.19	0.04	0.14	0.10	0.07	0.02
MgO	2.31	1.66	2.41	4.71	1.99	2.00	1.65
CaO	0.21	3.38	1.02	2.59	1.15	1.07	1.37
Na_2O	0.58	6.46	2.55	4.23	2.46	1.52	2.18
K_2O	3.78	2.08	2.68	3.84	2.32	2.53	1.22
TiO_2	0.52	0.67	0.65	0.99	0.68	0.54	0.62
P_2O_5	0.12	0.01	0.15	0.03	0.15	0.09	0.05
LOI	5.89	n.m.	n.m.	n.m.	n.m.	n.m.	1.28
Total	100	98.4	99.4	99.3	98.4	92.1	100.9

2413 [a] See Figure 3 for sample locations.

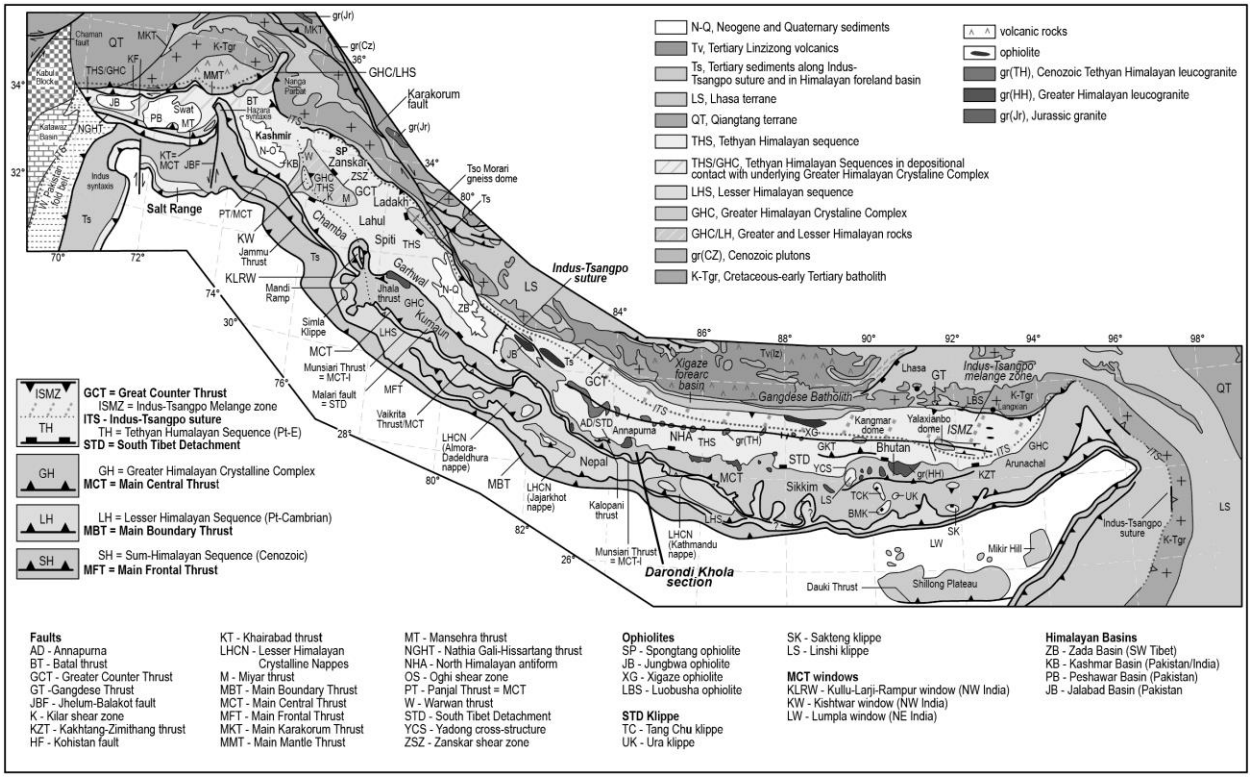

Figure 1. Geological map of the Himalayas after Yin (2006). Geological map of the Himalayas after Yin (2006). See Figure 2 for a cross-section through central Nepal and Figures 3-5 for the sample transect taken across the MCT shear zone along the Darondi Khola. See supplementary files for this figure in color.

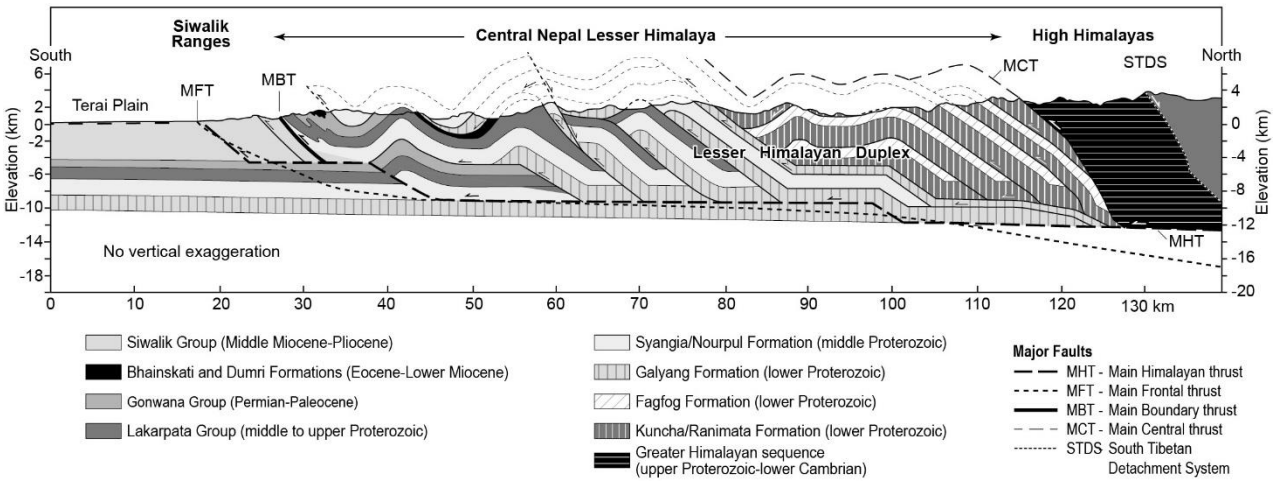

Figure 2. Generalized cross-section through the Himalayas in central Nepal after DeCelles (2015) and Robinson et al. (2006). See additional cross-sections in the range in DeCelles et al. (2020).

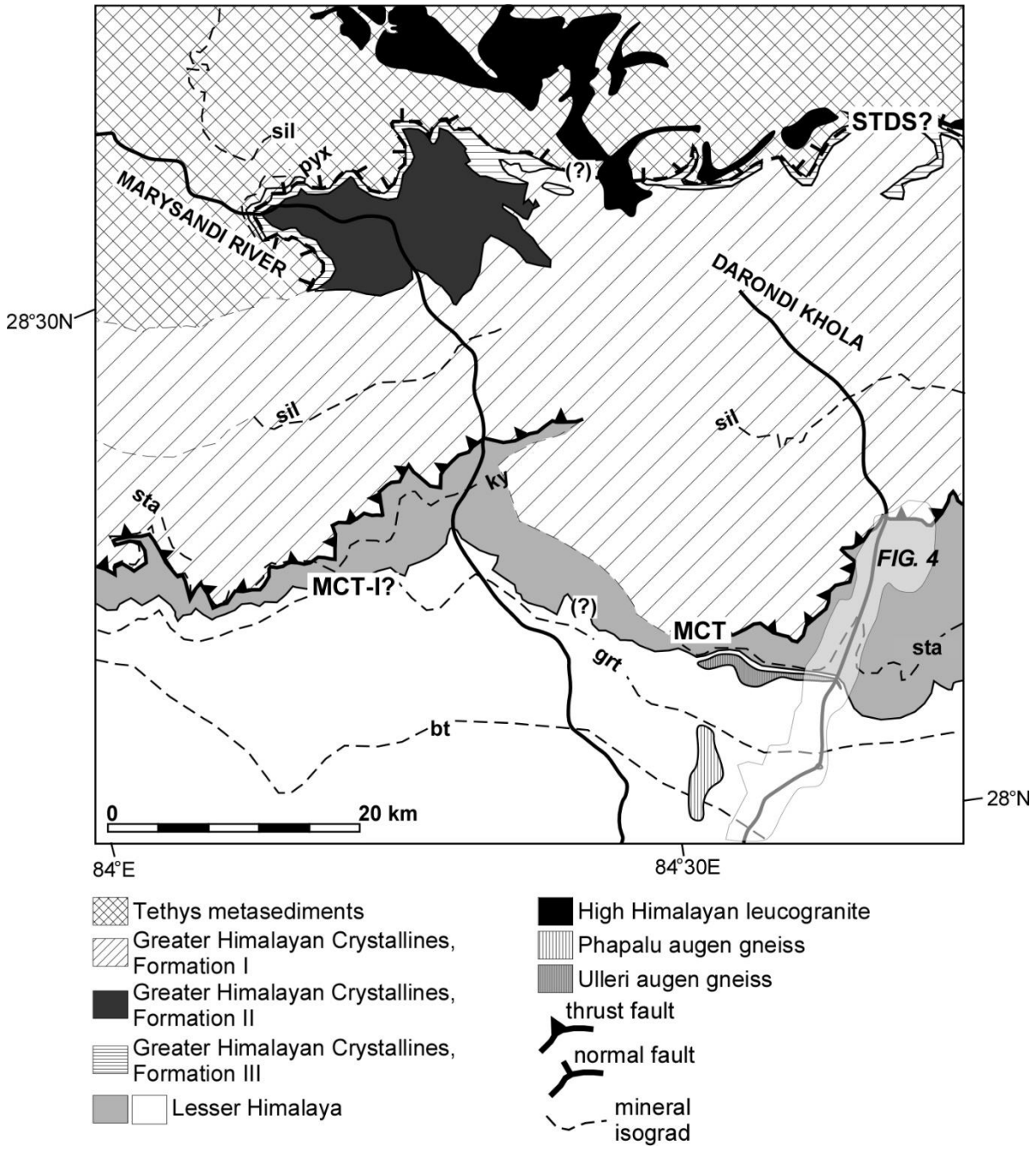

Figure 3. Generalized geological map of the Annapurna-Manaslu-Ganesh region of central Nepal after Colchen et al. (1980). Isograds are dashed and labeled: bt= biotite, grt= garnet; ky= kyanite; sta= staurolite; sil= sillimanite; pyx= pyroxene, carbonate lithologies. STDS? = the presence of the South Tibetan Detachment is debated; MCT= Main Central Thrust; MCT-I?= the presence of Arita's (1983) thrust at the base of the MCT shear zone is debated.

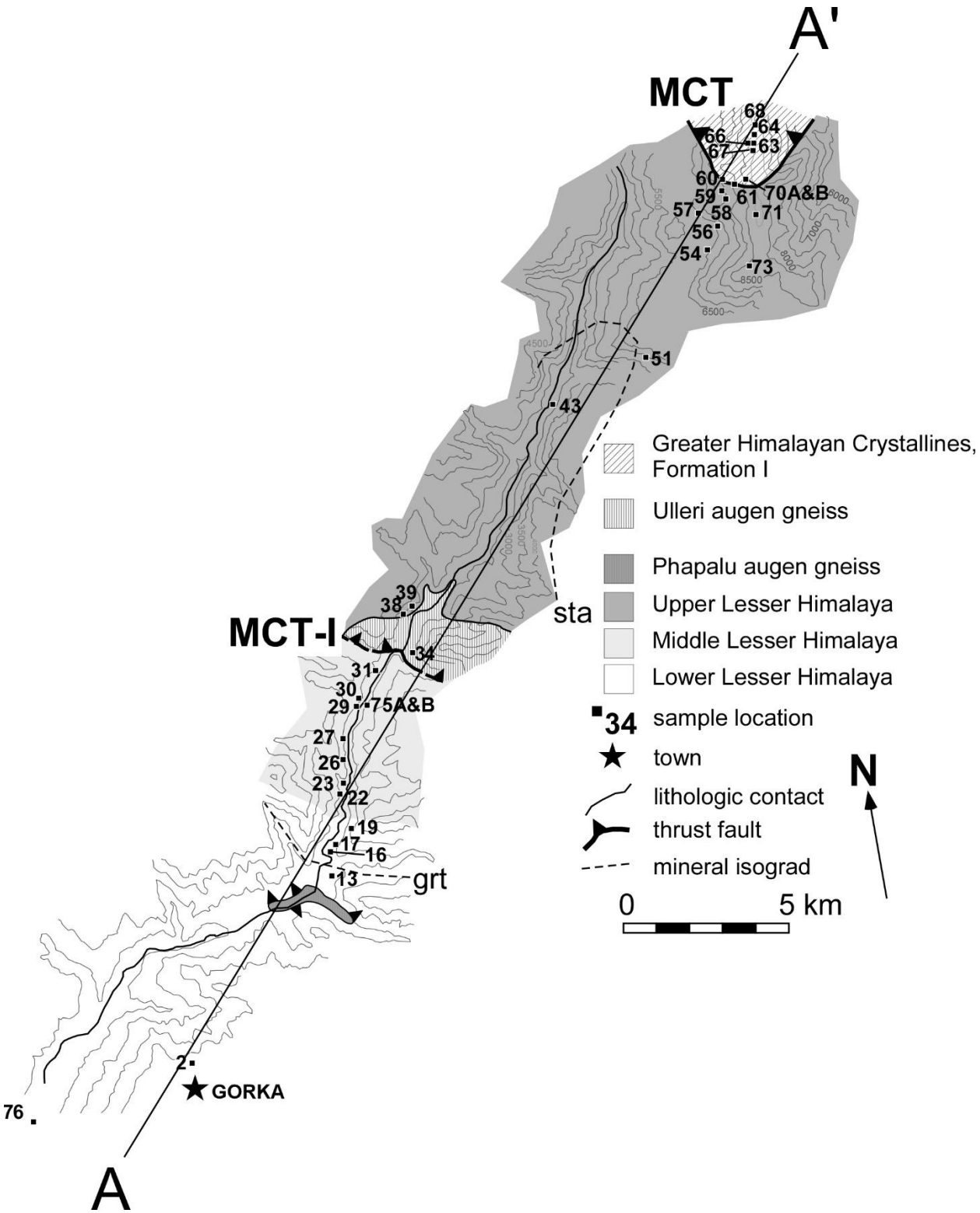

Figure 4. Sample location map from rocks collected along the Darondi Khola. The contour interval is 500 ft. See Figure 3 for the location of this transect on the geological map of the Himalayas. Samples are indicated by "DH#" in the text. Isograds are dashed and labeled (grt= garnet; stau= staurolite). See figure 5 for a cross-section along A-A'.

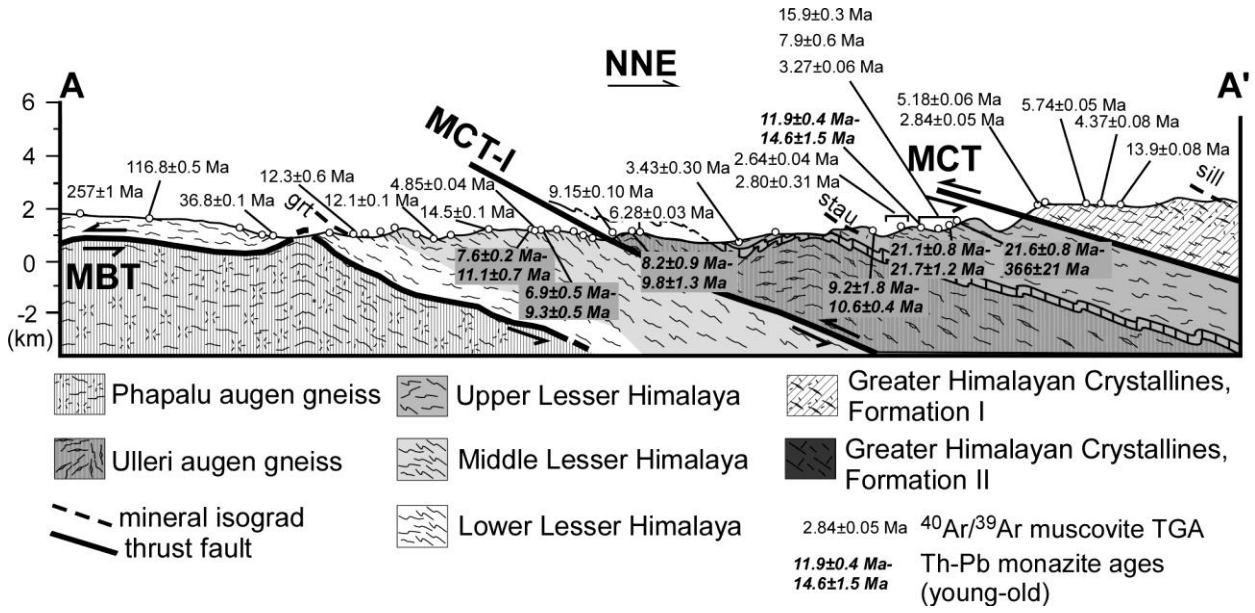

Figure 5. Cross-section across the Darondi Khola section showing available muscovite $^{40}Ar/^{39}Ar$ and Th-Pb ages after Catlos et al. (2001). See Figure 4 for line of section.

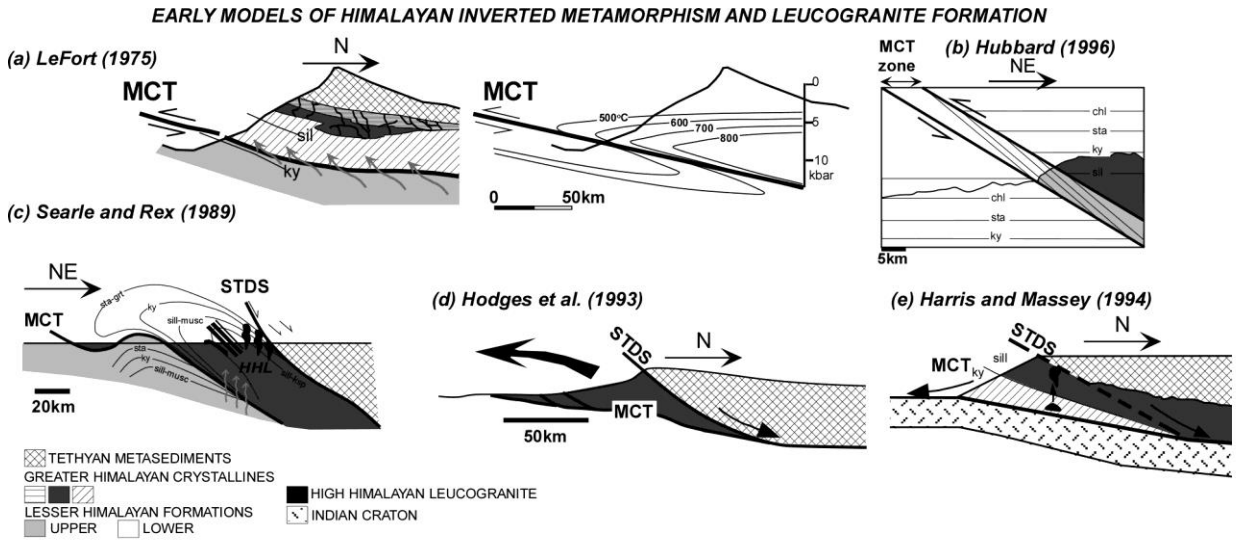

Figure 6. Cross-sections of early models of Himalayan inverted metamorphism and leucogranite formation. (A) The "hot-iron" model of LeFort 1975. (B) Juxtaposing right-way-up metamorphic isograds after Hubbard (1996). (C) A combination of models in panels (A) and (B) after Searle and Rex (1989). Wedge extrusion models after (D) Hodges et al. (1993) and (E) Harris & Massey (1994).

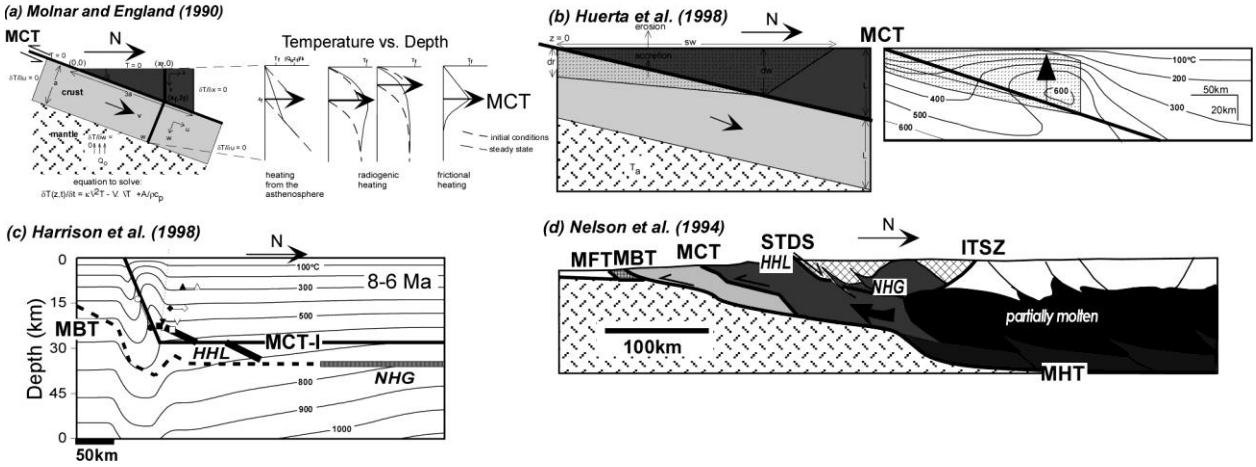

Figure 7. Cross-sections of early kinematic models of Himalayan inverted metamorphism and leucogranite formation. (A) After Molnar and England (1990). (B) After Huerta et al. (1998). (C) After Harrison et al. (1989). (D) After Nelson et al. (1996).

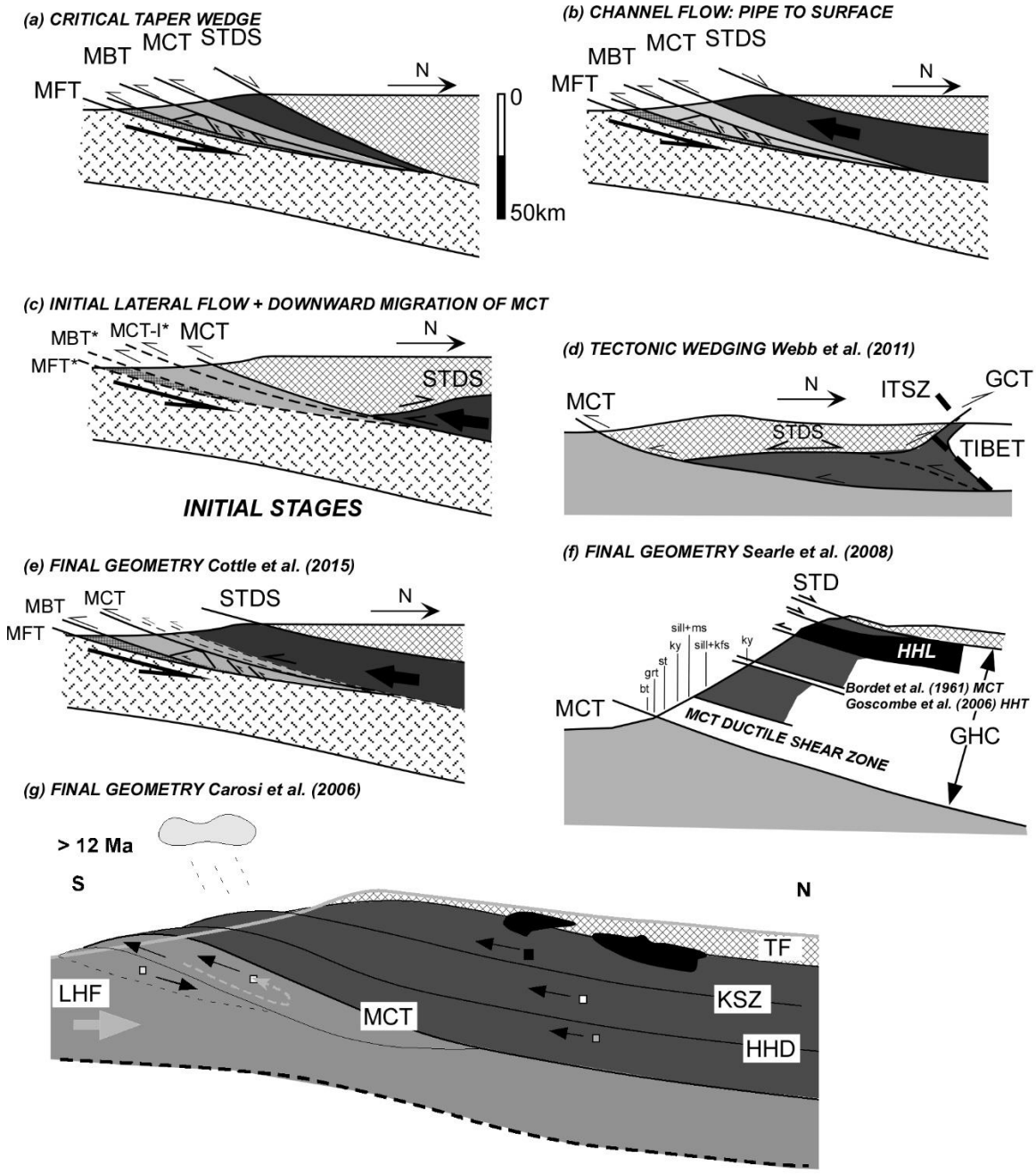

Figure 8. (A) An illustration of the critical taper model. (B) Schematic of channel flow and wedge extrusion. (C) A combination of critical taper and tectonic wedging of the GHC. A "*" indicates an incipient fault. (D) Illustration of GHC tectonic wedging after Webb et al. (2011). Panels (E) and (F) show the final geometry of the range, which has affected the position and definition of the MCT. Panel (G) showing the development of the MCT shear zone as rocks shown as squares within the footwall accrete to the hanging wall of the MCT. Faults within the GHC include the Kalopani shear zone (KSZ) and High Himalayan discontinuity (HHD). Panels (A), (B), (C), and (E) are after Cottle et al. (2015), panel (F) is after Searle et al. (2008), and panel (G) after Carosi et al. (2006).

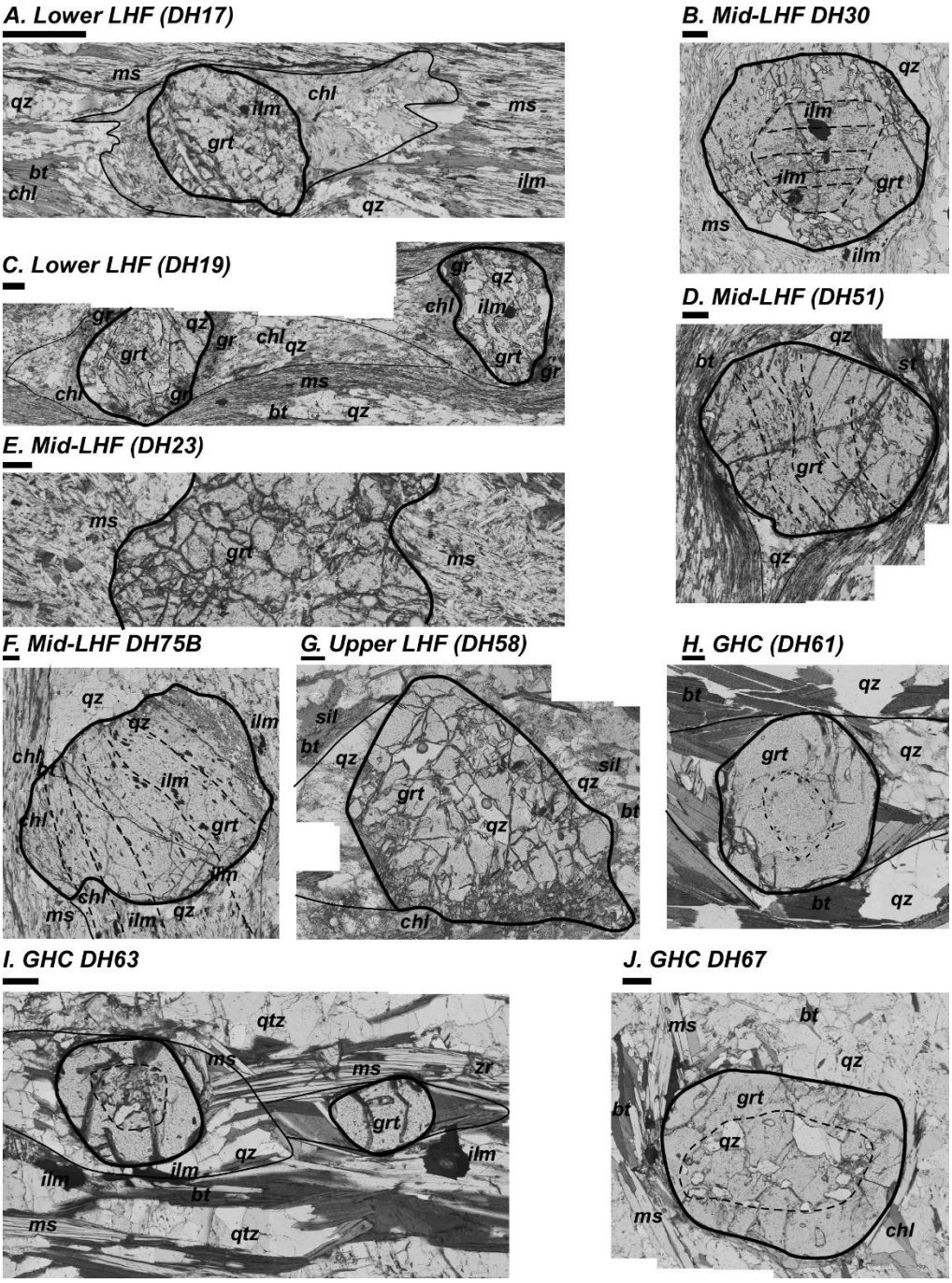

Figure 9. Selected petrographic (plane-polarized light) images of samples along the Darondi Khola showing the relationship of the garnet porphyroblasts and rock textures. Garnets are outlined using bold lines. Pressure shadows and inclusion trails are indicated by lighter and dashed lines, respectively. Mineral abbreviations after Whitney and Evans (2010). Panels are labeled with the sample numbers. The scale bar for each image is 200 um. See Figures 4 and 5 for sample locations. See supplementary files for this figure in color.

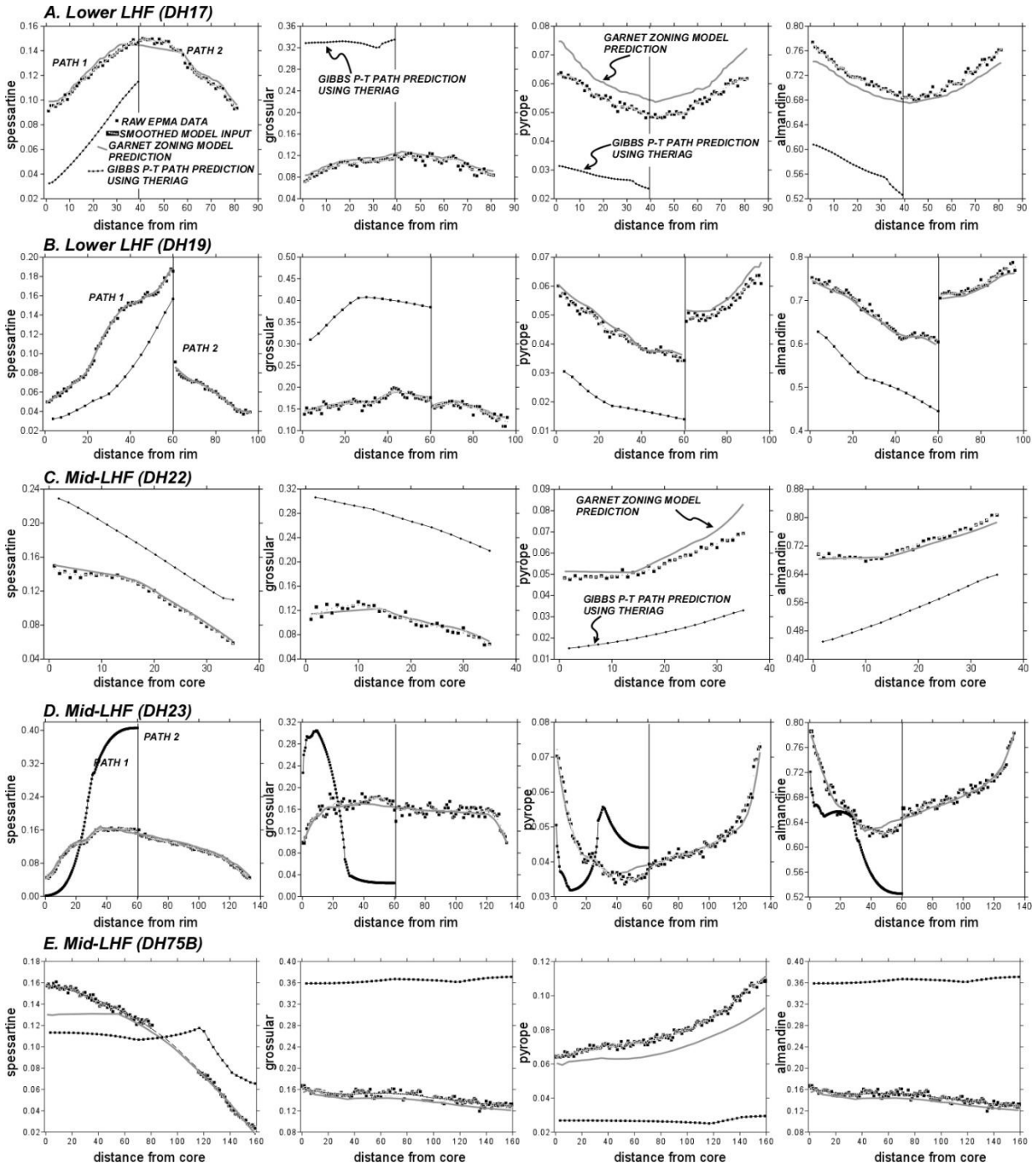

Figure 10. Compositional transects across garnets in lower LHF samples (A) DH17 and (B) DH19, and middle LHF samples (C) DH22, (D) DH23, and (E) DH75B. Distance is in analytical points, and the spacing between the points is ~20μm. The larger black squares are the raw electron microprobe data, whereas the smaller black squares near the EPMA data points are the smoothed data used for input into the model to generate the high-resolution P-T paths. The high-resolution P-T paths predict garnet zoning, which is shown by the bold gray lines. TheriaG was used to predict the garnet zoning for the Gibb's P-T paths, and these are also indicated.

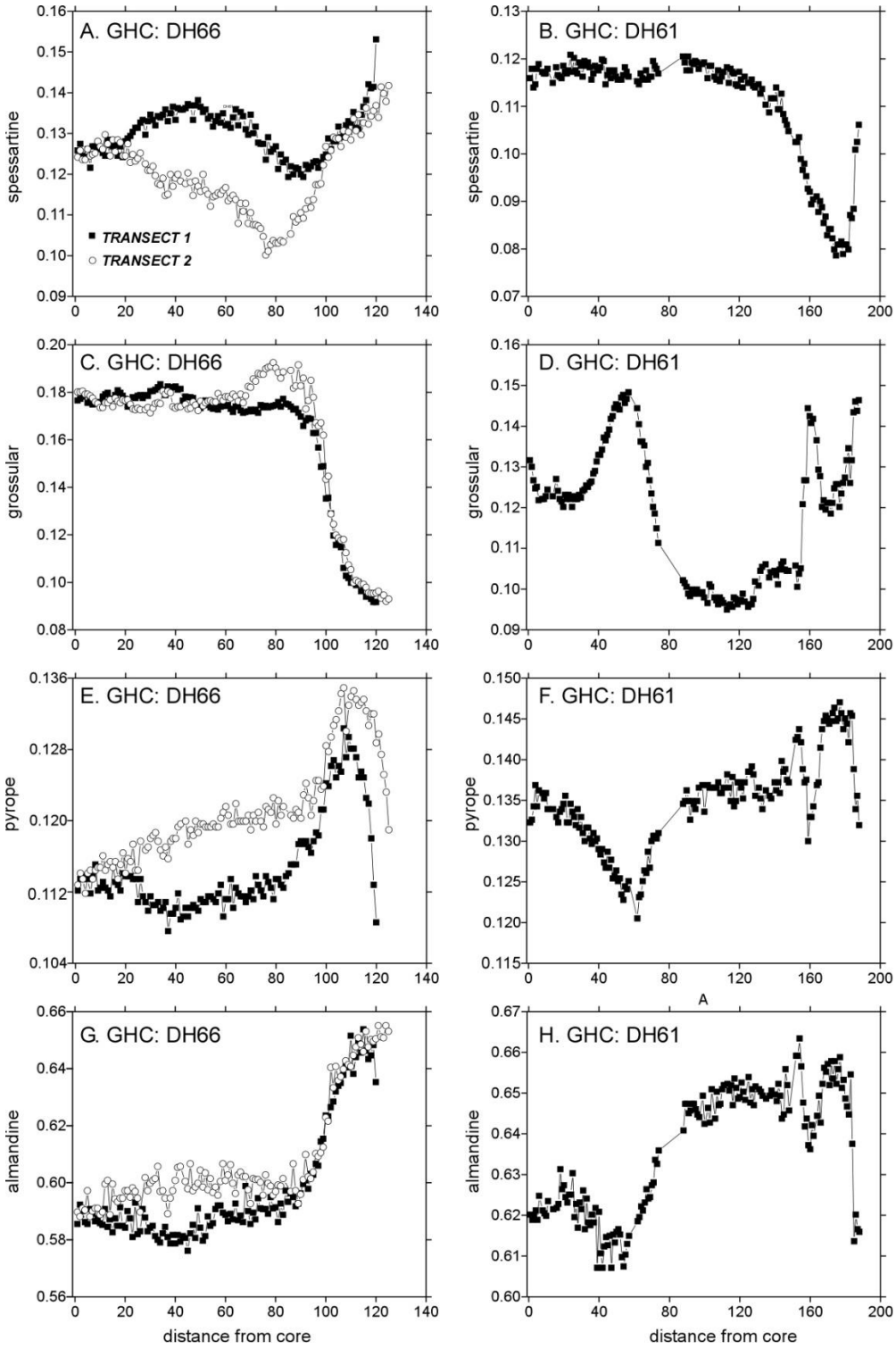

Figure 11. Compositional transects across garnets in GHC samples DH66 (two transects) in (A) spessartine, (C) grossular, (E) pyrope, and (G) almandine. Panels (B), (D), (F), and (H) are compositional transects in spessartine, grossular, pyrope, and almandine, respectively, across a garnet in sample DH61. Distance from the garnet core is in analytical points, and the spacing between the points is ~20μm.

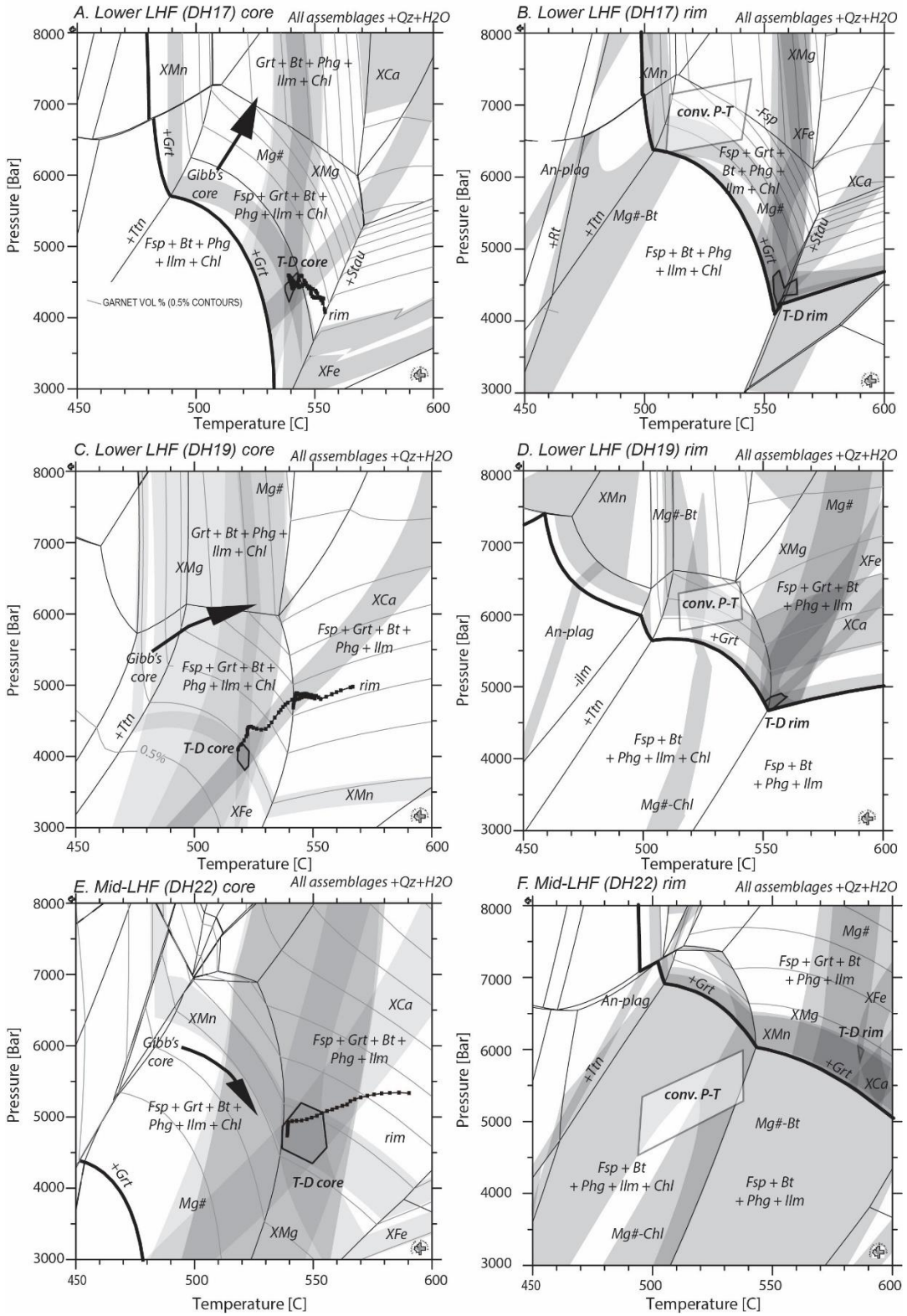

Figure 12. Isochemical phase diagrams from lower LHF samples DH17 (A) garnet core and (B) garnet rim, DH19 (C) core and D (rim), and mid-LHF sample DH22 (E) core and (F) rim. See text for entire figure caption.

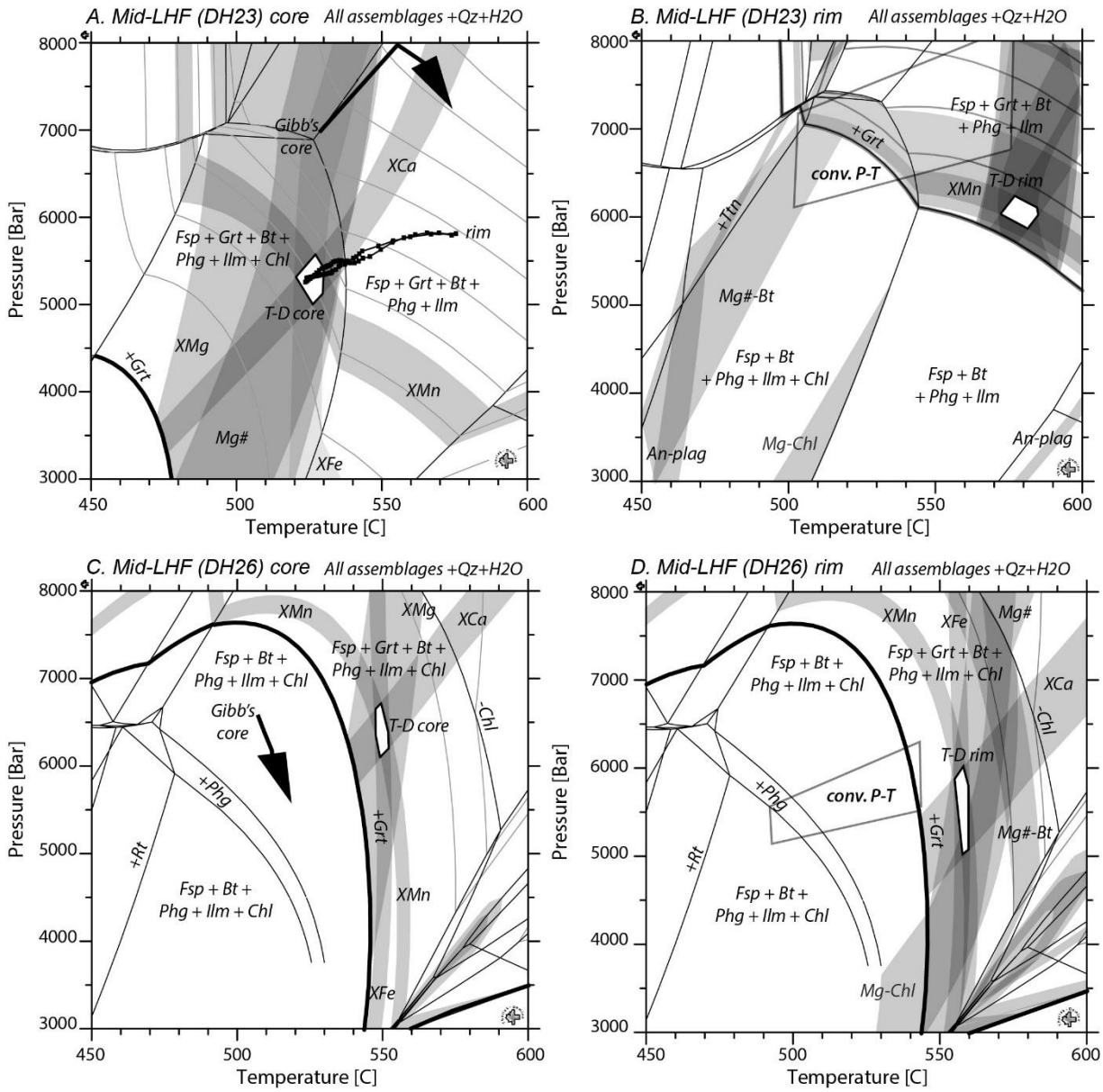

Figure 13. Isochemical phase diagrams from middle LHF samples DH23 (A) garnet core and (B) rim and DH26 (C) core and (D) rim. See Figures 4 and 5 for sample locations. Detailed caption is the same as in Figure 12. High-resolution P-T paths for sample DH23 were generated from two garnet core-to-rim transects after the approach of Moynihan & Pattison (2013). These are compared to the P-T paths obtained using the Gibb's method for the samples using the same data by Kohn et al. (2001). No data was available for the garnet transect for sample DH26, so a high-resolution P-T path was not created. In this case, the rock bulk composition (Table 3) was used for both core and rim panels.

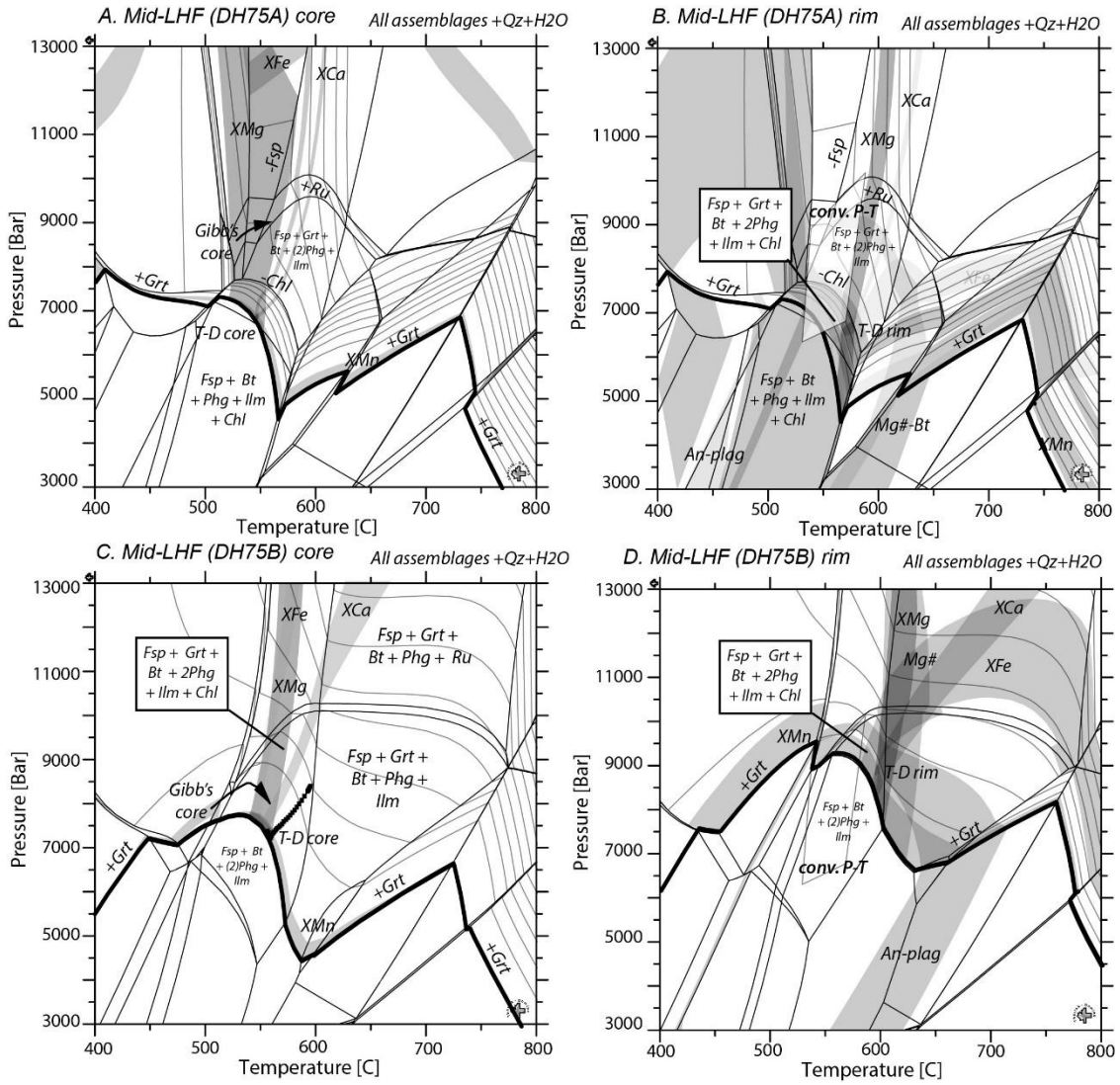

Figure 14. Isochemical phase diagrams from middle LHF samples DH75A (A) garnet core and (B) rim and DH75B (C) core and (D) rim. See Figures 4 and 5 for sample locations. Detailed caption is the same as in Figure 12. High-resolution P-T paths for sample DH75B were generated from garnet core-to-rim transects after the approach of Moynihan & Pattison (2013). These are compared to the P-T paths obtained using the Gibb's method for the samples using the same data by Kohn et al. (2001). The Gibb's path was also reported for sample DH75A. The starting point of the Gibb's P-T paths is labeled with "Gibb's core." The isochemical phase diagram for the garnet rim in sample DH75B was created using the final effective bulk composition generated by Theriak-Domino. In this case, isopleths for the garnet compositions reported for garnet rims are overlain on the diagram, as well as matrix mineral compositions isopleths for ±0.01 An-content for plagioclase (Kohn et al. 2001). Intersecting isopleths are indicated by the polygon and labeled as "T-D rim." No data was available for the garnet transect for sample DH75A, so a high-resolution P-T path was not created, and the rock bulk composition (Table 3) was used for both core and rim panels. In the rim panels, data are compared to the conventional P-T conditions for the samples (grey polygon) using the same data reported by Kohn et al. (2001).

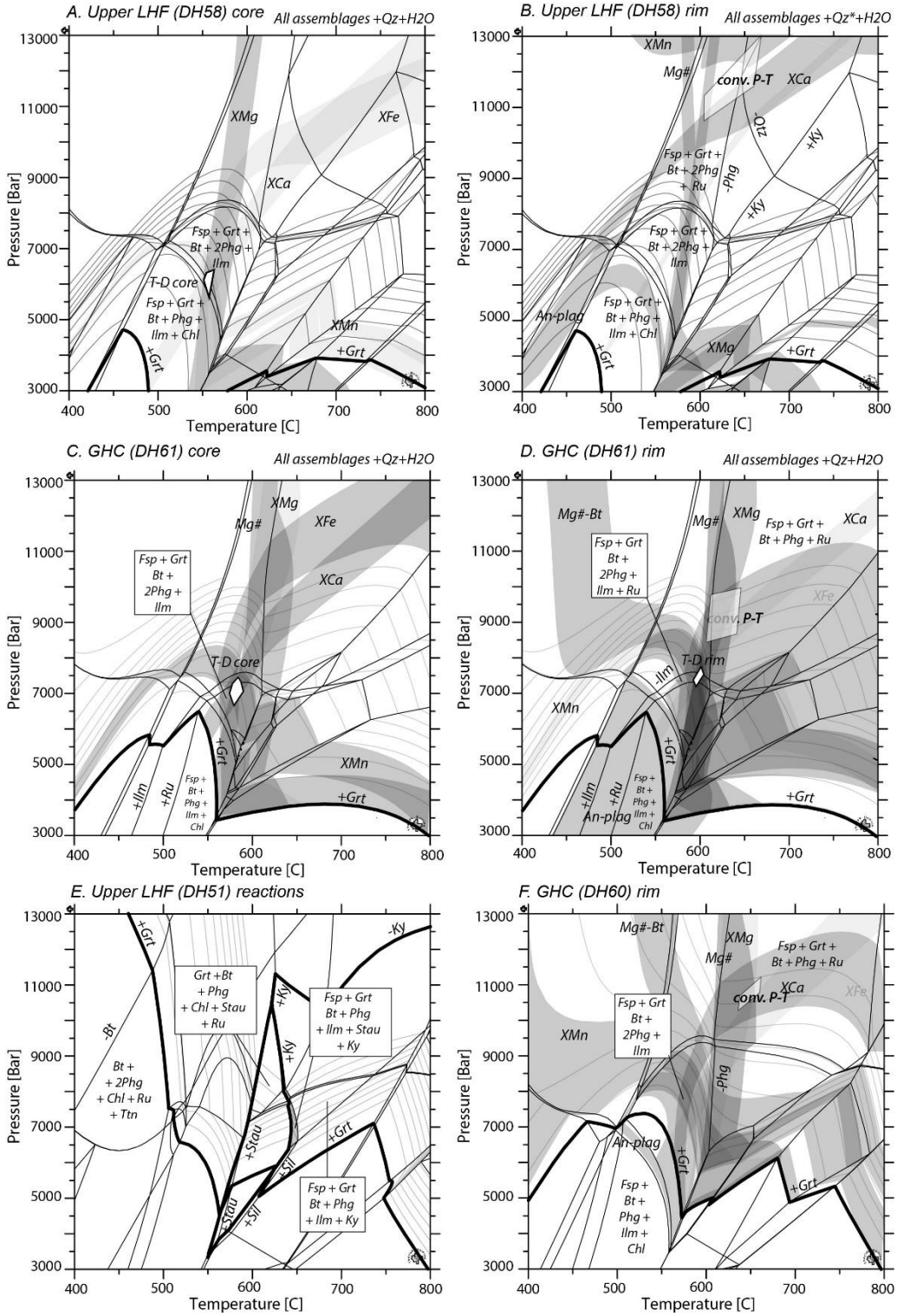

Figure 15. Isochemical phase diagrams from upper LHF samples DH58 (A) garnet core and (B) rim and (E) DH51 showing the mineral reactions only. The figure also includes isochemical phase diagrams from GHC sample DH61 (C) core and (D) rim, and DH60 (F) garnet rim data only. See text for detailed caption.

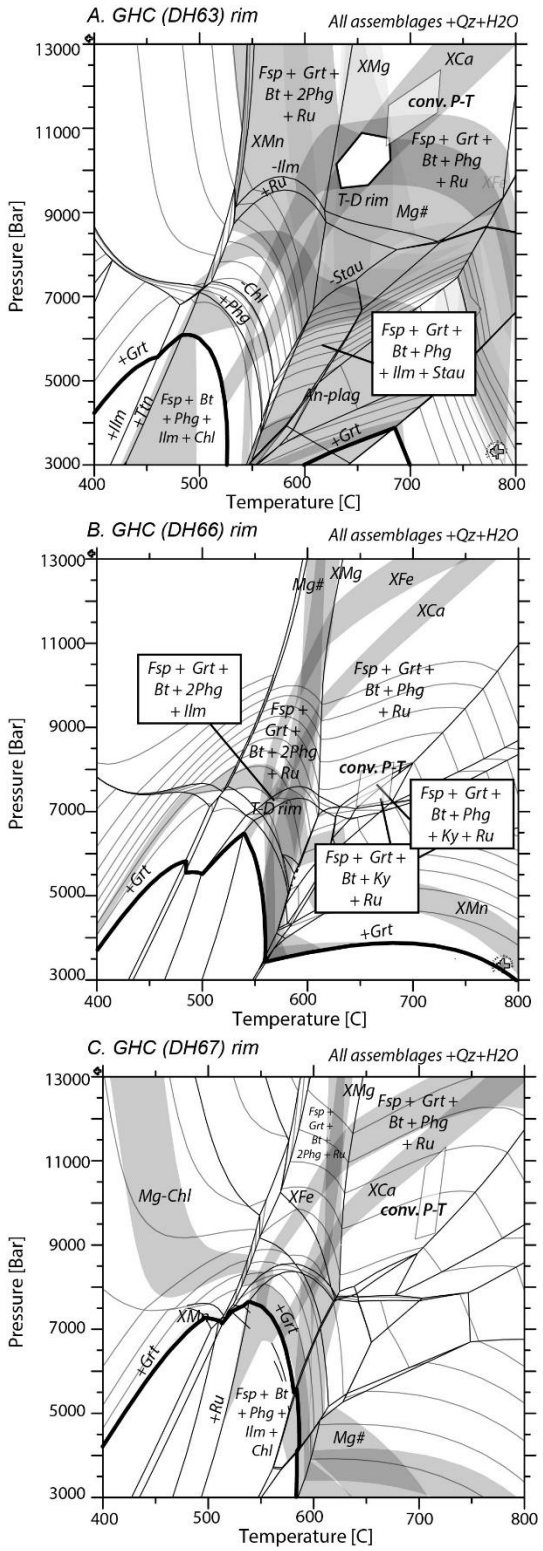

Figure 16. Isochemical phase diagrams from GHC samples (A) DH63, (B) DH66, and (C) DH67. See Figures 4 and 5 for sample locations. See manuscript text for detailed caption.

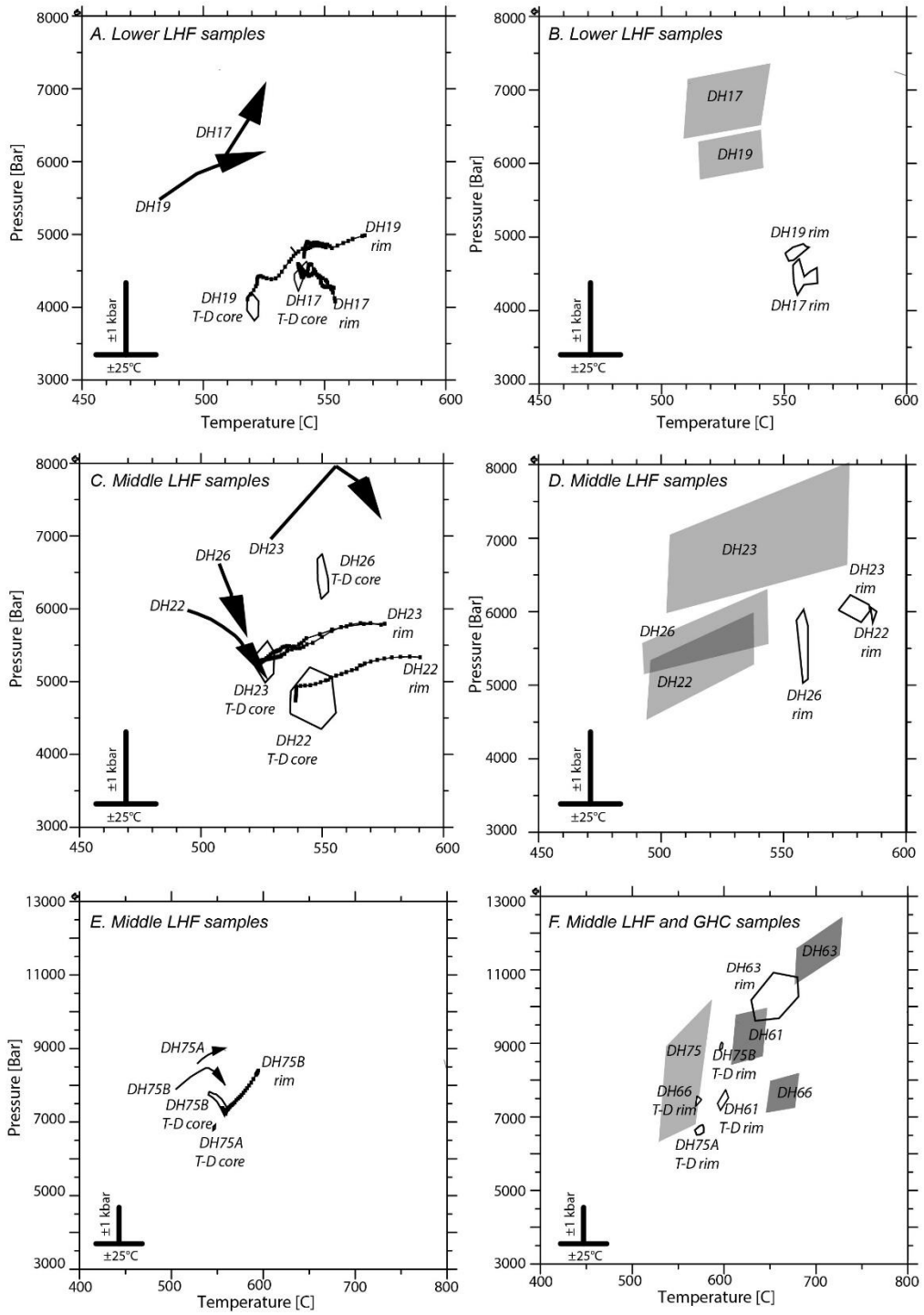

Figure 17. Summary of the P-T conditions and paths reported in Figures 12-16. In panels (A), (C), and (E), Gibb's P-T paths are shown as bold arrows and high-resolution P-T paths are labeled with core and rim points. In panels (B), (D), and (F), rim data generated using isopleth (white polygons) and conventional thermobarometry (grey polygons) are compared. Uncertainty scales in T (±25°C) and P (±1 kbar) are shown as insets in each panel.

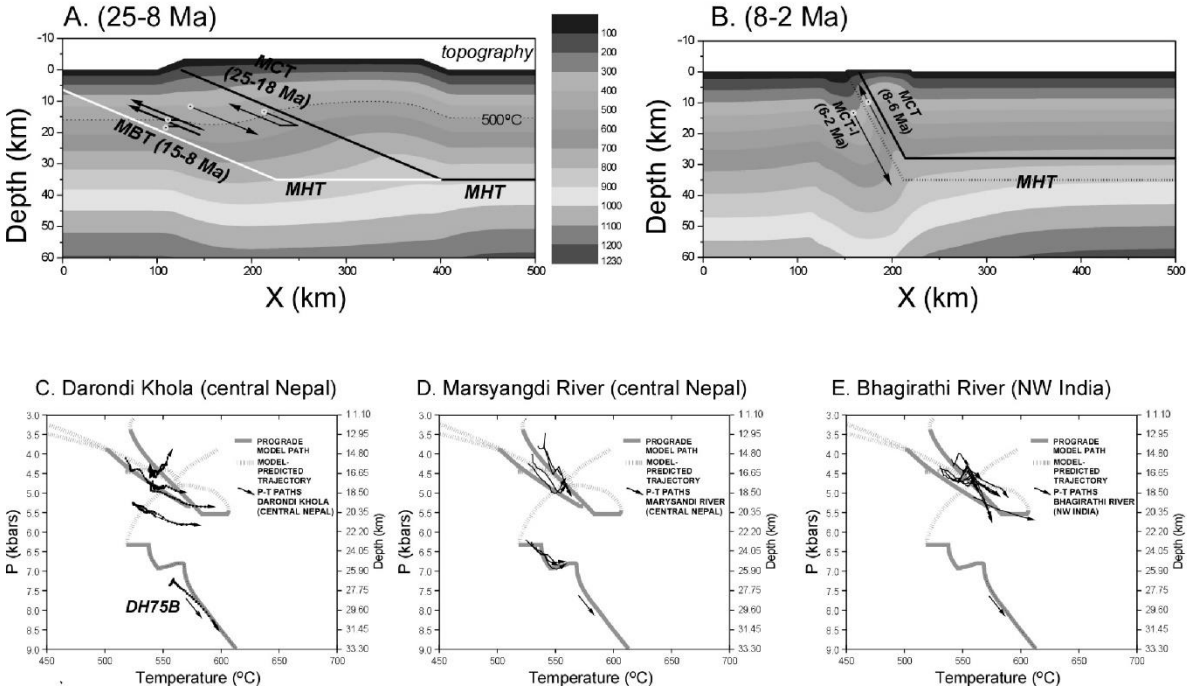

Figure 18. (A) Thermal-kinematic model cross-section after Catlos et al. (2018) showing the MCT (dark line) and MBT (white line) from 25 to 8 Ma. The MCT and MBT sole into the MHT at depth. Isothermal sections in degree increments are indicated by the scale bar. The isotherms show the thermal situation at 18 Ma after MCT slip. Example sample trajectories on the diagram are represented by arrows with dots at the initial and heads at the final position. The MCT is active from 25 to 18 Ma, whereas slip transfers to the MBT from 15 to 8 Ma. (B) The model cross-section of the reactivation of the MCT shear zone from 8 to 2 Ma. Both the MCT and MCT-I sole into the MHT at depth. This panel represents the thermal situation at 6 Ma right before the development of MCT shear zone inverted metamorphism. Example sample trajectories are shown. (C) P-T diagram showing the trajectories of the model predictions for samples panels A and B and high-resolution P-T paths for the Darondi Khola samples. Sample DH75B is identified. Panels (D) and (E) show the same model predictions but high-resolution P-T paths from the Marsyangdi River (Catlos et al., 2018) and Bhagirathi River transects (Catlos et al., 2020). See supplementary files for this figure in color.

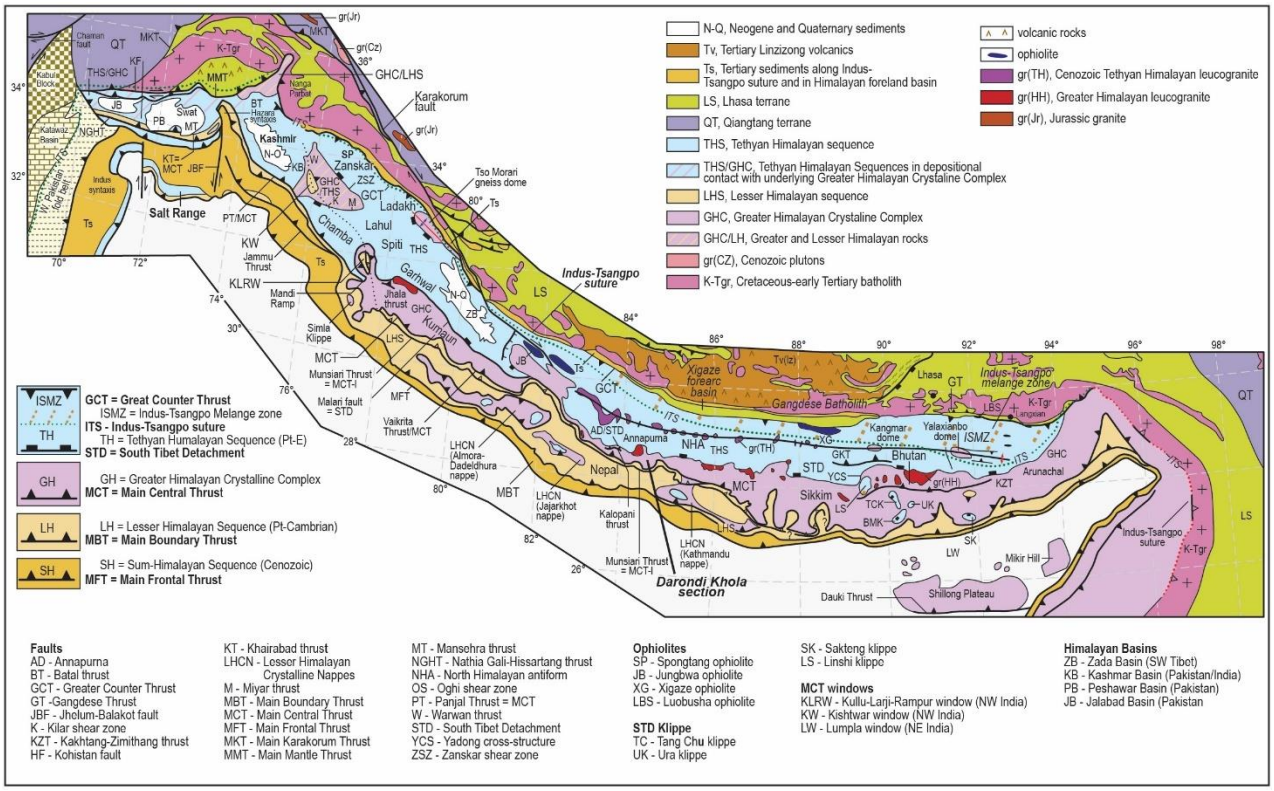

Figure S1. Geological map of the Himalayas after Yin (2006). Geological map of the Himalayas after Yin (2006). See Figure 2 for a cross-section through central Nepal and Figures 3-5 for the sample transect taken across the MCT shear zone along the Darondi Khola.

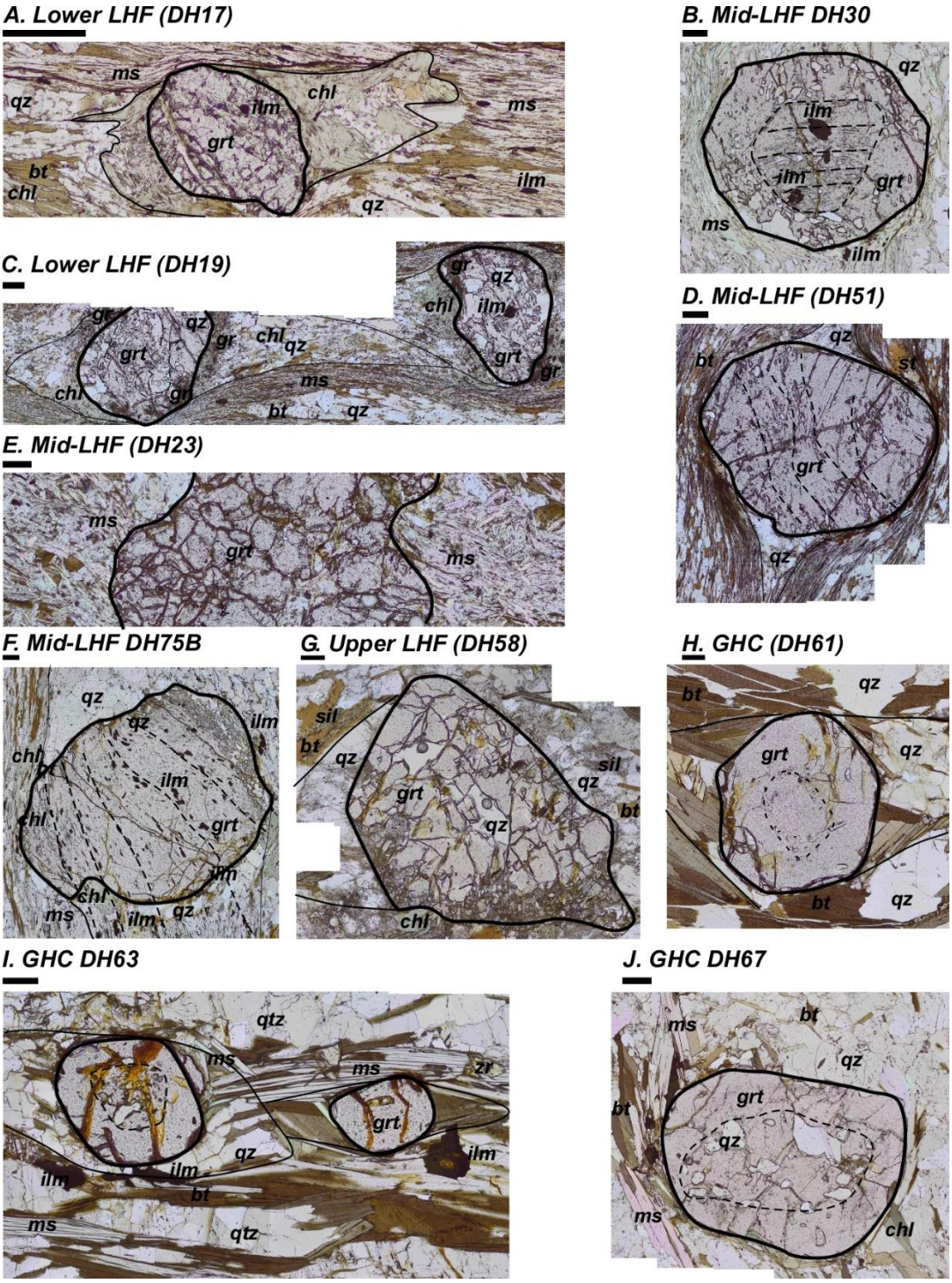

Figure S9. Selected petrographic (plane polarized light) images of samples along the Darondi Khola showing the relationship of the garnet porphyroblasts and rock textures. Garnets are outlined using bold lines. Pressure shadows and inclusion trails are indicates by lighter and dashed lines, respectively. Mineral abbreviations after Whitney and Evans (2010). Panels are labeled with sample number. The scale bar for each image is 200 μm. See Figures 4 and 5 for sample locations.