TIMING AND SOURCE OF MELTING AT THE EASTERN EDGE OF THE GURLA

MANDHATA CORE COMPLEX, NW NEPAL HIMALAYA

by

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A view looking south down the Chuwa Khola. Snowy peaks are beautifully exposed here above tree line. I am crossing the now timid Chuwa Khola on a log bridge, while Dr. Godin and our trusty Nepali guides lead the way.
ABSTRACT

Located at the eastern edge of the Gurla Mandhata core complex in the NW Nepal Himalaya, the Chuwa Khola exposes stromatic metatexite, calc-silicate gneiss, augen orthogneiss, and schlieren-structured diatexite, all crosscut by a leucogranitic dyke and sill network that culminates in the peraluminous Chuwa granite at the structurally highest level. Distributed shear sense indicators are consistent with top-to-the-southwest ductile extrusion of the Himalayan metamorphic core as observed elsewhere in the Himalaya.

In situ U-Th/Pb monazite petrochronology conducted on the Chuwa granite yields an interpreted mean crystallization age of ca. 18 Ma, with no ages younger than 16.5 ± 0.6 Ma. The dyke and sill network yields an interpreted mean crystallization age of ca. 19.5 Ma, with a minimum age of 15.8 ± 0.6 Ma. The southernmost migmatite samples yield similar mean dates interpreted to be the migmatization age (ca. 18.5 Ma), but also contain monazite ages as young as 12.8 ± 0.5 Ma. Yttrium content of the monazite in the migmatite increases with decreasing age, suggesting garnet breakdown and retrograde metamorphism from ca. 18 Ma to 12 Ma.

The dyke and sill network are interpreted as a feeder system to the overlying Chuwa granite, based on their similar (ca. 18 Ma) age and geochemical signature. Migmatization occurred as young as ca. 13 Ma as a result of orogen-parallel extension. It is suggested that the dyke and sill network and the coeval Chuwa granite were emplaced during southward-directed crustal extrusion prior to orogen-parallel extension, whereas the Chuwa Khola migmatite rocks record the transition from orogen perpendicular extrusion of the Himalayan metamorphic core to orogen parallel extensional exhumation at ca. 15 Ma to 13 Ma. The Gurla Mandhata core complex and the Chuwa Khola rocks have been affected by a coeval thermal pulse typical of southward extrusion of the Himalayan metamorphic core from ca. 22 Ma to 16 Ma. Although, the Gurla Mandhata core complex records top-to-the-west/
northwest sense of shear at ca. 15 Ma to 13 Ma, the Chuwa Khola exhibits dominant top-to-the southwest suggesting the existence of a strain partitioning boundary between the two areas.
ACKNOWLEDGEMENTS

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Thank you to the following people for their analytical and technical assistance: Agatha Dobosz for her help with thin section mapping and mineral characterization on the scanning electron microscope; Brian Joy for his help with X-ray chemical mapping of monazites on the electron microprobe; and Andrew Kylander-Clark (UCSB) for his help with guiding monazite petrochronology. I would also like to thank my thesis examination committee, Dr. Dawn Kellett and Dr. Daniel Layton-Matthews.

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## Himalayan Features

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<thead>
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<th>Abbreviation</th>
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<tr>
<td>GHS</td>
<td>Greater Himalayan sequence</td>
</tr>
<tr>
<td>GMD</td>
<td>Gurla Mandhata detachment</td>
</tr>
<tr>
<td>GMH</td>
<td>Gurla Mandhata-Humla fault system</td>
</tr>
<tr>
<td>HMC</td>
<td>Himalayan metamorphic core</td>
</tr>
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<td>IYSZ</td>
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<td>LHS</td>
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## Elements

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<tr>
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<td>Europium (63)</td>
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<td>Eu*</td>
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<tr>
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<td><strong>Afs</strong></td>
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<td>Calcite</td>
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<tr>
<td><strong>Di</strong></td>
<td>Diopside</td>
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<td><strong>Grt</strong></td>
<td>Garnet</td>
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<td><strong>Sil</strong></td>
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CHAPTER 1

INTRODUCTION

1.1 Overview of the Himalaya

The Himalaya represents the most spectacular active continental collision in the world and therefore provides the ideal natural laboratory to study processes governing the evolution of mountain belt systems. The mountain range first began to form ca. 55 Ma to 50 Ma when the Indian plate collided with Eurasia and subsequently evolved into a southward-propagating thrust system involving rocks from the northern paleo-continental margin of India (Green et al., 2008; Najman et al., 2010; Hu et al., 2016; Najman et al., 2017). Part of the Himalayan deformation has also been linked with ophiolite obduction around ca. 70 Ma (Spontang ophiolite, Tso Morari eclogites, e.g. Searle et al., 1997; Corfield et al., 2001; Pedersen et al., 2001; Ahmad et al., 2008; Singh et al., 2013; Wilke et al., 2015; Jonnalagadda et al., 2019).

The rocks involved in the collision have recorded limited overprinting, therefore enabling the distinction between Himalayan and pre-Himalayan deformation (e.g. Deniel et al., 1987; Le Fort et al., 1987; Hodges and Silverberg, 1988; Inger and Harris, 1992; Hodges et al., 1994; Hodges et al., 1996; Godin et al., 2001; Kellett et al., 2014). The Himalayan system is also ideal to study because of its known tectonic plate configuration, plate convergence rates (Jade et al., 2011; Ader et al., 2012; Thakur et al., 2014; Vernant et al., 2014; Panda et al., 2018) and recent thermal and structural evolution (e.g. Godin, 2003; Searle et al., 2003; Yin et al., 2010; Mathew et al., 2013; Landry et al., 2016; Braden et al., 2017).

The Himalayan system exposes extensive volumes of high metamorphic-grade rocks and granites, mostly found in the hanging wall of the early Miocene Main Central thrust (e.g. Burg et al., 1984; Stephenson et al., 2001; Catlos et al., 2004; Martin et al., 2005; Imayama and Arita, 2008; Searle et al., 2008; Larson and Godin, 2009; Larson et al., 2010; Tobgay et al., 2010; McKenzie et al., 2011; Yakymchuk and Godin, 2012; Mottram et al., 2014a; Braden et al., 2017; Braden et al., 2018; Mukherjee et al., 2019; Braden et al., 2020; Hopkinson et al., 2020; Godin et al., 2021).

The Himalaya also exposes extensive volumes of migmatites, granites and granitic dykes, which are products of crustal melt (e.g. Searle and Fryer, 1986; Brown, 2001; Godin et al., 2001;
Harris et al., 2004; Searle et al., 2008; Jain et al., 2013; Weinberg, 2016; Palin et al., 2018; Cottle et al., 2019). These magmatic rocks are now exposed due to exhumation processes such as erosion and normal-sense faults. Granitic dyke and sill networks are interpreted as ‘feeder’ systems to nearby granitic laccoliths (e.g. Crawford and Windley, 1990; Searle and Godin, 2003; Annen et al., 2006; Godin et al., 2006b; Weinberg, 2016). Cenozoic Himalayan granites are subdivided into two roughly parallel, near E-W striking intrusive belts, the North Himalayan granites and the High Himalayan leucogranites (Debon et al., 1986; Crawford and Windley, 1990; Guo and Wilson, 2012; Liu et al., 2019). These different manifestations of crustal melts can all be found within the study area along the Chuwa Khola (River in Nepali), in northwest Nepal (Fig. 1.1).

**Figure 1.1.** Google Earth Satellite imagery showing political boundaries, the location of the study area, and the Gurla Mandhata core complex. The study area is marked by a white rectangle, near N30° E82.5°.
1.2 Scope of this study

This thesis investigates the geology, structural style, and timing of the magmatic rocks within the Chuwa Khola, on the eastern edge of the Gurla Mandhata core complex (Fig. 1.2). The main purpose of this thesis is to determine the tectonometamorphic history of the rocks exposed in the Chuwa Khola. The secondary objective of this study is to use the results from the Chuwa Khola to broaden the understanding of the evolution of the nearby Gurla Mandhata core complex (Fig. 1.2).

Figure 1.2. Regional map of the northwest Nepal showing the Gurla Mandhata core complex and the Chuwa Khola (from Godin et al. (2021), modified from Murphy et al. (2002); Murphy and Copeland (2005); Murphy and Burgess (2006); Pullen et al. (2011); McCallister et al.
This thesis aims to address the following research questions:

- Are the three manifestations of magmatic rocks within the Chuwa Khola, namely the migmatite, the dyke and sill network, and the Chuwa granite, genetically related?
- Is the Chuwa granite a North Himalayan or a High Himalayan granite?
- Are the melt crystallization ages within the Chuwa Khola compatible with the Gurla Mandhata core complex evolution or with typical southward extrusion of the Himalayan metamorphic core?
- What is the nature of the eastern boundary of the Gurla Mandhata core complex?

These questions are addressed through detailed field mapping, petrographic and microstructural analysis, geochemical analysis, and finally in situ U-Th/Pb monazite petrochronology. Field mapping and the collection of structural measurements and oriented samples were undertaken in the Spring of 2018 and comprised a detailed 55 km ~ N-S transect along the Chuwa Khola. This transect built on previous preliminary mapping by Murphy and Copeland (2005) and Yakymchuk and Godin (2012). Field mapping provides the geological context for the collected samples. Thin section analysis of oriented samples informs on igneous and metamorphic petrology along the Chuwa Khola, while U-Th/Pb monazite petrochronology provides timing constraints on the thermal events. This approach provides the basis to assess the relationships between the magmatic rocks within the Chuwa Khola. We then apply these results to the broader regional context of the Gurla Mandhata core complex. The findings of this thesis contribute to limited research that has been done in the western and central portions of the Gurla Mandhata core complex.

This thesis is presented in chapter format. The Introduction chapter (Chapter 1) is followed by a literature review on the Himalayan orogen, metamorphic core complexes and domes within the Himalayan, Himalayan granites, principles of geochronology, and previous research in Chuwa Khola and upper Karnali Valley (Chapter 2). Chapter 3 details the major
rock units in the Chuwa Khola, field relationships, petrography, microstructural observations, and the results from geochemical analyses. Chapter 4 presents the methodology and quantitative results of in situ U-Th/Pb monazite petrochronology. Chapter 5 integrates the results from the previous chapters to form the interpretations that address the research questions presented above. Finally, Chapter 6 summarizes the main conclusions from this study and suggests recommendations for future research.
CHAPTER 2

LITERATURE REVIEW

2.1 The Himalayan orogen

The Himalayan orogen is a 2500 km long mountain range that was formed by the continuous convergence of the Indian and Eurasian plates and ultimately collision at ca. 55 Ma to 50 Ma (Green et al., 2008; Najman et al., 2010; Hu et al., 2016; Najman et al., 2017). The collision resulted in the closure of the Tethys sea, southward imbrication of the northern Indian paleocontinental margin, and northward subduction of the lower crust of the Indian plate below Eurasia (Godin et al., 2006a). The Himalaya is geographically well defined, from Nanga Parbat (8125m) in northern Pakistan to the west, to Namche Barwa (7755m) in southeast Tibet to the east (Fig. 2.1) (Le Fort, 1975; Hodges, 2000; Yin, 2006). The Himalaya are curved in map view and therefore segments along the length of the orogen have different angles of obliquity with the present-day convergence vector (Fig. 2.1) (Bendick and Bilham, 2001; Styron et al., 2011).

Figure 2.1. Google Earth Satellite imagery of the Himalayan and Tibetan regions. The orange lines indicate the north and south boundaries of the Himalayan orogenic wedge, with the Indus-
Yarlung Zangpo suture zone (IYSZ) to the north and the Main Frontal thrust (MFT) to the south. The west and east boundaries of the Himalaya are marked by Nanga Parbat (in northern Pakistan) and Namche Barwa syntaxes (in southeast Tibet), respectively. The study area is marked by a white rectangle, near N30° E82.5° (modified from Pan et al. (2004); Yin (2006); Hu et al. (2016)).

The orogen is composed of deformed Paleoproterozoic to early Cenozoic rocks from the pre-collisional northern margin of the Indian plate, Cenozoic granites, and foreland basin sedimentary rocks. The northern boundary of the Himalaya is marked by the Indus-Yarlung Zangpo suture zone, which separates Himalayan rocks of Indian provenance from Asian rocks. The southernmost extent of orogen-related deformation is marked by the Main Frontal thrust (Fig. 2.1) (Yin, 2006), although some Himalayan deformation is propagating south of the Main Frontal thrust (Duvall et al., 2020).

Four lithotectonic units make up the Himalaya, which are from north to south the Tethyan sedimentary sequence, the Greater Himalayan sequence, the Lesser Himalayan sequence, and the Sub-Himalaya (Fig. 2.2) (Heim and Gansser, 1939; Gansser, 1964; Le Fort, 1975; Searle et al., 1987; Hodges, 2000; Yin and Harrison, 2000; Yin, 2006). The Tethyan sedimentary sequence is the northernmost and structurally highest lithotectonic unit in the Himalayan orogen (Fig. 2.2). The Tethyan sedimentary sequence comprises a polydeformed package of unmetamorphosed to low metamorphic grade Paleozoic to early Cenozoic sedimentary rocks (Garzanti, 1999; Godin, 2003; Aikman et al., 2008; Montomoli et al., 2017a; Martin, 2017b). The rocks that now make up the Tethyan sedimentary sequence were originally deposited on the northern paleocontinental margin of India. The Tethyan sedimentary sequence records the evolution of the Tethys sea from the pre-rift stage (Cambrian – Ordovician) to the breakup of Gondwana in the early Cretaceous and subsequent sedimentation until the closure of the Tethys sea in the Paleogene (Garzanti, 1999; Hodges, 2000; Yin, 2006; Montomoli et al., 2017a).

The Greater Himalayan sequence is a package of Neoproterozoic to Ordovician metasedimentary and igneous rocks that have been pervasively deformed and metamorphosed at amphibolite to granulite facies and intruded by Cenozoic granitic rocks (Fig. 2.2) (Hodges et al.,
Three main units make up the Greater Himalayan sequence. Unit I is a kyanite-sillimanite grade pelitic schist, gneiss and migmatite unit found at the structurally lowest position. Unit II comprises calc-silicate gneiss, marble and psammitic schist and gneiss and overlies Unit I. Unit III is interlayered biotite schist and Ordovician augen orthogneiss (Hodges et al., 1996; Hodges, 2000; Gehrels et al., 2011). In some localities, the Greater Himalayan sequence also contains hornblende-biotite schist and micaceous marble (Gleeson and Godin, 2006) and Miocene leucogranitic intrusions (Searle and Godin, 2003; Gleeson and Godin, 2006; Godin et al., 2006a; Carosi et al., 2010; Yakymchuk and Godin, 2012; Carosi et al., 2014).
The Himalayan metamorphic core is a tectonometamorphic unit confined between the Main Central thrust and the South Tibetan detachment and comprises Greater Himalayan sequence and metamorphosed Lesser Himalayan sequence affinity rocks. MFT: Main Frontal thrust, MBT: Main Boundary thrust, MCT: Main Central thrust, STD: South Tibetan detachment, IYZS: Indus-Yarlung Zangpo suture zone, NHA: North Himalayan antiform, NHGD: North Himalayan gneiss domes.

The Lesser Himalayan sequence comprises Paleoproterozoic to early Mesoproterozoic clastic sedimentary, carbonate, magmatic, granitic, and volcanic rocks, all deposited and intruded proximal to the northern margin of the Indian plate, late Carboniferous to Permian sedimentary rocks, Eocene to early Miocene early foreland-basin sedimentary rocks (Brookfield, 1993; Upreti, 1999; DeCelles et al., 2000; DeCelles et al., 2004; Richards et al., 2005; Kohn et al., 2010; Gehrels et al., 2011; Long et al., 2011; Martin et al., 2011; Mottram et al., 2014a). The Lesser Himalayan sequence has been duplexed and weakly metamorphosed (maximum greenschist facies). Structurally, the Lesser Himalayan sequence lies below the Greater Himalayan sequence, in the footwall of the Main Central thrust and in the hanging wall of the Main Boundary thrust (Schelling and Arita, 1991; Schelling, 1992; DeCelles et al., 1998a; DeCelles et al., 1998b; DeCelles et al., 2001; Robinson and Martin, 2014; DeCelles et al., 2016; Martin, 2017a; Martin, 2017b).

The Sub-Himalaya is composed of Eocene-Oligocene sedimentary rocks as well as Neogene sedimentary rocks of the Siwaliks group produced by erosion from the rising Himalaya and deposited at the foreland-most edge of the orogen (Fig. 2.2) (DeCelles et al., 1998a; Najman, 2006).

The four lithotectonic units are bounded by crustal scale ductile shear zones and fault systems. From north to south these are the South Tibetan detachment, the Main Central thrust, the Main Boundary thrust, and the Main Frontal thrust (Fig. 2.2) (Hodges, 2000; Yin and Harrison, 2000; Yin, 2006). The Main Central thrust, Main Boundary thrust, and Main Frontal thrust all sole into a low angle fault termed the Main Himalayan thrust, the basal detachment of the orogen (Schelling and Arita, 1991; Zhao et al., 1993; Nelson et al., 1996). The South Tibetan detachment is a north-dipping normal-sense shear zone and fault that separates the structurally highest Tethyan sedimentary sequence from the Greater Himalayan sequence (Fig. 2.2) (Caby et
al., 1983; Burg et al., 1984; Burchfiel et al., 1992; Hodges et al., 1992; Hodges, 2000; Kellett et al., 2019). The South Tibetan detachment initiated as early as ca. 30 Ma to 29 Ma in western Nepal (Soucy La Roche et al., 2016), and may have ceased diachronously across the extent of the Himalayan orogen, from ca. 20 Ma to 11 Ma (Godin et al., 2006b; Kellett et al., 2009; Leloup et al., 2010; Chambers et al., 2011; Kellett et al., 2013; Webb et al., 2017; Montomoli et al., 2017b; Kellett et al., 2019).

The Main Central thrust was originally defined as a structural and metamorphic boundary with kyanite metamorphic-grade rocks of the Greater Himalayan sequence in the hanging wall against greenschist metamorphic grade rocks of the Lesser Himalayan sequence in the footwall (Heim and Gansser, 1939; Gansser, 1964; Bordet et al., 1971; Caby et al., 1983). However, the Main Central thrust and the protolith boundary between the Greater Himalayan sequence and the Lesser Himalayan sequence do not always coincide as the hanging wall of the Main Central thrust zone locally contains rocks from the Lesser Himalayan sequence (Fig. 2.3) (e.g. Larson and Godin, 2009; Larson et al., 2010; Tobgay et al., 2010; McKenzie et al., 2011; Yakymchuk and Godin, 2012; Mottram et al., 2014a; Braden et al., 2018; Mukherjee et al., 2019; Braden et al., 2020; Hopkinson et al., 2020; Godin et al., 2021). The Main Central thrust initiated ca. 23 Ma to 20 Ma (late Oligocene to early Miocene) after a period of crustal thickening that weakened the middle-lower crust (Kohn et al., 2005; Cottle et al., 2015; Fan and Murphy, 2020).

The Main Boundary thrust separates the Lesser Himalayan sequence from the structurally lowest Sub-Himalaya (Fig. 2.2) (Mugnier et al., 1994; Meigs et al., 1995; Hodges, 2000; Yin, 2006; DeCelles et al., 2020). The Main Frontal thrust is the seismically active orogenic front (Fig. 2.2) that locally propagate southward into the Ganga plain as “outer” frontal thrusts (e.g. Duvall et al., 2020). The Main Frontal thrust separates the Sub-Himalaya in its hanging wall from the Quaternary sediments of the Indus-Ganges-Brahmaputra foreland basin in its footwall (Wesnousky et al., 1999; Burgess et al., 2012).
2.2 The Himalayan metamorphic core

The Greater Himalayan sequence has historically been defined as a sequence of orthogneiss, paragneiss, and granite in the hanging wall of the Main Central thrust, based on a combination of lithological, structural, and metamorphic characteristics (Gansser, 1964; Le Fort, 1975). However, highly-metamorphosed Lesser Himalayan sequence rocks are locally preserved in the hanging wall of the Main Central thrust (Bollinger et al., 2006; Chakungal et al., 2010; Tobgay et al., 2010; McKenzie et al., 2011; Mottram et al., 2014a; Braden et al., 2017; Braden et al., 2018; Mukherjee et al., 2019; Hopkinson et al., 2020). Should the Greater Himalayan sequence be defined structurally as being in the hanging wall of the Main Central thrust or should it be defined as a stratigraphic package independent from its position with respect to the Main Central thrust? As such, the Greater Himalayan sequence has recently been defined based on protolith or structural definitions (Fig. 2.3) (Braden et al., 2017).

To reconcile the challenges with naming conventions of metamorphic rocks in the Himalaya, an alternative term, the Himalayan metamorphic core (HMC) is defined to refer to all rocks that record evidence of Cenozoic mid-crustal deformation, metamorphism, melting and cooling (Cottle et al., 2015). The Himalayan metamorphic core can include rocks of Greater Himalayan sequence and Lesser Himalayan sequence protolith affinity (Cottle et al., 2015; Gibson et al., 2016; Braden et al., 2018; Godin et al., 2021). The Himalayan metamorphic core records an Ordovician thermal event associated with the Bhimphedian event developed along the northern margin of Gondwana (Godin et al., 2001; Cawood et al., 2007) as well as two phases of Cenozoic Himalayan metamorphism (Vannay and Hodges, 1996). The first Cenozoic phase is an Eocene-Oligocene high-pressure and moderate-temperature phase referred to as the Eohimalayan phase, which is a result of crustal thickening beginning at 35 Ma (Hodges and Silverberg, 1988; Inger and Harris, 1992; Hodges et al., 1994; Hodges et al., 1996; Godin et al., 2001; Kellett et al., 2014). The second Cenozoic phase is an Oligocene-Miocene high-temperature and moderate-pressure phase referred to as the Neohimalayan phase, which coincides with thrusting along the Main Central thrust, production of High Himalayan leucogranites (Deniel et al., 1987; Le Fort et al., 1987), and the onset of the South Tibetan detachment at higher structural levels (Burchfiel et al., 1992; Godin et al., 2001).
Figure 2.3. Protolith definition of the Greater Himalayan sequence (GHS) and Lesser Himalayan sequence (LHS) versus structural definition of the Main Central thrust (MCT) zone and tectonometamorphic definition of the Himalayan metamorphic core (HMC). The protolith definitions define the GHS and LHS by their distinct protolith ages regardless of the position of the MCT zone. The structural definition places the HMC in the hanging wall of the Main Central thrust, with the high strain, high metamorphic grade Main Central thrust zone incorporating both Greater and Lesser Himalayan sequence protolith rocks into the Himalayan metamorphic core (modified from Braden et al., 2017).

The decompression path observed in metamorphic rocks of the Himalayan metamorphic core has been interpreted by some to be associated with southward extrusion of the middle crust during coeval activity of the Main Central thrust and the South Tibetan detachment (e.g. Lee et al., 2006; Godin et al., 2006a; Kohn, 2008; Carosi et al., 2010; Streule et al., 2010; Larson et al., 2011; Yakymchuk and Godin, 2012). Two end-member hypotheses are used to explain the extrusion of the Himalayan metamorphic core. (1) The Channel flow model describes a prolonged flow of a weak, viscous crustal layer between relatively rigid yet deformable bounding crustal slabs (e.g. Beaumont et al., 2004; Searle and Szulc, 2005; Godin et al., 2006a; Streule et al., 2010; Parsons et al., 2016). The weak layer is related to the presence of melts at mid-crustal depth, which weakens the crust and localizes deformation (Nelson et al., 1996; Rosenberg and
Handy, 2005). The channel flow model aims to explain features common to metamorphic hinterlands of many large orogenic systems, and hinges on a rigorous understanding of the timing of various melts with respect to the age of major fault systems. (2) The wedge extrusion model describes the translation and extrusion of Greater Himalayan sequence material in the hanging wall of a critical tapered wedge maintained by internal deformation, underthrusting, and focused erosion (e.g. Webb et al., 2007; Kohn, 2008; He et al., 2015; He et al., 2016). The wedge extrusion model predicts relatively low temperatures at high pressures for both Greater and Lesser Himalayan sequence rocks (Bollinger et al., 2006; Kohn, 2008). The wedge extrusion model also predicts peak P-T conditions within the kyanite stability field and generally increasing pressures and temperatures structurally upward (Kohn, 2008).

Differentiating between the Greater Himalayan sequence and highly-metamorphosed Lesser Himalayan sequence is therefore key. The protolith definitions of the Greater Himalayan sequence and the Lesser Himalayan sequence differentiate the two units based on their ages, which can be assessed with Sm-Nd isotope analyses. $^{147}$Sm, $^{143}$Nd, and $^{144}$Nd are the naturally occurring isotopes considered for this method. $^{147}$Sm decays to $^{143}$Nd with a half-life of $1.06 \times 10^{11}$ years and $^{144}$Nd with a half-life of $2.23 \times 10^{15}$ years, long enough to be considered stable at geologic time scales (DePaolo and Wasserburg, 1976; Goldstein et al., 1984). When melt is extracted from the mantle, the melt has a $^{143}$Nd/$^{144}$Nd ratio that is subsequently altered by the decay of Sm present in the system at the time of extraction. Therefore, the measured $^{143}$Nd/$^{144}$Nd and $^{147}$Sm/$^{144}$Nd in the sample versus the same ratios in the depleted mantle, along with the divergence of the isotopic evolution lines in the sample can be used to calculate an age at which the melt was extracted from the mantle (DePaolo and Wasserburg, 1976). Because these deviations are very small, epsilon notation, $\varepsilon$Nd$_{(t)}$, is commonly used, where one epsilon unit represents one part per 10,000 deviation from the depleted mantle evolution line (DePaolo and Wasserburg, 1976). The $\varepsilon$Nd$_{(t)}$ value is the calculated epsilon value at a given age t, whereas $\varepsilon$Nd$_{(0)}$ is the current epsilon value calculated at the present day. In the Himalaya, $\varepsilon$Nd$_{(0)}$ values below -19 are assigned to the Lesser Himalayan sequence, whereas values above -19 are typically Greater Himalayan sequence, though there are some Lesser Himalayan sequence results with higher $\varepsilon$Nd$_{(0)}$ values (Parrish and Hodges, 1996; Ahmad et al., 2000; Robinson et al., 2001; Martin et al., 2005; Richards et al., 2005; Murphy, 2007; Imayama and Arita, 2008; Tobgay et al., 2010; McKenzie et al., 2011; Mottram et al., 2014a; Godin et al., 2021).
2.3 Metamorphic core complexes and domes within the Himalaya

Gneiss domes are common features within orogenic systems around the world (e.g. Duncan, 1984; Amato et al., 1994; Teyssier and Whitney, 2002; Borradaile and Gauthier, 2003; Yin, 2004; Gordon et al., 2008; Langille et al., 2012; Platt et al., 2015; Jessup et al., 2019). Gneiss domes were first defined and discussed in the mid-twentieth century (Eskola, 1948). Gneiss domes are classified as either fault-related or fault-unrelated (Yin, 2004). In the Himalaya, fault-related gneiss domes appear to be most common, and are either compression-related (e.g. North Himalayan gneiss domes) (Burg et al., 1984; Debon et al., 1986; Lee et al., 2000; Lee et al., 2004; Watts and Harris, 2005; Aoya et al., 2006; Quigley et al., 2006; Larson et al., 2010), extension-related (e.g. Himalayan metamorphic core complexes, Leo Pargil, and Ama Drime) (Thiede et al., 2006; Jessup et al., 2008; Cottle et al., 2009a; Langille et al., 2010; Crouzet et al., 2012; Langille et al., 2012; Lederer et al., 2013; Kellett et al., 2014; Langille et al., 2014), or strike-slip-related (e.g. Karakoram mountains, western Himalaya) (Yin, 2004; Murphy and Copeland, 2005; Murphy and Burgess, 2006; Godin et al., 2021).

2.3.1 Compression related gneiss domes – North Himalayan gneiss domes

The North Himalayan gneiss domes are exposed along the North Himalayan antiform between the South Tibetan detachment and the Indus-Yarlung Zangpo suture zone (Fig. 2.2A) (Hodges, 2000; Jessup et al., 2019). These gneiss domes are typically cored by granite, gneiss, and migmatite and are surrounded by a deformed metasedimentary shell (Burg et al., 1984; Debon et al., 1986; Lee et al., 2000; Lee et al., 2004; Watts and Harris, 2005; Aoya et al., 2006; Quigley et al., 2006; Larson et al., 2010). Examples of North Himalayan gneiss domes include, but are not limited to, Mabja dome (e.g. Lee et al., 2004), Malashan dome (e.g. Aoya et al., 2006), Kangmar dome (e.g. Chen et al., 1990; Lee et al., 2000), Kampa dome (e.g. Quigley et al., 2006), Yardoi dome (e.g. Gao et al., 2012), Changgo culmination (e.g. Larson et al., 2010), and Lhagoi Kangri dome (e.g. Diedesch et al., 2016) (Fig. 2.4).

The North Himalayan gneiss domes are interpreted as windows through the folded South Tibetan detachment into the metamorphic core of the Himalaya and are linked with out-of-sequence deformation and crustal thickening (Lee et al., 2000; Lee et al., 2004; Godin et al., 2006b; Lee and Whitehouse, 2007; Larson et al., 2010). Alternatively, geodynamic models suggest that the North Himalayan gneiss domes may have formed as a result of motion of the
extruding mid-crustal channel, combined with ongoing contraction of the entire orogen, causing the colder rheologically stronger lower plate in the hinterland mid-crust to act as a “plunger,” deflecting the melt-weakened Himalayan metamorphic core mid-crustal channel upwards (Model HT111 discussed in Beaumont et al., 2004; Jamieson et al., 2006). This creates a ramp-flat geometry of the Main Himalayan thrust that causes deflection of the Himalayan metamorphic core and forces it up and over the ramp, creating a dome in the mid-crust (Beaumont et al., 2004; Jamieson et al., 2006; Grujic et al., 2011; Warren et al., 2011). The North Himalayan gneiss domes could also be linked with a south-dipping Himalayan back thrust, referred to as the Great Counter thrust, which lies between the Indus-Yarlung Zangbo suture zone and the South Tibetan detachment (Ratschbacher et al., 1994; Makovsky et al., 1999; Yin, 2006).

2.3.2 Extension-related Himalayan metamorphic core complexes

In contrast to the North Himalayan gneiss domes, the Leo Pargil dome (e.g. Thiede et al., 2006; Langille et al., 2012; Lederer et al., 2013; Langille et al., 2014) and the Ama Drime massif (e.g. Jessup et al., 2008; Cottle et al., 2009a; Langille et al., 2010; Crouzet et al., 2012; Kellett et al., 2014) are core complexes that have been formed as a result of orogen-parallel extension (Fig. 2.4). The Leo Pargil dome was exhumed from mid-crustal depths along oppositely dipping normal faults between ca. 16 Ma to 10 Ma (Thiede et al., 2006; Langille et al., 2012). The Ama Drime Massif was also exhumed between oppositely dipping normal faults between ca. 13 Ma to 11 Ma (Jessup et al., 2008; Cottle et al., 2009a). The Gurla Mandhata core complex differs slightly from the Leo Pargil dome and the Ama Drime massif because the Gurla Mandhata core complex is bound by a single normal fault – the Gurla Mandhata detachment – as opposed to two normal faults (Murphy et al., 2002; Murphy and Copeland, 2005; Murphy, 2007; McCallister et al., 2014; Godin et al., 2021). The Gurla Mandhata core complex is interpreted as a transtensional strike-slip dome because it coincides with a dilational jog within the strike-slip system of the Karakoram fault that feeds into the West Nepal fault system. Doming of the Gurla Mandhata core complex has alternatively been interpreted to have occurred prior to E-W extension in the Himalaya (ca. 15 Ma to 13 Ma) (Godin et al., 2021).
2.4 Himalayan granites

Granitic rocks in the Himalaya are subdivided into three groups: (1) pre-Himalayan mid-late Paleoproterozoic granites usually preserved in the Lesser Himalayan sequence (e.g. Kohn et al., 2010), (2) pre-Himalayan Ordovician granites mostly exposed in the Greater Himalayan sequence (e.g. Gehrels et al., 2011), and (3) Cenozoic granites emplaced in proximity to the South Tibetan detachment (e.g. Debon et al., 1986).

2.4.1 Pre-Himalayan granites

Pre-Himalayan magmatic rocks are preserved in both the Lesser Himalayan sequence and the Greater Himalayan sequence (Hodges, 2000; Yin, 2006; Kohn et al., 2010). Orthogneiss preserved at the base of the Lesser Himalayan sequence are typically Paleoproterozoic (ca. 1.8 Ga) (e.g. DeCelles et al., 2000; Célérier et al., 2008; Chambers et al., 2008; Kohn et al., 2010). These rocks are generally mylonitic, quartz + alkali-feldspar + plagioclase + muscovite + biotite orthogneiss (Schelling, 1992; Miller et al., 2000; Gibson et al., 2016; Larson et al., 2016; Larson et al., 2017; Larson et al., 2019). The orthogneiss has various names across the Himalaya, some of which include: Ulleri, Melung, Melug-Salleri, Phaplu, and Num (Larson et al., 2019), and are alternatively interpreted as originating in a passive margin (e.g. Brookfield, 1993; Upreti, 1999; Gehrels et al., 2006), a continental arc (e.g. Kohn et al., 2010), or a rift related environment (e.g. Bhat et al., 1994; Bhat et al., 1998; Ahmad et al., 1999; Sakai et al., 2013; Larson et al., 2019).

In the Greater Himalayan sequence, pre-Himalayan magmatic rocks are preserved in the form of Unit III granitic augen orthogneiss that can be traced almost continuously from eastern to central Nepal (Le Fort et al., 1986), to as far east as Bhutan (Hodges, 2000). This unit has been dated at lower Ordovician, ca. 480 Ma to 470 Ma (Debon et al., 1986; Le Fort and Rai, 1999; Godin et al., 2001; Ogasawara et al., 2018; Palin et al., 2018). This Upper Cambrian-Lower Ordovician magmatism occurred at continental scale and is linked to the Bhimphedian event (e.g. Cawood et al., 2007). This event is related to an Andean-type margin that developed at the northern margin of the Indian continent following the assembly of Gondwana (Debon et al., 1986; Le Fort et al., 1986; DeCelles et al., 2000; Godin et al., 2001; Miller et al., 2001; Gehrels et al., 2003; Cawood et al., 2007; Martin et al., 2007; Gehrels et al., 2011; Stübner et al., 2017; Palin et al., 2018). The augen orthogneiss yields a large range of initial Sr isotopic ratio, from 0.755 to 0.89 (Guillot and Le Fort, 1995).
2.4.2 Himalayan granites

The onset of Himalayan collision in the Cenozoic induced crustal thickening and crustal melting throughout the extent of the orogen from at least 35 Ma to 7 Ma, with some Eocene ages being reported as well (Debon et al., 1986; Larson et al., 2010; Aikman et al., 2012; Guo and Wilson, 2012; Weinberg, 2016; Hopkinson et al., 2020). This widespread anatexis therefore occurred some 15 Ma to 20 Ma after the onset of collision, and lasted some 25 Ma or more (Le Fort et al., 1987; Weinberg, 2016). Cenozoic Himalayan granites are subdivided into two roughly parallel, near E-W striking intrusive belts, the North Himalayan granites and the High Himalayan leucogranites (Fig. 2.4) (Debon et al., 1986; Deniel et al., 1987; Crawford and Windley, 1990; Harrison et al., 1997; Guo and Wilson, 2012; Liu et al., 2019). The North Himalayan granites are exposed along the trace of the North Himalayan antiform, intruding both gneiss domes and the overlying Tethyan sedimentary sequence (Fig. 2.4) (Burchfiel et al., 1992; Hodges, 2000; King et al., 2011; Guo and Wilson, 2012; Weinberg, 2016). The High Himalayan leucogranites are typically located in the Greater Himalayan sequence in the immediate footwall of the South Tibetan detachment and into the Tibetan Sedimentary sequence (Fig. 2.4) (Weinberg and Searle, 1999; Searle and Godin, 2003; Guo and Wilson, 2012; Carosi et al., 2013; Weinberg, 2016). The High Himalayan leucogranites become scarce near Nanga Parbat, while the North Himalayan granites fade out in the Kailas region (Fig. 2.4) (Debon et al., 1986).

Both the High Himalayan leucogranites and the North Himalayan granites are generally granitoids or adamellites, peraluminous, with a variable amount of biotite and muscovite, and are commonly leucocratic (Debon et al., 1986; Guo and Wilson, 2012). The Himalayan granites also contain tourmaline, cordierite, and sometimes garnet, sillimanite, and andalusite (Debon et al., 1986; Visona et al., 2012; Weinberg, 2016). The High Himalayan leucogranites yield ages that range from ca. 25 Ma to 12 Ma and overlap with the North Himalayan granite ages of ca. 18 Ma to 9 Ma (Lecho, 2008; Larson et al., 2010; Guo and Wilson, 2012; Weinberg, 2016), with some North Himalayan granites as old as ca. 35 Ma (e.g. Jessup et al., 2019). North Himalayan and High Himalayan granites are both hypothesized to form at mid-crustal depth in the hinterland of the Himalayan orogen, with the younger melts being closest to the hinterland. The High Himalayan leucogranites are therefore typically older and located farther south than the North Himalayan granites (Fig. 2.4).
North Himalayan granites are usually richer in dark minerals, quartz, and calcium, but are poorer in alkalis and feldspars, compared with the High Himalayan leucogranites (Debon et al., 1986). North Himalayan granites are characterized by high heavy and light rare earth element ratios, as well as high yttrium contents (King et al., 2011). North Himalayan granite melt source either originates from the Greater Himalayan sequence (e.g. King et al., 2011; Xie et al., 2018), or the nearby metasedimentary units (e.g. Tethyan sedimentary rocks) of North Himalayan gneiss domes (e.g. Aikman et al., 2008).

In contrast to North Himalayan granites, High Himalayan leucogranites have low or very low heavy to light rare earth element ratios (Debon et al., 1986). High Himalayan leucogranites are subdivided into the tourmaline leucogranites and the two-mica leucogranites (e.g. Guillot and Le Fort, 1995; Visona and Lombardo, 2002; Guo and Wilson, 2012). The tourmaline leucogranites have abundant tourmaline and muscovite, while the two-mica leucogranites have abundant biotite and muscovite, but no tourmaline (Guo and Wilson, 2012). The tourmaline leucogranites most likely formed by muscovite and biotite dehydration melting (Visona and Lombardo, 2002), while the two-mica leucogranites are interpreted to represent different melt fractions of a layered, metasedimentary protolith, probably of Greater Himalayan sequence affiliation (e.g. Visona and Lombardo, 2002; Hopkinson et al., 2017; Yang et al., 2019). Both the tourmaline leucogranite and the two-mica leucogranite are interpreted to have a sedimentary source (e.g. Deniel et al., 1987; Visona and Lombardo, 2002), commonly interpreted as a mixture of the Lesser and Greater Himalayan sequence (e.g. Murphy, 2007; Pullen et al., 2011; Guo and Wilson, 2012; Hopkinson et al., 2020). The Manaslu leucogranite of central Nepal is the type-example of a High Himalayan leucogranite (e.g. Deniel et al., 1987; Brown, 1994; Searle and Godin, 2003; Larson et al., 2011; Cottle et al., 2019). The Manaslu leucogranite consists of quartz + plagioclase + alkali-feldspar + tourmaline + muscovite + biotite, is peraluminous, and has emplacement ages that range from 24 Ma to 12 Ma (Deniel et al., 1987; Copeland and Harrison, 1990; Harrison et al., 1995; Harrison et al., 1999; Searle and Godin, 2003; Cottle et al., 2019). Advances in remote sensing technology have allowed for the mapping of the Himalayan granites, applied to domes along the North Himalayan antiform (e.g. Watts and Harris, 2005; Larson et al., 2010; Wang et al., 2020).
Defining the Chuwa granite as either a High Himalayan or North Himalayan granite will add to the understanding of the source and exhumation history of the Chuwa granite (e.g. King et al., 2011; Guo and Wilson, 2012; Hopkinson et al., 2020).

**Figure 2.4.** Main Himalayan domes and granites superimposed on shaded relief (GTOPO 30 USGS). The North Himalayan gneiss domes are concentrated along the trace of the North Himalayan antiform (dashed black line), while the extensional core complexes are associated with local extensional fault systems such as grabens and transtensional strike-slip faults. The North Himalayan granites are also concentrated along the trace of the North Himalayan antiform, while the High Himalayan leucogranites are found structurally just below the South Tibetan detachment. The Chuwa granite is found on the eastern termination of the Gurla Mandhata core complex (modified from Armijo et al. (1986); Hodges (2000); Searle and Godin (2003); Watts and Harris (2005); Thiede et al. (2006); Yin (2006); Langille et al. (2010); Larson et al. (2010); Guo and Wilson (2012); Yang et al. (2019); (Godin et al., 2021)). IYSZ: Indus-Yarlung.
2.5 Principles of geochronology

The U-Th/Pb system provides the ability to determine radiometric ages of rocks and minerals with reasonable precision, accuracy, and efficiency (Faure, 1977; Faure and Mensing, 2005). Recent advances in the field of geochronology have led to the emergence of petrochronology, which is the interpretation of isotopic dates in light of complementary isotopic or elemental information from the same mineral(s) (Kylander-Clark et al., 2013). In this section, I review the U-Th/Pb decay system and U-Th/Pb petrochronology approach.

2.5.1 U-Th/Pb decay system principles

The U-Th/Pb system has been used for more than 100 years in the field of geochronology. This system is a powerful tool because three chronometers produce Pb isotopes: $^{235}$U → $^{207}$Pb (half-life of 0.70 Ga), $^{238}$U → $^{206}$Pb (half-life of 4.47 Ga), and $^{232}$Th → $^{208}$Pb (half-life of 14.01 Ga) (Jaffey et al., 1971; Steiger and Jager, 1977; Davis et al., 2003). These three daughter Pb isotopes also occur as primordial nuclides. The ratio of $^{204}$Pb to $^{206}$Pb, $^{207}$Pb, and $^{208}$Pb can be used as a baseline because they are predictable over geologic time. The ratios are used to estimate the extra amounts of radiogenic Pb in the sample as a result of the decay of $^{238}$U, $^{235}$U, and $^{232}$Th. This information can then be used in the age equations (e.g. equation 1, where t is time (expressed in years) and lamda is the decay constant) to determine the date of the U or Th-bearing mineral (Faure and Mensing, 2005).

$$t_{208} = \left(\frac{1}{\lambda_{232}}\right) \ln \left(\frac{^{208}Pb}{^{206}Th}\right) + 1$$

(equation 1)

A key component when using the U-Th/Pb system in dating minerals is ensuring that the conditions for secular equilibrium are met (e.g. Sheppard et al., 2008; Papadopoulos et al., 2013). Secular equilibrium is achieved in a U or Th bearing mineral because the decay rates of the intermediate daughters are equal to that of their parents (Faure and Mensing, 2005). Therefore, when secular equilibrium is established, and a closed system is assumed, the rate at which a stable daughter at the end of a decay chain is produced is equal to the rate of decay of its parent at the beginning of the chain. Therefore, it can be stated that the decay of U and Th in
minerals where secular equilibrium is established can be treated as directly occurring due to the decay of $^{238}\text{U}$, $^{235}\text{U}$, and $^{232}\text{Th}$ (Faure and Mensing, 2005). Secular equilibrium is disturbed when either parents or daughter isotopes are added to or leave the system, this can happen in multiple different ways (Rosholt, 1983). The half-lives of $^{238}\text{U}$, $^{235}\text{U}$, and $^{232}\text{Th}$ are all significantly longer than the half-lives of their corresponding daughters. Therefore, these three systems satisfy the conditions for the establishment of secular equilibrium. In Cenozoic monazite, the $^{208}\text{Pb}/^{232}\text{Th}$ date is often the most reliable, because excess $^{206}\text{Pb}$ (referred to as unsupported $^{206}\text{Pb}$ because it comes from the decay of Th not $^{238}\text{U}$) can cause the $^{206}\text{Pb}/^{238}\text{U}$ dates to be older than the actual crystallization ages (Parrish, 1990).

Historically, the U-Th/Pb system has been predominantly used for dating zircons, with a significant increase in studies of this nature between the 1960s and the 2000s (Davis et al., 2003). Zircon was recommended early on as a chronometer based on its U content, resistance to alteration, and the fact that it most likely does not contain any common Pb (e.g. Davis et al., 2003), along with Monazite (e.g. Schärer, 1984; Schärer et al., 1986; Parrish, 1990).

2.5.2 U-Th/Pb petrochronology

Petrochronology has been defined as "the interpretation of isotopic dates in light of complementary isotopic or elemental information from the same mineral(s)" (Kylander-Clark et al., 2013). More broadly petrochronology is defined as "linking time (ages or rates) with specific rock-forming processes and their physical conditions" (Kohn et al., 2017). Petrochronology builds on in situ dating of minerals by collecting complementary trace-element information via split-stream laser ablation inductively coupled plasma mass spectrometer (Kylander-Clark et al., 2013). Petrochronology comprises six main components, of which the two most significant for this thesis are: first, the chemical zoning of the minerals, often assessed through X-ray mapping, assists in matching mineral (re)crystallization to specific igneous, metamorphic or deformation events, or the presence or absence of other minerals (Kylander-Clark et al., 2013), and second, the presence or absence of inclusions, as well as the concentration of certain trace elements (e.g. Y and Eu/Eu*) guide what minerals are present or absent at the time of growth for the host phase (Kylander-Clark et al., 2013).

The most widely used minerals in petrochronology are zircon, monazite, titanite, and rutile. Monazite is a light REE phosphate mineral that occurs as an accessory mineral in a range
of rock types, such as granitic or magmatic rocks (Parrish, 1990). Monazite contains abundant U and Th but does not incorporate Pb into its structure (Parrish, 1990). Monazite can be used to date the crystallization age of a rock, in particular peraluminous granitic rocks, where the presence of inherited zircon grains often prevent a precise U-Pb age to be determined for the magmatic zircons, and metamorphism in amphibolite and granulite grade metapelites (Zhu and O’Nions, 1999; Foster et al., 2002; Spear and Pyle, 2002; Gibson et al., 2004). Monazite has also proved useful in the field of petrochronology because of the documented links between age domains and chemical zones (e.g. yttrium) in monazite grains (e.g. Gibson et al., 2004; Braden et al., 2017). Monazite has been used to relate U-Th/Pb dates to pressure-temperature paths (e.g. Yakymchuk and Brown, 2014; Hacker et al., 2019), and has also been used as a chronometer in ultra-high pressure and temperature conditions (e.g. Holder et al., 2015; Holder et al., 2018).

In the Himalaya, U-Th/Pb monazite petrochronology has been used extensively in the past two decades. It has emerged as a leading technique in dating shear zones (Gehrels et al., 2006; Carosi et al., 2010; Mottram et al., 2014b; Mottram et al., 2015; Soucy La Roche et al., 2016; Braden et al., 2017; Braden et al., 2018), determining the timing of the pressure-temperature path of metamorphism (Martin et al., 2007; Cottle et al., 2009b; Larson et al., 2011; Palin et al., 2014; Stübner et al., 2014; Regis et al., 2016), and dating melt formation and pluton assembly (Kohn et al., 2005; Cottle et al., 2009b; Larson et al., 2011; Rubatto and Chakraborty, 2013; Cottle et al., 2019).

### 2.6 Previous research in the Chuwa Khola and upper Karnali valley

The Chuwa Khola is located in the far northwest of Nepal (Figs. 2.1, 2.2). Parts of the Chuwa Khola have been previously mapped by Murphy and Copeland (2005) and Yakymchuk and Godin (2012). Murphy and Copeland (2005) focused on the Gurla Mandhata core complex, a migmatite-cored gneiss dome, its links to the Karakoram fault system and the nearby Indus-Yarlung Zangpo suture zone, and its possible connection to orogen-parallel extension and exhumation. Yakymchuk and Godin (2012) focused on the southern-most extent of the Chuwa Khola, and on the role that metamorphism and deformation play on the development of inverted metamorphic gradients.

The Chuwa Khola marks the easternmost limit of the Gurla Mandhata core complex (Fig. 2.5). The core complex has been the object of preliminary geochronology, thermochronology,
and isotopic studies over the last two decades (Murphy et al., 2002; Murphy and Copeland, 2005; Murphy, 2007; McCallister et al., 2014; Nagy et al., 2015; Godin et al., 2021). To the south, the Chuwa Khola feeds into the Humla Karnali (Fig. 2.6) (Murphy and Copeland, 2005; Yakymchuk and Godin, 2012; Antolín et al., 2013; Nagy et al., 2015). This thesis aims to build on and draw links between previous work done in the Chuwa Khola, as well as the Gurla Mandhata core complex, and the upper Humla Karnali valley (Fig. 2.6).

![Oblique Google Earth Satellite imagery of the Gurla Mandhata core complex and the Chuwa Khola regions. The highest elevation is reached at the summit of Gurla Mandhata (7728 m), whereas the junction of the Karnali River and Chuwa Khola below Simikot is at 2100 m. Simikot is marked (elevation: 3036 m), as well as the Chuwa Khola and the Gurla Mandhata core complex.](image)

**Figure 2.5.** Oblique Google Earth Satellite imagery of the Gurla Mandhata core complex and the Chuwa Khola regions. The highest elevation is reached at the summit of Gurla Mandhata (7728 m), whereas the junction of the Karnali River and Chuwa Khola below Simikot is at 2100 m. Simikot is marked (elevation: 3036 m), as well as the Chuwa Khola and the Gurla Mandhata core complex.

Mapping in the Gurla Mandhata core complex has revealed five primary rock units: augen gneiss, marble/calc-silicate/metasedimentary, garnet-biotite metapelitic, sillimanite- garnet-biotite- metapelitic, and leucogranite bodies (Godin et al., 2021). The rocks in the Gurla Mandhata core complex yield mixed Greater Himalayan sequence (GHS) and Lesser Himalayan sequence (LHS) material, with $\varepsilon$Nd(0) ranging from -25 to -15, suggesting that both GHS and LHS rocks are exposed in the Gurla Mandhata core complex (Murphy, 2007; Godin et al., 2021).
The Gurla Mandhata core complex is bound to the west by a west-dipping normal fault termed the Gurla Mandhata detachment, which has exhumed mid-crustal rocks in its footwall (Fig. 2.6) (Murphy et al., 2002). The Gurla Mandhata detachment is interpreted to be an E-W extensional feature that has accommodated at least 66 km of top-to-the-west normal shear (Murphy et al., 2002) from ca. 15 Ma to 7 Ma (Murphy and Copeland, 2005). The Gurla Mandhata detachment is interpreted to be kinematically linked to the northwest with the Karakoram fault system since 14 Ma to 11 Ma (Fig. 2.4) (Searle et al., 1998; Murphy et al., 2000; Phillips et al., 2004; Murphy and Burgess, 2006; Valli et al., 2007; Leech, 2008). Both fault systems have been interpreted to be active at the same time and have accommodated similar amounts of right-lateral slip (Murphy et al., 2002; McCallister et al., 2014). A seismic reflection profile conducted across the Karakoram fault system, near its southeastern terminus shows that the Karakoram fault system is only an upper-crustal feature feeding into the Gurla Mandhata detachment (Gao et al., 2016).

The Gurla Mandhata core complex is interpreted to be a result of contemporaneous E-W extension and north-south shortening (Murphy and Copeland, 2005). It has been interpreted to be a structural and metamorphic culmination that was established in the Oligocene to early Miocene during the crustal thickening stage (Eohimalayan) before being overprinted by the extensional Gurla Mandhata detachment in the mid-Miocene (Godin et al., 2021). It has alternatively been proposed that the Gurla Mandhata core complex formed as a result of underlying duplexing along the Greater Himalaya ramp (Gao et al., 2016).

The most abundant lithology of the magmatic rocks found in the Gurla Mandhata core complex is muscovite-tourmaline bearing granite (Murphy et al., 2002). Recent studies have shown that the anatectic melts in the center of the Gurla Mandhata core complex yield no monazite ages younger than 16 Ma (Godin et al., 2021), prior to the hypothesized change from south directed extrusion of the Himalayan metamorphic core to E-W extension at ca. 15 Ma to 13 Ma (Nagy et al., 2015). The magmatic rocks on the western edge of the Gurla Mandhata core complex (Fig. 2.6) are late Miocene granitic intrusions, which are interpreted as forming as a result of decompression during the doming (Murphy and Copeland, 2005). These melts are correlated with E-W extension associated with the Gurla Mandhata detachment (Fig. 2.6) at the same time, 15 Ma to 7 Ma (Murphy and Copeland, 2005). These results show that the melts in the interior of the core complex are structurally lower and older, whereas the melts in the west are structurally higher and younger.
Figure 2.6. Compilation map showing previous work done in the Gurla Mandhata core complex and the Chuwa Khola (data from McCallister et al. (2014) (red), Murphy et al. (2002); Murphy (2007) (green), Murphy and Copeland (2005) (dark blue), Godin et al. (2021) (light blue), this work (purple), Yakymchuk and Godin (2012) (yellow), Nagy et al. (2015) (orange), and Pullen et al. (2011) (pink), from Godin et al. (2021), modified from Murphy et al. (2002); Murphy and Copeland (2005); Murphy and Burgess (2006); Pullen et al. (2011); McCallister et al. (2014)). TSS: Tethyan sedimentary sequence, GHS: Greater Himalayan sequence, LHS: Lesser Himalayan sequence, STD: South Tibetan detachment, GMD: Gurla Mandhata detachment, MCT: Main Central thrust, GMH: Gurla Mandhata-Humla fault system, WNFS: West Nepal fault system.
The Xiao Gurla complex (Fig. 2.6), exposed to the north of the Gurla Mandhata core complex, is interpreted to share similar footwall units as the Gurla Mandhata core complex (Pullen et al., 2011). Xiao Gurla leucogranites yield an average U/Pb crystallization age of ca. 19 Ma (Pullen et al., 2011), suggesting that the intrusions in this area also predate the initiation of E-W extension along the Gurla Mandhata detachment, similar to what is seen in the structurally lowest sections in the interior of the Gurla Mandhata core complex. The leucogranites exposed in the Xiao Gurla complex are interpreted to be derived from the anatexis of both Greater Himalayan sequence and Lesser Himalayan sequence rocks (Pullen et al., 2011).

The location of the Gurla Mandhata core complex coincides with a significant change in thickness of the Himalayan metamorphic core, from ∼25-26 km in the western Himalaya to ∼10-20 km in the central Himalaya (Parsons et al., 2016; Fan and Murphy, 2020). Lateral variations in volume and age of Miocene granites from the northwest Himalaya to southeastern Tibet are also marked by the Gurla Mandhata core complex (Leech, 2008), where the Karakoram fault system terminates and transfers slip either to the Indus-Yarlung Zangpo suture zone or the Gurla Mandhata detachment (Murphy et al., 2002; Murphy and Copeland, 2005; McCallister et al., 2014).

The E-W oriented upper Humla Karnali valley lies in the southern area between the Chuwa Khola and the Gurla Mandhata core complex (Fig. 2.6). The upper Humla Karnali valley follows the trace of the south dipping Gurla Mandhata-Humla fault system (Murphy and Copeland, 2005; Nagy et al., 2015). Metamorphism in this area has been constrained by U-Th/Pb monazite geochronology between 19 Ma and 15 Ma, and is interpreted to be associated with south directed extrusion of the Himalayan metamorphic core (Nagy et al., 2015). In this region, the orogen parallel ESE-WNW muscovite lineation (Murphy and Copeland, 2005; Nagy et al., 2015) yielded $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology dates suggesting the orogen-parallel shearing was active between ca. 13 Ma and 10 Ma (Nagy et al., 2015). Therefore, in the upper Humla Karnali valley (Fig. 2.6), the transition from south-directed extrusion of the Himalayan metamorphic core to orogen parallel extension occurred between ca. 15 Ma and 13 Ma (Nagy et al., 2015). This transition is also observed farther south in the Humla Karnali valley, south of the village of Simikot, where the transition from north-south shortening to E-W extension is recorded between ca. 8.6 Ma and 6 Ma in Greater Himalayan sequence rocks that show an inverted metamorphic
gradient (Yakymchuk and Godin, 2012). This mid-Miocene transition to orogen parallel extension is also reported in southwest Nepal, near the Dadeldhura klippe shear zones, where south directed extrusion of the Himalayan metamorphic core is documented to have ceased earlier, by 16 Ma (Antolín et al., 2013).

The Pulan shear zone is located some 50 km northwest of the upper Humla Karnali valley in Tibet, and feeds into the Pulan basin. The Pulan shear zone shows pervasive top-to-the-west sense of shear and defines a boundary between Greater Himalayan sequence and Tethyan sedimentary sequence rocks. In the footwall of the Pulan shear zone the south directed extrusion of the Himalayan metamorphic core is slightly older, interpreted to have ceased between ca. 22 Ma and 15 Ma (Xu et al., 2013). The change from south directed extrusion of the Himalayan metamorphic core to orogen parallel extension therefore seems to propagate southeast from the Pulan shear zone through the Gurla Mandhata detachment into the upper Humla Karnali Valley (e.g. the Gurla Mandhata-Humla fault system) (Murphy et al., 2002; Murphy and Copeland, 2005; Yakymchuk and Godin, 2012; Xu et al., 2013; Murphy et al., 2014; Nagy et al., 2015), with the cessation of southward directed extrusion being older in the northwest than it is in the southeast. Farther southeast, the Gurla Mandhata-Humla fault system branches south and southeast to link up with the active West Nepal (strike-slip) fault system (McCallister et al., 2014; Murphy et al., 2014; Silver et al., 2015), where this E-W extension is hypothesized to still be active today (Murphy et al., 2014).
3.1 The Chuwa Kholo

The study area is located along the Chuwa Khola in the far northwestern Nepal Himalaya (Fig. 3.1). The Chuwa Kholo is a south-flowing river exposing the Himalayan metamorphic core and a Cenozoic granite at the eastern termination of the Gurla Mandhata core complex (Murphy and Copeland, 2005; Yakymchuk and Godin, 2012). The Chuwa Kholo is positioned along the trace of the North Himalayan antiform and in the footwall of the South Tibetan detachment (Fig. 3.1).

Figure 3.1. Simplified geologic map of the Nepal, Bhutan, and North Indian Himalaya (from Godin et al. (2021), modified from Murphy and Copeland (2005); McQuarrie et al. (2008); Antolín et al. (2013); Soucy La Roche et al. (2018a)). MFT: Main Frontal thrust, MBT: Main Boundary thrust, MCT: Main Central thrust, STD: South Tibetan detachment, IYZS: Indus-Yarlung Zangpo suture zone, NHA: North Himalayan antiform, NHGD: North Himalayan gneiss domes.

Five major rock units are exposed along the Chuwa Kholo: stromatic metatexite ± schist, calc-silicate schist/gneiss, augen orthogneiss, schlieren-structured diatexite, and granite.
Twenty-two outcrops were mapped along the Chuwa Khola. Their locations and structural measurements are included in Appendix A.

Figure 3.2. Detailed geologic map of the Chuwa Khola, NW Nepal Himalaya, with location of cross section A-A’ and U-Th/Pb sample locations. Samples are also included from Yakymchuk and Godin (2012) on the map and the stereographic projections. The mean foliation in the Chuwa
Khola is N290°/15°NE. The mineral elongation lineations plunge shallowly to the east in the southern panel of the Chuwa Khola (red points) and rotate to plunge shallowly to the northeast (white points) in the northern panel of the Chuwa Khola. Stereographic projections were produced with Stereonet (v. 10.2.9) software package (Allmendinger et al., 2013; Cardozo and Allmendinger, 2013). Contour interval is 1 sigma and counting area is 34.62% of net area.

The foliated stromatic metatexite (quartz + plagioclase + alkali-feldspar + biotite ± muscovite ± sillimanite ± garnet; with 15% leucosome per volume) is exposed at the structurally lowest level in the southern part of the Chuwa Khola (Fig. 3.4A, B, C). Biotite ± sillimanite schist is present in the stromatic metatexite unit in the structurally lowest levels of the Chuwa Khola (Fig. 3.4D). Leucosomes in the metatexite are predominantly 1-2 cm thick, mostly continuous (some discontinuous, particularly in the schist), and spaced approximately 1 cm apart (Fig. 3.4A, B). The restite layers are also discontinuous, and are 0.2-1 cm thick. Micro-folding of the melts and south verging folds are seen in this unit (Fig. 3.4C). The percentage of leucosome in the stromatic metatexite ± schist increases from the structurally lower to the structurally higher level (Fig. 3.3). The stromatic metatexite contains sheared leucogranitic dykes and sills (quartz + plagioclase + alkali-feldspar + biotite ± tourmaline ± muscovite) (Fig. 3.4D). In thin section, the stromatic metatexite unit displays broken down garnets (Fig. 3.5A), and the biotite schist portion of the stromatic metatexite unit does not (Fig. 3.5B). Quartz ribbons show evidence of grain boundary migration and subgrain rotation dynamic recrystallization textures (Fig. 3.5C, D), indicative of dynamic recrystallization mechanism between 400-500°C to > 500°C (Law, 2014).

**Figure 3.3.** NNE-SSW cross section along the transect line in the Chuwa Khola, with station locations, U-Th/Pb sample locations, and shear zone boundaries.
Figure 3.4. Field photographs of the main rock units of the Chuwa Khola. A) Stromatic metatexite ± schist (stromatic metatexite seen here, melts are sometimes discontinuous and 1-2 cm thick). AM-01. B) Stromatic metatexite ± schist (stromatic metatexite seen here, melts in discontinuous blobs 3-4 cm thick). C) Stromatic metatexite ± schist (schist seen here, with a

The foliated calc-silicate schist/gneiss (diopside + calcite + biotite + hornblende) contains layer parallel melts (10% leucosome per volume) and sheared leucogranitic dykes and sills (quartz + plagioclase + alkali-feldspar + biotite ± tourmaline ± muscovite). Leucogranitic dykes and sills are pervasive in this unit and often show cross-cutting relationships and are sheared and boudinaged in a dominant top-south sense (Fig. 3.4E). The contact between the calc-silicate schist/gneiss and the stromatic metatexite ± schist is sheared, showing top-to-the-southwest reverse sense of shear (Fig. 3.6), as illustrated at station AM-11 (Fig. 3.6) In thin section, the calc-silicate schist/gneiss (diopside + calcite + biotite + hornblende) displays a recrystallized (annealed) texture devoid of microscopic fabric and shear-sense indicators (Fig. 3.5E).

The augen orthogneiss (quartz + alkali-feldspar + plagioclase + biotite ± muscovite) is foliated with 20% leucosome per volume. The mica aggregates, quartz-feldspar aggregates, and quartz rods define a north/northeast (N020°) plunging mineral lineation (Fig. 3.2). Pervasive C/S/C’ fabrics defined by biotite schlieren banding, as well as σ- and δ-type augen porphyroclasts, are consistent with top-to-the-southwest reverse sense of shear (Fig. 3.4F, G). Migmatized layers are present within the augen orthogneiss, defined by quartz and feldspar wispy leucosome. In the field this unit is in contact with the stromatic metatexite ± schist and the schlieren-structured diatexite (Fig. 3.3). In thin section the augen orthogneiss unit has biotite ± muscovite ± sillimanite arrayed in C/S/C’ fabric consistent with top-to-the-southwest reverse sense of shear (Fig. 3.5F, G). Quartz grains show grain boundary migration dynamic recrystallization texture (Fig. 3.5G), suggestive of dynamic recrystallization at > 500°C (Law, 2014).
Figure 3.5. Photomicrographs of selected samples in the Chuwa Khola. A) Mineral assemblage of stromatic metatexite ± schist (stromatic metatexite seen here in plane light), quartz + plagioclase + alkali-feldspar + biotite + muscovite + sillimanite + garnet. AM-01. B) Mineral assemblage of stromatic metatexite ± schist (biotite schist seen here), quartz + biotite + plagioclase + alkali-feldspar. Foliation slightly dipping to the NE. AM-11A. C) Stromatic metatexite ± schist (stromatic metatexite seen here in cross polarized light). Quartz ribbon showing grain boundary migration (GBM) and foliation dipping to the NE. AM-01. D) Stromatic metatexite ± schist (stromatic metatexite seen here in cross polarized light). Quartz grains showing subgrain rotation (SGR) and grain boundary migration. AM-08B. E) Mineral assemblage of calc-silicate schist/gneiss, diopside + calcite + biotite + hornblende. AM-19B. F) Mineral assemblage of augen orthogneiss, quartz + alkali-feldspar+ plagioclase + biotite + sillimanite. AM-20. G) Quartz ribbon in the augen orthogneiss showing grain boundary migration and subgrain rotation. Foliation dipping to the NE. AM-06. H) Mineral assemblage of
granite, quartz + plagioclase + alkali-feldspar + biotite + sillimanite. No foliation or sense of shear is observed. AM-14. I) Quartz recrystallization textures of granite in the form of grain boundary migration and subgrain rotation. No foliation or sense of shear is observed. AM-12. Mineral abbreviates after (Whitney and Evans, 2010).

The schlieren-structured diatexite (quartz + plagioclase + alkali-feldspar + tourmaline + biotite + muscovite ± garnet) is foliated, with the foliation being defined by biotite and aligned sillimanite. The melts are equigranular and pervasive at outcrop scale, with 60% leucosome per volume. The restite (biotite banding) is minimal and discontinuous at outcrop scale. This unit is in contact with the stromatic metatexite ± schist and the augen orthogneiss (Fig. 3.3).

The granite (quartz + plagioclase + alkali-feldspar + biotite ± muscovite ± sillimanite) is exposed at the structurally highest level in the northern part of the Chuwa Khola (Fig. 3.3). The granite is medium to coarse grained, massive, and equigranular, and exhibits in places a weakly-developed foliation (Fig. 3.4H). The granite is in contact with the calc-silicate schist/gneiss unit (Fig. 3.7). This intrusive contact is seen about 200 meters up the cliff face at station AM-19 (Fig. 3.7). In thin section, the granite shows a very slight foliation, defined by micas (Fig. 3.5H, I). Quartz in this unit displays grain boundary migration with minor subgrain rotation textures, consistent with temperatures > 500°C (Fig. 3.5I) (Law, 2014).

3.1.2 The Chuwa Khola magmatic rock system

Three different types of magmatic rocks are exposed in the Chuwa Khola. The first type is the leucosome portion of the stromatic metatexite ± schist at the structurally lowest part of the Chuwa Khola. The second type consists of a dyke and sill network that predominantly intrudes the stromatic metatexite ± schist and the calc-silicate schist/gneiss units. These intrusions consist of layer parallel intrusive melts, with a minor amount of layer cross-cutting dykes (Fig. 3.7). The dyke and sill network is locally boudinaged and sheared predominantly in a top-to-the-south/southwest reverse sense (Fig 3.6). Some relative time constraints can also be placed on the dyke and sill network. It intrudes both the stromatic metatexite ± schist and the calc-silicate schist/gneiss, and then is sheared. The third type is a large, predominantly equigranular granite exposed at the structurally highest levels of the Chuwa Khola (Fig. 3.2).
Figure 3.6. Line diagram showing the field relationship between the stromatic metatexite ± schist, the calc-silicate schist/gneiss unit, and the dyke and sill network (AM-11). The dyke and sill network here is predominantly layer parallel and is boudinaged and sheared consistent with top-to-the-southwest sense of displacement.

Figure 3.7. Line diagram showing the field relationship of the dyke and sill network and the granite in the Lare Khola (AM-19). In this example, the dyke and sill network is intruding the
calc-silicate schist/gneiss unit. The melts are predominantly layer parallel and increase in thickness towards the calc-silicate schist/gneiss and granite contact.

3.2 Structural style in the Chuwa Khola

The units in the Chuwa Khola form a north dipping homoclinal package, with the granite at the structurally highest level to the north (Fig. 3.3). All units are pervasively sheared with intrafolial folds and display varying degrees of partial melting, with the percentage of leucosome increasing from structurally lowest to highest (Figs. 3.3, 3.6). Intrusive contacts are observed between the leucogranitic dyke and sill network/the calc-silicate schist/gneiss and the dyke network/the stromatic metatexite ± schist (Fig. 3.6). Intrusive contacts are also observed between the granite/calc-silicate schist/gneiss (Fig. 3.7).

The gneissic foliation and the schistosity define the planar elements (Fig. 3.4A, B, C, E, F, G). This fabric generally strikes west/northwest and dips shallowly to the north/northeast (average N290°/15°NE, Fig. 3.2). This planar fabric was observed in all the units, including faintly in the Chuwa granite. At the microscopic scale, this foliation is defined by aligned minerals (predominantly micas) (Fig. 3.5A, B, C, F, G).

Mineral elongation lineations are defined by a variety of minerals (e.g. mica aggregates, sillimanite, quartz-feldspar aggregates, and quartz rods) in the Chuwa Khola. There are two structural domains within the Chuwa Khola. In the southern panel of the Chuwa Khola, the mineral elongation lineations plunge shallowly to the east (red points on the mineral lineation stereonet – Fig. 3.2) within a dextral shear zone (Fig. 3.2). Towards the north in the Chuwa Khola, the mineral elongation lineations rotate to plunge shallowly to the northeast, with a few exceptions (white points on the mineral lineation stereonet – Fig. 3.2). I interpret that this dextral shear zone (Fig. 3.2) has overprinted the ~ north plunging mineral elongation lineations. The stromatic metatexite ± schist unit contains an east/northeast plunging mineral lineation defined by sillimanite (Fig. 3.4A, B, C). The calc-silicate schist/gneiss unit contains a northeast plunging mineral lineation defined by biotite and hornblende (Fig. 3.4E), whereas the augen orthogneiss unit exhibits an east/northeast plunging mineral lineation defined by elongated quartzofeldspathic augen (Fig. 3.4F, G).

The folds in the Chuwa Khola are tight to isoclinal with E-W trending hinge lines (Fig.3.4C). Minor folds in the Chuwa Khola are commonly observed as south verging folds. At
the outcrop scale large transposition folds are observed (showing intrafolial folding) verging to the south (Fig. 3.4C).

All major units in the Chuwa Khola display abundant top-to-the-south/southwest reverse sense of shear indicators, such as C/S/C’ fabrics and asymmetric porphyroclasts (Fig. 3.4D, F, G). The leucogranitic dyke and sill network is similarly pervasively sheared in a top-to-the-south/southwest reverse sense.

3.3 Whole rock geochemical characterization of melts

X-ray fluorescence (XRF) whole rock and inductively coupled plasma mass spectrometry (ICP-MS) whole rock trace element geochemical analysis was performed on a stromatic metatexite ± schist sample (AM-08B), two leucogranitic dyke samples (AM-11B, AM-19B), and two granite samples (AM-12, AM-15B) by Bureau Veritas Commodities Canada Ltd. For the complete data set, please refer to the supplementary material (Table D1 in Appendix D). These analyses were performed to appropriately classify the various igneous rocks in the Chuwa Khola according to their chemical compositions.

All five of the analysed samples plot within the peraluminous field of an alumina saturation diagram that shows the molar concentrations of Al$_2$O$_3$ compared to CaO, normalized to (Na$_2$O + K$_2$O + CaO) (Fig. 3.8), indicating that all analysed magmatic rocks are oversaturated in alumina. One leucogranitic dyke sample (AM-19B) is weakly peraluminous, perhaps a reflection of the calc-silicate gneissic host rock of the dyke. The samples from this study have been compared with the Manaslu and Everest area leucogranites (Fig. 3.8). The magmatic rocks from this study are all less saturated in alumina and more saturated in calcium than the Manaslu and Everest area leucogranites (Fig. 3.8).
The alumina saturation diagram showing the five samples that were analysed in this thesis, as well as other Himalayan examples (Manaslu - purple, Deniel et al., 1987; Everest - blue, Visona et al, 2012). All five samples are peraluminous. The two granite samples, metatexite, and one leucogranitic dyke sample are all strongly peraluminous. The second leucogranitic dyke sample is weakly peraluminous. Alumina saturation diagram produced with ioGAS (v.7.2).

Geochemical data obtained from the samples are also plotted on a total alkali versus silica (TAS) diagram (Fig. 3.9). Four samples (AM-08B, AM-11B, AM-12, AM-15B) plot within the granite field, while one sample (AM-19B) falls within the quartz monzanaite field (Fig. 3.9). The samples from this study have been compared with the Manaslu, Malashan, and Everest area leucogranites (Fig. 3.9). The Everest leucogranite plots within the same field on the TAS diagram that the majority of the magmatic rocks from this study plot in (the granite field - Fig. 3.9). The Manaslu and Malashan leucogranites plot in different fields of the TAS diagram when compared with the magmatic rocks from this study (Fig. 3.9).
Figure 3.9. Total alkali versus silica (TAS) diagram generated from the geochemical analyses of five key magmatic rock samples from this thesis, as well as other Himalayan examples (Manaslu - purple, Deniel et al., 1987; Everest - blue, Visona et al, 2012). The two granite samples, metatexite, and one leucogranitic dyke sample plots within the granite field, confirming the field observations. The other leucogranitic dyke sample falls just out of the granite field and plots within the quartz monzonite field. TAS diagram produced with ioGAS (v.7.2) (Middlemost, 1994).
CHAPTER 4

U-Th/Pb MONAZITE PETROCHRONOLOGY

4.1 Introduction – Purpose of the petrochronology approach

The melts rocks in the Chuwa Khola were dated using the U-Th/Pb monazite petrochronology approach. Melts rocks in the Chuwa Khola were dated to determine how the timing of the magmatic rocks relate to each other, and how they relate to the magmatic rocks in the Gurla Mandhata core complex to the west. Monazite was chosen as the chronometer for this study because U-Th/Pb monazite petrochronology has emerged as a leading dating tool in the Himalaya over the past two decades, specifically in dating melt formation (e.g. Kohn et al., 2005; Cottle et al., 2009b; Larson et al., 2011; Rubatto and Chakraborty, 2013; Cottle et al., 2019). Petrochronology was employed because the interpretation of dates in the context of trace element data significantly assists in matching mineral (re) crystallization to specific igneous, metamorphic or deformation events (Kylander-Clark et al., 2013).

4.2 Sample location, description, and justification

The Chuwa Khola magmatic rock system preserves three types of magmatic rocks: migmatization in the stromatic metatexite ± schist, a leucogranitic dyke and sill network, and a peraluminous granite (see Chapter 3 for field and petrological descriptions).

Cross section line A-A’ (Fig. 4.1) displays where the seven U-Th/Pb samples are located along the length of the Chuwa Khola. The first two samples are the stromatic metatexite ± schist, AM-01 and AM-08B (Table 4.1). They are the southernmost and structurally lowest samples in the Chuwa Khola (Fig. 4.1). Sample AM-21B (Table 4.1) is the meta-quartz arenite unit. This sample is greyed out in cross section line A-A’ because the meta-quartz arenite unit is not on the cross section (Fig. 4.1). Two leucogranitic dyke samples from the middle panel of the Chuwa Khola, AM-11B and AM-19B (Table 4.1), are relatively close to the base of the Chuwa granite. Granite samples AM-12 and AM-15B (Table 4.1) are the northernmost and structurally highest samples from the Chuwa Khola (Fig. 4.1).
Figure 4.1. Simplified cross section showing the seven U-Th/Pb sample locations within the study area. AM-01. AM-21 (meta-quartz arenite sample) is grey because it is located west of the cross-section line. Cross section line A-A' is positioned on Fig. 3.2.

Sample AM-01 is a stromatic metatexite ± schist containing quartz + plagioclase + alkali-feldspar + biotite ± muscovite ± sillimanite ± garnet; with 15% leucosome per volume (Fig. 4.2A). Leucosomes in the metatexite are predominantly 1-2 cm thick, mostly continuous (some discontinuous, particularly in the schist), and spaced approximately 1 cm apart (Fig. 4.2A). In thin section, the stromatic metatexite sample AM-01 displays degraded garnets and a NE-SW foliation (Fig. 4.2B). The leucosomes were targeted in sample AM-01 for petrochronology to determine the monazite crystallization date, to be able to interpret the melt crystallization ages.

Table 4.1. In situ U-Th/Pb monazite petrochronology sample locations.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM-01</td>
<td>29°57.553'</td>
<td>081°53.698'</td>
</tr>
<tr>
<td>AM-08B</td>
<td>30°02.119'</td>
<td>082°00.991'</td>
</tr>
<tr>
<td>AM-11B</td>
<td>30°05.299'</td>
<td>082°01.843'</td>
</tr>
<tr>
<td>AM-12</td>
<td>30°10.258'</td>
<td>082°02.263'</td>
</tr>
<tr>
<td>AM-15B</td>
<td>30°14.801'</td>
<td>082°02.355'</td>
</tr>
<tr>
<td>AM-19B</td>
<td>30°07.210'</td>
<td>082°00.724'</td>
</tr>
<tr>
<td>AM-21B</td>
<td>29°59.107'</td>
<td>081°50.729'</td>
</tr>
</tbody>
</table>

Note: World Geodetic System (WGS) 1984 geodetic datum.

Sample AM-08B is a stromatic metatexite ± schist containing 20% leucosome per volume (Fig. 4.2C). Leucosomes of the metatexite in this sample are predominantly 3-4 cm thick, mostly discontinuous, and spaced approximately 1 cm apart (Fig. 4.2C). Sample AM-08B is structurally higher than sample AM-01, and exhibits 20% of of leucosome per volume. In thin section, the stromatic metatexite sample AM-08B shows micas that are larger and in more random orientation when compared with thin section AM-01, however the same NE-SW foliation is seen (Fig. 4.2D). In thin section AM-08B there is also more quartz grain boundary migration than in thin section AM-01 (Fig. 4.2D). The leucosomes were targeted in sample AM-08B for petrochronology to determine the monazite crystallization date, to be able to interpret the melt crystallization ages.

Sample AM-11B is a leucogranitic dyke composed of quartz + plagioclase + alkali-feldspar + biotite ± tourmaline ± muscovite that cross cuts the stromatic metatexite ± schist (Fig. 4.2E). This unit is typically sheared and boudinaged (Fig. 4.2E). In thin section, the leucogranitic dyke sample, AM-11B is medium grained and has no observable foliation (Fig. 4.F). The dyke and sills were targeted for petrochronology to determine the monazite crystallization date, to be
able to interpret the melt crystallization ages. In addition, this sample was targeted to get a
maximum age of shearing at this structural level in the Chuwa Khola.

Sample AM-19B is a leucogranitic dyke (Fig. 4.2G). The dyke and sill network is
typically sheared and boudinaged (Fig. 4.2G). This unit also typically cross cuts various other
units within the Chuwa Khola. At this location it cross cuts the calc-silicate schist/gneiss. In thin
section, the leucogranitic dyke sample, AM-19B is medium grained and has a NW-SE foliation
(Fig. 4.2H). The dyke and sills were targeted for petrochronology to determine the monazite
crystallization date, to be able to interpret the melt crystallization ages. In addition this particular
sample was targeted to get an age of shearing the base of the Chuwa granite.

Sample AM-12 is a massive, biotite-rich, peraluminous granite (Fig. 4.2I). The granite is
composed of quartz + plagioclase + alkali-feldspar + biotite ± muscovite ± sillimanite and is
found at the structurally highest level of the Chuwa Khola. In thin section this sample is
equigranular and medium to coarse grained and shows a slight SE-NW foliation (Fig. 4.2J). This
granite sample was targeted for petrochronology to determine the monazite crystallization date,
and therefore to interpret the Chuwa granite crystallization age.

Sample AM-15B is a massive, biotite-rich, peraluminous granite (Fig. 4.2K). This granite
sample is the structurally highest sample collected from the Chuwa Khola. In thin section this
sample is equigranular and medium to coarse grained and shows a weak NE-SW foliation (Fig.
4.2L). This granite sample was targeted for petrochronology to determine the monazite
crystallization date, and therefore to interpret the Chuwa granite crystallization age.

Sample AM-21B is a metasandstone. This metasandstone is composed of
predominantly quartz, with plagioclase + alkali-feldspar + biotite + muscovite + garnet. A thin,
sub-horizontal, boudinaged, muscovite-bearing leucogranitic dyke is seen in outcrop cross
cutting transposed meta-quartz arenite (Fig. 4.2M). In thin section, meta-quartz arenite sample,
AM-21B shows fine grained micas in a preferred orientation, arrayed in C/S/C’ fabric consistent
with top-to-the-southwest sense of shear (Fig. 4.2N). This unit also shows quartz ribbons in thin
section.

4.3 Methods: In situ U-Th/Pb monazite petrochronology

In situ U-Th/Pb monazite petrochronological analysis was carried out at University of California,
Santa Barbara (UCSB). Two stromatic metatexite ± schist samples (AM-01; Fig. 4.2A, B,
AM-08B; Fig. 4.2C, D), two leucogranitic dyke samples (AM-11B; Fig. 4.2E, F, AM-19B; Fig. 4.2G, H), two granite samples (AM-12; Fig. 4.2I, J, AM-15B; Fig. 4.2K, L), and one meta-quartz arenite sample (AM-21B; Fig. 4.2M, N) were analysed. These samples were selected to be a representative of the forms of magmatic rocks observed in the Chuwa Khola.

Monazite contains abundant U and Th but is resistant to Pb diffusion at high temperatures, making it the ideal geochronometer for this study (e.g. Parrish, 1990). In situ dating allows for the preservation of the microstructural context of each monazite grain, allowing for a more accurate interpretation of the results.

Monazite grains were identified and located in seven thin sections using a Mineral Liberation Analysis (MLA) 650 field emission gun environmental scanning electron microscope (SEM) at Queen’s Facility for Isotope Research (QFIR). Backscattered electron (BSE) images enabled the unique x-y coordinate as well as the structural context of each monazite grain to be known in thin section (e.g. Fig. 4.3) (Appendix B).

Figure 4.3. Backscattered electron image, showing all monazites in thin section AM-01 that were analysed on the microprobe at Queen’s Facility for Isotope Research.
Monazite grains greater than 20 μm in size and with favourable morphology (minimal cracks and pits) for U-Th/Pb petrochronological analysis were then targeted using a JEOL JXA-8230 electron microprobe at QFIR (Appendix B – 90 monazite grain in total; Appendix B, Table 1). The electron microprobe was used to take high resolution BSE images of the monazite grains to show their morphology and structural context (e.g. Fig. 4.4A, B). The electron microprobe also produced X-ray chemical maps of yttrium (Y) (e.g. Fig. 4.4C), uranium (U) (e.g. Fig. 4.4D), calcium (Ca) (e.g. Fig. 4.4E), thorium (Th) (e.g. Fig. 4.4F), and silicon (Si) (e.g. Fig. 4.4G) for each monazite grain using X-ray wavelength dispersive spectrometry (Appendix B).

**Figure 4.4.** Electron microprobe images for monazite 01a of thin section AM-01 (stromatic metatexite ± schist). A) Backscattered electron image showing the monazite morphology. B) BSE image showing the structural context of this monazite. C) X-ray chemical map showing...
relative yttrium content. D) X-ray chemical map showing relative uranium content. E) X-ray chemical map showing relative calcium content. F) X-ray chemical map showing relative thorium content. G) X-ray chemical map showing relative silicon content. The scale bar applies to all X-ray chemical maps because they are relative contents.

The electron microprobe experimental conditions were set at an acceleration voltage of 15 kV, beam current of 200 nA, dwell time of 100 ms and step size of 0.5-1.0 μm. The complete data set acquired from the work done on the electron microprobe, including the BSE image of each thin section (showing monazite locations), and the electron microprobe images (showing each monazite’s morphology, structural setting, and chemical zonation) can be found in Appendix B.

In situ U-Th/Pb and trace element data were acquired at UCSB using a Photon Machines 193 nm ArF Excimer laser ablation system connected via split stream to a multi-collector Nu Plasma (U/Th-Pb data) and an Agilent 7700S Quadrupole (trace element data) inductively-coupled plasma mass spectrometer. Two primary reference monazites, 44069 (U/Pb standard) (e.g. Aleinikoff et al., 2006) and Bananiera, otherwise known as Stern (trace element standard) (e.g. Kylander-Clark et al., 2013) were used roughly every tenth laser spot to recalibrate the system. Secondary reference monazites 554 (e.g. Harrison et al., 1999), Manangotry (e.g. Horstwood et al., 2003), and Trebilcook (e.g. Tomascak et al., 1996), were analyzed over the course of the analytical sessions to verify the calibrations. Reference monazites are used because they reproduce to within 2σ of the accepted value. Secondary reference monazites are used to demonstrate that the primary standard calibration is correct, by reproducing the known ages of these standards (within 2σ). The U, Th, Pb isotope data and trace element date were collected using a laser spot size of ~ 8 μm and a pit depth of ~ 24 μm. Analytical procedures are outlined in Kylander-Clark et al. (2013).
Spot selection was based on the BSE images previously acquired at QFIR. Eighty monazite grains in total were targeted at UCSB. Ten monazite grains analysed at QFIR were deemed to have unfavorable morphologies (cracks, not large enough, etc.), and consequently were excluded from further analysis at UCSB. Appendix C, Table 1, presents the complete list of monazite grains targeted for in situ U-Th/Pb and trace element data, laser spot locations, and resulting dates from each. Results from twelve laser spots were excluded from interpretation because of unfavourable locations and the error associated with each spot (e.g. Fig. 4.5, spot 2) (Appendix C, Table 2 for exclusion reasoning).

In Cenozoic monazite, the $^{208}\text{Pb}/^{232}\text{Th}$ date is commonly the most reliable, as the presence of excess $^{206}\text{Pb}$ can cause the $^{206}\text{Pb}/^{238}\text{U}$ dates to be older than the actual crystallization ages (Parrish, 1990). Therefore, reported dates refer to the $^{208}\text{Pb}/^{232}\text{Th}$ date. All dates are reported to ± 2σ. In this thesis, the term “date” refers to a result calculated from measured isotopic ratios or total concentrations using decay equations (Schoene, 2014), whereas the term “age” refers to the geologic interpretation of a date in a tectonometamorphic context.
4.3.1 Methods: Trace element measurements

In situ trace element data and U-Th/Pb data were acquired at UCSB using a Photon Machines 193 nm ArF Excimer laser ablation system connected via split stream to an Agilent 7700S Quadrupole (trace element data) inductively-coupled plasma mass spectrometer and a multi-collector Nu Plasma ICP-MS (U/Th-Pb data). Trace element data in parts per million (ppm) were normalized to the chondrite values (McDonough and Sun, 1995) to allow for comparison between samples. The Y content, Gd to Yb ratio and Eu* ([Eu (ppm)/(Sm (ppm) + Gd (ppm)]^0.5)) were plotted versus the 208Pb/232Th date for each sample.

Y in monazite can be used as a proxy for garnet growth or breakdown in the rock as Y is preferentially taken up by garnet over monazite during mineral growth (Spear and Pyle, 2002; Kohn et al., 2005). For example, retrograde metamorphism result in garnet breakdown, and therefore release of Y into the system, resulting in an increase in Y taken up by monazite forming under the same conditions (Kohn et al., 2005). In contrast, prograde metamorphism results in garnet growth, and therefore a decrease in the availability of Y for incorporation into other mineral phases, including monazite (Kohn et al., 2005).

The ratio of Gd to Yb in a monazite grain is used to approximate the behaviour of heavy rare earth elements (HREE). Garnet preferentially incorporates HREE over LREE, therefore an increasing Gd/Yb in monazite suggests garnet growth, while a decreasing Gd/Yb suggests garnet breakdown (Zhu and O'Nions, 1999).

A decrease in Eu* may indicate feldspar growth and melt crystallization (Rubatto et al., 2006; Mottram et al., 2014b; Holder et al., 2015). However, it is important to note that monazite Eu* may also reflect changes in fO2 and therefore changes in Eu^{2+}/Eu^{3+} and Eu^{3+}/Eu_{total} (Holder et al., 2018). A test can be performed to evaluate if changes in bulk rock fO2 have been recorded in the monazite Eu*. If Eu^{3+}/Eu_{total} (therefore fO2) remained constant, then the changes in Eu* should be positively correlated with Sr, since Sr^{2+} has a near identical ionic radius and will therefore have the same compatibility in each phase (Holder et al., 2018).

Finally, trace element data were used to produce spider plots (REE elements listed (La to Lu, Pm missing) on the x-axis and measured REE data normalized to the chondrite values on the y-axis). In these magmatic rocks feldspar is the only mineral capable of fractionating Eu from the REE. Therefore, a negative Eu anomaly can be used to infer the growth of feldspar at this time in the melt system (Rubatto and Chakraborty, 2013). Furthermore, the negative Eu anomaly can
speak to the relative reducing conditions present in the system, as much of the Eu is present in the melt as Eu$^{+2}$ (Rubatto and Hermann, 2007; Stepanov et al., 2012).

4.4 Results

The full set of U/Th-Pb monazite petrochronology data for the seven thin sections analysed at UCSB is provided in Appendix D. More specifically, Table D2 in Appendix D provides for each laser spot the x-y position, U and Th concentrations, isotopic Pb, U, and Th ratios and corresponding calculated dates, and finally various elemental proportions (ppm and chondrite normalized) from the monazite grains (Table D2 – supplementary material).

4.4.1 Stromatic metatexite ± schist (AM-01)

Fourteen monazite grains from the matrix of the stromatic metatexite unit (Sample AM-01; 148 analyses) yield dates from 24.0 ± 0.9 Ma to 13.2 ± 0.6 Ma with an average date of 17.7 Ma (excluding data from poorly located laser spots or yielding dates with greater than 15% error) (Fig. 4.6A; Table D2 in Appendix D). The monazite grains that have a long axis (eleven in total have long axes) are aligned with the NE-SW matrix foliation; only three more circular grains are randomly oriented in the matrix (Appendix B). Analysed monazite grains range in size from ~ 100 μm to as large as ~ 350 μm in length (Appendix C). Monazite grains in this sample are irregularly zoned in Y; some show distinct zoning between core and rim (Appendix C, e.g. AM-01 mnz 01a), while others do not (Appendix C, e.g. AM-01 mnz 04). One monazite grain contains an inclusion of zircon (AM-01 mnz 17), and two monazite grains show zircon growing in direct contact (AM-01 mnz 01b, AM-01 mnz 16). Monazite grains tend to be pitted and cracked, with only one grain showing no pits or cracks (AM-01 mnz 16).

The date histogram for stromatic metatexite sample AM-01 shows a peak monazite date at 18.5 Ma and a minimum monazite date at 13.2 Ma (Fig. 4.6A). The $^{208}$Pb/$^{232}$Th versus $^{206}$Pb/$^{238}$U concordia plot indicates that data for sample AM-01 are slightly off concordia. This is most likely due to excess unsupported $^{206}$Pb in the system (Fig. 4.6B). Analyses also indicate a significant increase in Y in younger dates (Fig. 4.6B).
**Figure 4.6.** A) Date histogram for stromatic metatexite ± schist sample AM-01, showing \(^{208}\text{Pb}/^{232}\text{Th}\) dates (Ma) from 30 Ma to present, the relative probability of each date (purple line), and the relative amounts of Y. B) \(^{208}\text{Pb}/^{232}\text{Th}\) versus \(^{206}\text{Pb}/^{238}\text{U}\) concordia plot of date data obtained from sample AM-01. Ellipses are coloured based on relative Y content (green: low Y, red: high Y) and are 2σ. Concordia plot produced using IsoplotR (Vermeesch, 2018).

The REE spider plot for stromatic metatexite sample AM-01 shows a steady decrease in rare earth element concentrations (normalized to the chondrite values after McDonough and Sun (1995)) from the light to the heavy rare earth elements and a negative Eu anomaly (Fig. 4.7).
Figure 4.7. The REE chondrite normalized spider plot for sample AM-01, stromatic metatexite ± schist. This spider plot shows REE Lanthanum to REE Lutetium, with the exception of REE Promethium, chondrite normalized after McDonough and Sun (1995). There is a negative Europium anomaly.

The Y (Fig. 4.8A), Eu* (Fig. 4.8B), and Gd/Yb (Fig. 4.8C) contents have all been plotted against the $^{208}\text{Pb}/^{232}\text{Th}$ dates. Y content increases as the system decreases in age, which may indicate garnet breakdown and retrograde metamorphism (Figs. 4.6B, 4.8A) (Spear and Pyle, 2002; Kohn et al., 2005). There is a negative Eu anomaly (Fig. 4.7), and Eu* decreases with younger dates (Fig. 4.8B), which suggest feldspar growth and melt crystallization (Rubatto et al., 2006; Mottram et al., 2014b; Holder et al., 2015). The Gd/Yb also decreases with younger dates, potentially suggesting garnet breakdown and therefore retrograde metamorphism (Fig. 4.8C) (Zhu and O’Nions, 1999). Finally, the plot of Sr versus Eu* (Fig. 4.8D) displays a positive correlation between Sr and Eu*, which indicates that the Eu* is not reflecting changes in the bulk rock $f/\text{O}_2$ and therefore interpretations can be drawn based on Eu* (Holder et al., 2018).
Figure 4.8. Rare earth element data for stromatic metatexite ± schist sample AM-01. A) Yttrium (Y) content in ppm plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). B) Eu* ([Eu (ppm)/(Sm (ppm) + Gd (ppm))^{0.5}]) content plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). C) Gd/Yb ratio plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). D) Sr plotted against Eu*.

### 4.4.2 Stromatic metatexite ± schist (AM-08B)

Nine monazite grains from the matrix of the stromatic metatexite unit (Sample AM-08B; 69 analyses) yield dates from 48.3 ± 4.7 Ma to 12.8 ± 0.5 Ma with an average date of 21.1 Ma (excluding data from poorly located laser spots or yielding dates with greater than 15% error) (Fig. 4.9A; Table D2 in Appendix D). Five of the monazite grains that have a long axis (seven in total have long axes) are aligned with the NE-SW matrix foliation; while two of the monazite grains that have a long axis are randomly oriented in the matrix. Two more circular grains are randomly oriented in the matrix as well (Appendix B). Analysed monazite grains range in size from ~ 70 μm to as large as ~ 125 μm in length (Appendix C). Monazite grains in this sample are irregularly zoned in Y; some show distinct zoning between core and rim (Appendix C, e.g. AM-08B mnz 01, 16), while others do not (Appendix C, e.g. AM-08B mnz 04, 08). Four monazite
grains contain inclusions (AM-08B mnz 05, 07, 09, 16). Monazite grains tend to be pitted and cracked, with only one grain showing no pits or cracks (AM-08B mnz 01).

The date histogram for stromatic metatexite sample AM-08B shows a peak monazite date at 18.5 Ma and a minimum monazite date at 12.8 Ma (Fig. 4.9A). The $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot indicates that most data for sample AM-08B are slightly off concordia. This is most likely due to excess unsupported $^{206}\text{Pb}$ in the system (Fig. 4.9B).

**Figure 4.9.** A) Date histogram for stromatic metatexite ± schist sample AM-08B, showing $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma) from 55 Ma to present, and the relative probability of each date (purple line), and the relative amounts of Y. B) $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot of date data obtained from sample AM-08B. Ellipses are coloured based on relative Y content (green: low Y, red: high Y) and are 2σ. Concordia plot produced using IsoplotR (Vermeesch, 2018).

The REE spider plot for stromatic metatexite sample AM-08B shows a steady decrease in rare earth element concentrations (normalized to the chondrite values after McDonough and Sun (1995)) from the light to the heavy rare earth elements and a negative Eu anomaly (Fig. 4.10).
Figure 4.10. The REE chondrite normalized spider plot for sample AM-08B, stromatic metatexite ± schist. This spider plots shows REE Lanthanum to REE Lutetium, with the exception of REE Promethium, chondrite normalized after McDonough and Sun (1995). There is a negative Europium anomaly.

The Y (Fig. 4.11A), Eu* (Fig. 4.11B), and Gd/Yb (Fig. 4.11C) contents have all been plotted against the $^{208}\text{Pb}/^{232}\text{Th}$ dates. Y content increases as the system decreases in age, which may indicate garnet breakdown and retrograde metamorphism (Fig. 4.11A) (Spear and Pyle, 2002; Kohn et al., 2005). There is a negative Eu anomaly (Fig. 4.10), and Eu* decreases with younger dates (Fig. 4.11B), which suggest feldspar growth and melt crystallization (Rubatto et al., 2006; Mottram et al., 2014b; Holder et al., 2015). The Gd/Yb is constant with time (Fig. 4.11C). Finally, the plot of Sr versus Eu* (Fig. 4.11D) displays a slight positive correlation between Sr and Eu*, which may indicate that the Eu* is not reflecting changes in the bulk rock $f\text{O}_2$ and therefore interpretations can be drawn based on Eu* (Holder et al., 2018).
Figure 4.11. Rare earth element data for stromatic metatexite ± schist sample AM-08B. A) Yttrium (Y) content in ppm plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). B) Eu* ($[\text{Eu (ppm)}/(\text{Sm (ppm)} + \text{Gd (ppm)})^{0.5}]$) content plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). C) Gd/Yb ratio plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). D) Sr plotted against Eu*.

4.4.3 Leucogranitic dyke (AM-11B)

Three monazite grains from the matrix of the leucogranitic dyke (Sample AM-11B; 40 analyses) yield dates from 54.6 ± 7.1 Ma to 19.1 ± 0.7 Ma with an average date of 21.6 Ma (Fig. 4.12A; Table D2 in Appendix D). The three monazite grains have a long axis but are randomly oriented in the matrix (Appendix B). Analysed monazite grains range in size from ~ 40 μm to as large as ~ 340 μm in length (Appendix C). One monazite grain in this sample is moderately zoned in Y (Appendix C, AM-11B mnz 01); other grains in this sample are not zoned in Y (Appendix C, AM-11B mnz 02, 03). All three monazite grains contain inclusions (AM-11B mnz 01, 02, 03), with AM-11B mnz 01 showing multiple inclusions of zircon (Appendix B). Monazite grains tend to be pitted and cracked (AM-11B mnz 01, 02, with only one grain showing no pits or cracks (AM-11B mnz 01).
The date histogram for leucogranitic dyke sample AM-11B shows a peak monazite date at 20 Ma and a minimum monazite date at 19.1 Ma (Fig. 4.12A). The $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot indicates that data for sample AM-11B are discordant. This is most likely due to excess unsupported $^{206}\text{Pb}$ in the system (Fig. 4.12B). Analyses also indicate a significant increase in Y in younger dates (Fig. 4.12B).

**Figure 4.12.** A) Date histogram for leucogranitic dyke sample AM-11B, showing $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma) from 30 Ma to present, and the relative probability of each date (purple line), and the relative amounts of Y. B) $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot of date data obtained from sample AM-11B. Ellipses are coloured based on relative Y content (green: low Y, red: high Y) and are 2σ. Concordia plot produced using IsoplotR (Vermeesch, 2018).

The REE spider plot for leucogranitic dyke sample AM-11B shows a steady decrease in rare earth element concentrations (normalized to the chondrite values after McDonough and Sun (1995)) from the light to the heavy rare earth elements and a negative Eu anomaly (Fig. 4.13).
Figure 4.13. The REE chondrite normalized spider plot for sample AM-11B, leucogranitic dyke. This spider plot shows REE Lanthanum to REE Lutetium, with the exception of REE Promethium, chondrite normalized after McDonough and Sun (1995). There is a negative Europium anomaly.

The Y (Fig. 4.14A), Eu* (Fig. 4.14B), and Gd/Yb (Fig. 4.14C) contents have all been plotted against the $^{208}\text{Pb}/^{232}\text{Th}$ dates. Y content increases as the system decreases in age, which may indicate garnet breakdown and retrograde metamorphism (Figs. 4.12B, 4.14A) (Spear and Pyle, 2002; Kohn et al., 2005). There is a negative Eu anomaly (Fig. 4.13), which suggests feldspar growth and melt crystallization (Rubatto et al., 2006; Mottram et al., 2014b; Holder et al., 2015). Eu* is constant with time (Fig. 4.14B). The Gd/Yb is also constant with time (Fig. 4.14C). Finally, the plot of Sr versus Eu* (Fig. 4.14D) displays a positive correlation between Sr and Eu*, which indicates that the Eu* is not reflecting changes in the bulk rock $fO_2$ and therefore interpretations can be drawn based on Eu* (Holder et al., 2018).
Figure 4.14. Rare earth element data for leucogranitic dyke sample AM-11B. A) Yttrium (Y) content in ppm plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). B) Eu* ($([\text{Eu (ppm)}/(\text{Sm (ppm)} + \text{Gd (ppm)})^{0.5}])$ content plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). C) Gd/Yb ratio plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). D) Sr plotted against Eu*.

4.4.4 Leucogranitic dyke (AM-19B)

Twelve monazite grains from the leucogranitic dyke (Sample AM-19B; 139 analyses) yield dates from $341.6 \pm 20.9 \text{ Ma}$ to $15.8 \pm 0.6 \text{ Ma}$ with an average date of $22.8 \text{ Ma}$ (excluding data from poorly located laser spots or dates with greater than 15% error) (Table D2 in Appendix D). Considering only Cenozoic dates, the dates range from $36.9 \pm 2.0 \text{ Ma}$ to $15.8 \pm 0.6 \text{ Ma}$ with an average date of $19.1 \text{ Ma}$ (excluding data from poorly located laser spots or yielding dates with greater than 15% error) (Fig. 4.15A; Table D2 in Appendix D). Six of the monazite grains that have a long axis (eleven in total have long axes) are aligned with the NW-SE matrix foliation; while five of the monazite grains that have a long axis are randomly oriented in the matrix. One circular grain is randomly oriented in the matrix (Appendix B). Analysed monazite grains range in size from $\sim 70 \mu\text{m}$ to as large as $\sim 195 \mu\text{m}$ in length (Appendix C). Monazite grains in this sample are irregularly zoned in Y; some show moderate zoning between core and
rim (Appendix C, AM-19B mnz 01, 08, 12), while others do not (Appendix C, e.g. AM-19B mnz 02). The majority of monazite grains in this sample contain inclusions (Appendix B, e.g. AM-19B mnz 01). Monazite grains tend to be pitted and cracked, with only one grain showing no pits or cracks (AM-19B mnz 14).

The date histogram for leucogranitic dyke sample AM-19B shows a peak monazite date at 18.5 Ma and a minimum monazite date at 15.8 Ma (Fig. 4.15A). The $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot indicates that data for sample AM-19B are discordant. This is most likely due to excess unsupported $^{206}\text{Pb}$ in the system (Fig. 4.15B).

**Figure 4.15.** A) Date histogram for leucogranitic dyke sample AM-19B, showing $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma) from 55 Ma to present, and the relative probability of each date (purple line), and the relative amounts of Y. B) $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot of date data obtained from sample AM-19B. Ellipses are coloured based on relative Y content (green: low Y, red: high Y) and are 2σ. Concordia plot produced using IsoplotR (Vermeesch, 2018).

The REE spider plot for leucogranitic dyke sample AM-19B shows a steady decrease in rare earth element concentrations (normalized to the chondrite values after McDonough and Sun (1995)) from the light to the heavy rare earth elements and a negative Eu anomaly (Fig. 4.16).
Figure 4.16. The REE chondrite normalized spider plot for sample AM-19B, leucogranitic dyke. This spider plot shows REE Lanthanum to REE Lutetium, with the exception of REE Promethium, chondrite normalized after McDonough and Sun (1995). There is a negative Europium anomaly.

The Y (Fig. 4.17A), Eu* (Fig. 4.17B), and Gd/Yb (Fig. 4.17C) contents have all been plotted against the $^{208}\text{Pb}/^{232}\text{Th}$ dates. The Y content is constant with time (Fig. 4.17A). There is a negative Eu anomaly (Fig. 4.16), which suggests feldspar growth and melt crystallization (Rubatto et al., 2006; Mottram et al., 2014b; Holder et al., 2015). Eu* is constant with time (Fig. 4.17B). The Gd/Yb is also constant with time (Fig. 4.17C). Finally, the plot of Sr versus Eu* (Fig. 4.17D) displays a positive correlation between Sr and Eu*, which indicates that the Eu* is not reflecting changes in the bulk rock $fO_2$ and therefore interpretations can be drawn based on Eu* (Holder et al., 2018).
Figure 4.17. Rare earth element data for leucogranitic dyke sample AM-19B. A) Yttrium (Y) content in ppm plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). B) Eu* ($[\text{Eu (ppm)}/(\text{Sm (ppm)} + \text{Gd (ppm)})^{0.5}]$) content plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). C) Gd/Yb ratio plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). D) Sr plotted against Eu*.

4.4.5 Granite (AM-12)

Thirteen monazite grains from the matrix of the granite unit (Sample AM-12; 114 analyses) yield dates from 22.1 ± 1.2 Ma to 16.5 ± 0.5 Ma with an average date of 18.0 Ma (excluding data from poorly located laser spots or yielding dates with greater than 15% error) (Fig. 4.18A; Table D2 in Appendix D). The sample contains a weak SE-NW foliation. Seven of the monazite grains have a long axis and are randomly aligned with respect to the weakly developed matrix foliation; while six of the monazite grains are more circular grains are randomly oriented in the matrix as well (Appendix B). Analysed monazite grains range in size from ~ 50 μm to as large as ~ 120 μm in length (Appendix C). Monazite grains in this sample are irregularly zoned in Y; some show distinct zoning between core and rim (Appendix C, AM-12 mnz 01-11), while the two smallest grains do not (Appendix C, AM-12 mnz 12, 13).
Eleven monazite grains contain inclusions (AM-12 mnz 01, 08, 10, 11 do not). Monazite grains tend to be pitted and cracked, with only two grains showing no pits or cracks (AM-12 mnz 03, 04).

The date histogram for granite sample AM-12 shows a peak monazite date at 18 Ma and a minimum monazite date at 16.5 Ma (Fig. 4.18A). The $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot indicates that data for sample AM-12 are discordant. This is most likely due to excess unsupported $^{206}\text{Pb}$ in the system (Fig. 4.18B). Analyses also indicate a slight increase in Y in younger dates (Fig. 4.18B).

**Figure 4.18.** A) Date histogram for granite sample AM-12, showing $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma) from 25 Ma to present, and the relative probability of each date (purple line), and the relative amounts of Y. B) $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot of date data obtained from sample AM-12. Ellipses are coloured based on relative Y content (green: low Y, red: high Y) and are 2σ. Concordia plot produced using IsoplotR (Vermeesch, 2018).

The REE spider plot for granite sample AM-12 shows a steady decrease in rare earth element concentrations (normalized to the chondrite values after McDonough and Sun (1995)) from the light to the heavy rare earth elements and a negative Eu anomaly (Fig. 4.19).
Figure 4.19. The REE chondrite normalized spider plot for sample AM-12, granite. This spider plots shows REE Lanthanum to REE Lutetium, with the exception of REE Promethium, chondrite normalized after McDonough and Sun (1995). There is a negative Europium anomaly.

The Y (Fig. 4.20A), Eu* (Fig. 4.20B), and Gd/Yb (Fig. 4.20C) contents have all been plotted against the $^{208}\text{Pb}/^{232}\text{Th}$ dates. The Y content is constant with time (Fig. 4.20A). There is a negative Eu anomaly (Fig. 4.19), and Eu* decreases with younger dates (Fig. 4.20B), which suggest feldspar growth and melt crystallization (Rubatto et al., 2006; Mottram et al., 2014b; Holder et al., 2015). The Gd/Yb is constant with time (Fig. 4.20C). Finally, the plot of Sr versus Eu* (Fig. 4.20D) displays a positive correlation between Sr and Eu*, which indicates that the Eu* is not reflecting changes in the bulk rock $f\text{O}_2$ and therefore interpretations can be drawn based on Eu* (Holder et al., 2018).
Figure 4.20. Rare earth element data for granite sample AM-12. A) Yttrium (Y) content in ppm plotted against $^{208}$Pb/$^{232}$Th dates (Ma). B) Eu* ($\left(\frac{\text{Eu (ppm)}}{\text{Sm (ppm)} + \text{Gd (ppm)}\times 0.5}\right)$) content plotted against $^{208}$Pb/$^{232}$Th dates (Ma). C) Gd/Yb ratio plotted against $^{208}$Pb/$^{232}$Th dates (Ma). D) Sr plotted against Eu*.

4.4.6 Granite (AM-15B)

Seventeen monazite grains from the granite unit (Sample AM-15B; 144 analyses) yield dates from 445.8 ± 16.5 Ma to 16.5 ± 0.6 Ma with an average date of 35.8 Ma (excluding data from poorly located laser spots or yielding dates with greater than 15% error) (Table D2 in Appendix D). Considering only Cenozoic dates the dates range from 28.8 ± 2.1 Ma to 16.5 ± 0.6 Ma with an average date of 18.6 Ma (excluding data from poorly located laser spots or yielding dates with greater than 15% error) (Fig. 4.21A; Table D2 in Appendix D). The sample has a weak NE-SW foliation. Thirteen of the monazite grains have a long axis and are randomly aligned with respect to the matrix foliation, while four of the more circular monazite grains are randomly oriented in the matrix (Appendix B). Analysed monazite grains range in size from ~50 μm to as large as ~120 μm in length (Appendix C). Monazite grains in this sample are somewhat irregularly zoned in Y; some show moderate zoning between core and rim.
The date histogram for granite sample AM-15B shows a peak monazite date at 18 Ma and a minimum monazite date at 16.5 Ma (Fig. 4.21A). The $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot indicates that data for sample AM-15B are mostly discordant. This is most likely due to excess unsupported $^{206}\text{Pb}$ in the system (Fig. 4.21B). Analyses also indicate a slight increase in Y in younger dates (Fig. 4.21B).

The REE spider plot for granite sample AM-15B shows a steady decrease in rare earth element concentrations (normalized to the chondrite values after McDonough and Sun (1995) from the light to the heavy rare earth elements and a negative Eu anomaly (Fig. 4.22).
Figure 4.22. The REE chondrite normalized spider plot for sample AM-15B, granite. This spider plots shows REE Lanthanum to REE Lutetium, with the exception of REE Promethium, chondrite normalized after McDonough and Sun (1995). There is a negative Europium anomaly.

The Y (Fig. 4.23A), Eu* (Fig. 4.23B), and Gd/Yb (Fig. 4.23C) contents have all been plotted against the $^{208}\text{Pb}/^{232}\text{Th}$ dates. The Y content is constant with time (Fig. 4.23A). There is a negative Eu anomaly (Fig. 4.22), and Eu* decreases with younger dates (Fig. 4.23B), which suggest feldspar growth and melt crystallization (Rubatto et al., 2006; Mottram et al., 2014b; Holder et al., 2015). The Gd/Yb is also constant with time (Fig. 4.23C). Finally, the plot of Sr versus Eu* (Fig. 4.23D) displays a positive correlation between Sr and Eu*, which indicates that the Eu* is not reflecting changes in the bulk rock $f\text{O}_2$ and therefore interpretations can be drawn based on Eu* (Holder et al., 2018).
Figure 4.23. Rare earth element data for granite sample AM-15B. A) Yttrium (Y) content in ppm plotted against \(^{208}\text{Pb}/^{232}\text{Th}\) dates (Ma). B) Eu* (\([\text{Eu (ppm)}/(\text{Sm (ppm)} + \text{Gd (ppm)})^{0.5}]\)) content plotted against \(^{208}\text{Pb}/^{232}\text{Th}\) dates (Ma). C) Gd/Yb ratio plotted against \(^{208}\text{Pb}/^{232}\text{Th}\) dates (Ma). D) Sr plotted against Eu*.

4.4.7 Meta-quartz arenite (AM-21B)

Thirteen monazite grains from the meta-quartz arenite (Sample AM-21B; 99 analyses) yield dates from 1604.8 ± 68.3 Ma to 13.3 ± 0.5 Ma with an average date of 367.8 Ma (excluding data from poorly located laser spots or yielding dates with greater than 15% error) (Table D2 in Appendix D). Considering only Cenozoic dates the dates range from 47.0 ± 2.7 Ma to 13.3 ± 0.5 Ma with an average date of 23.8 Ma (excluding data from poorly located laser spots or yielding dates with greater than 15% error) (Fig. 4.24A; Table D2 in Appendix D). Nine of the monazite grains have a long axis and are aligned with the NW-SE matrix foliation. Four circular grains are randomly oriented in the matrix (Appendix B). Analysed monazite grains range in size from ~ 50 \(\mu\)m to as large as ~ 140 \(\mu\)m in length (Appendix C). Monazite grains in this sample are somewhat irregularly zoned in Y; some show moderate zoning between core and rim (Appendix C, e.g. AM-21B mnz 01, 03), while others do not (Appendix C, e.g. AM-15B mnz 08, 09, 13). Monazite
grains in this sample contain inclusions (Appendix B, e.g. AM-21B mnz 01, 14). Monazite grains tend to be pitted and cracked, with five grains showing no pits or cracks (AM-21B mnz 09, 10, 15, 16, 17).

The date histogram for meta-quartz arenite sample AM-21B shows a peak monazite date at 18 Ma (Fig. 4.24A). The $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot indicates that data for sample AM-21B are concordant and therefore internally consistent (Fig. 4.24B).

**Figure 4.24.** A) Date histogram for meta-quartz arenite sample AM-21B, showing $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma) from 80 Ma to present, and the relative probability of each date (purple line), and the relative amounts of Y. B) $^{208}\text{Pb}/^{232}\text{Th}$ versus $^{206}\text{Pb}/^{238}\text{U}$ concordia plot of date data obtained from sample AM-21B. Ellipses are coloured based on relative Y content (green: low Y, red: high Y) and are 2σ. Concordia plot produced using IsoplotR (Vermeesch, 2018).

The REE spider plot for meta-quartz arenite sample AM-21B displays a steady decrease in rare earth element concentrations (normalized to the chondrite values after McDonough and Sun (1995) from the light to the heavy rare earth elements and a negative Eu anomaly (Fig. 4.10).
Figure 4.25. The REE chondrite normalized spider plot for sample AM-21B, meta-quartz arenite. This spider plots shows REE Lanthanum to REE Lutetium, with the exception of REE Promethium, chondrite normalized after McDonough and Sun (1995).

The Y (Fig. 4.26A), Eu* (Fig. 4.26B), and Gd/Yb (Fig. 4.26C) contents have all been plotted against the $^{208}\text{Pb}/^{232}\text{Th}$ dates. There is no observable correlation between Y, Eu*, and Gd/Yb plotted against the $^{208}\text{Pb}/^{232}\text{Th}$ dates (Fig. 4.26A, B, C). Finally, the plot of Sr versus Eu* (Fig. 4.26D) displays a slight positive correlation between Sr and Eu*, which indicates that the Eu* is not reflecting changes in the bulk rock $f/O_2$ and therefore interpretations can be drawn based on Eu* (Holder et al., 2018), however there are no trends in Eu*.
Figure 4.26. Rare earth element data for meta-quartz arenite sample AM-21B. A) Yttrium (Y) content in ppm plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). B) Eu* ([Eu (ppm)/(Sm (ppm) + Gd (ppm))$^{0.5}$]) content plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). C) Gd/Yb ratio plotted against $^{208}\text{Pb}/^{232}\text{Th}$ dates (Ma). D) Sr plotted against Eu*.
4.5 Interpretation of results

Three different types of magmatic rocks were dated from the Chuwa Khola: the leucosome portion of the stromatic metatexite, leucogranitic dykes from the dyke and sill network, and the Chuwa granite. The stromatic metatexite ± schist unit has a peak date of 18.5 Ma and a minimum date of ca. 13 Ma. I interpret this to represent the age of peak monazite crystallization at 18.5 Ma, with monazite crystallization occurring until ca. 13 Ma (Figs. 4.6, 4.9, 4.27). I interpret this to represent a time of retrograde metamorphism in the southern flank of the Chuwa Khola. This is supported in both metatexite samples by the increase in Y and a decrease in Gd/Yb as the system decreases in age, suggesting garnet breakdown and therefore retrograde metamorphism. Both metatexite samples also display a negative Eu anomaly and a decrease in Eu* with younger dates in, which suggest feldspar growth and melt crystallization.

Leucogranitic dyke samples yield peak dates at 20 Ma (AM-11B, Fig. 4.12) and 18.5 Ma (AM-19B, Fig. 4.15), respectively. I interpret this to represent leucogranitic dyke and sill emplacement at ca. 19.5 Ma (Fig. 4.27). This is supported in both dyke and sill samples by the negative Eu anomalies, suggesting feldspar growth and melt crystallization. One leucogranitic dyke sample also display an increase in Y as the system decreases in age, suggesting this portion of the Chuwa Khola has also experienced garnet breakdown and therefore retrograde metamorphism. The leucogranitic dyke and sill network yields minimum dates of 19.1 Ma (AM-11B, Fig. 4.12) and 15.8 Ma (AM-19B, Fig. 4.15), respectively. I interpret this to represent the age of top-to-the-south/southwest shearing in the Chuwa Khola as both of these leucogranitic dyke samples have been sheared. Therefore, shearing in the Chuwa Khola has been active since at least ca. 19 Ma to 16 Ma.

The Chuwa granite yields a peak date of 18 Ma and a minimum date of 16.5 Ma, interpreted to represent the age of peak monazite crystallization at 18 Ma, with monazite crystallization occurring until ca. 16.5 Ma (Figs. 4.18, 4.21, 4.27). I interpret the peak date to represent the emplacement age of the Chuwa granite. This is supported by both granite samples displaying a negative Eu anomaly and a decrease in Eu* with younger dates in, which suggest feldspar growth and melt crystallization at this time.
Figure 4.27. Peak monazite crystallization ages of the stromatic metatexite, dyke and sill network, and the Chuwa granite. The age of shearing is the maximum age determined by dating the sheared leucogranitic dykes.
CHAPTER 5

INTERPRETATIONS AND DISCUSSION

In this chapter, I interpret the geological and geochronological results, and discuss the implications and principal contributions of this thesis in the context of the research questions presented in Chapter 1. Field relationships, geochemical analysis, and petrochronological constraints from Chapters 3 and 4 are integrated in Section 5.1 to interpret the genetic linkages between the three types of magmatic rocks observed in the Chuwa Khola. Section 5.2 discusses the implications of the interpretation presented in Section 5.1. Section 5.3 integrates field results, geochemical analysis, and petrochronological constraints to characterize of the Chuwa granite. Finally, Section 5.4 discusses the Chuwa Khola with respect to the eastern limit of the Gurla Mandhata core complex and presents an evolutionary model that combines data from both the Chuwa Khola and the Gurla Mandhata core complex.

5.1 Magmatic rock relationships in the Chuwa Khola

The Chuwa Khola exposes five major mappable units and three major manifestations of magmatic rocks (Fig. 3.2). The magmatic rocks within the Chuwa Khola share very similar mineralogy and geochemical characteristics (Fig. 5.1), and in situ U-Th/Pb monazite petrochronology yields similar ages (Figs. 5.1, 5.2D, E, 5.3D, E, 5.4D, E). Consequently, the three different types of magmatic rocks are interpreted to be genetically linked.

The stromatic metatexite, leucogranitic dyke and sill network, and Chuwa granite are all mineralogically similar, containing quartz + plagioclase + alkali-feldspar + biotite (± muscovite ± sillimanite ± garnet ± tourmaline). In outcrop, the dyke and sill network is boudinaged and sheared. In thin section, the stromatic metatexite displays a prominent NE dipping foliation, whereas the leucogranitic dyke and sill network and the granite are more massive and only show a faint foliation. Geochemical analyses of five magmatic rock samples indicate that they are all peraluminous and plot close to one another on the alumina saturation diagram (Fig. 5.1). One leucogranitic dyke sample plots in the weakly peraluminous field (Fig. 5.1), which could be because it is hosted in a calc-silicate gneiss. The melts in the Chuwa Khola all yield a negative Eu anomaly (e.g. Fig. 5.1B, all other spider plots can be seen in Chapter 4 – Figs. 4.8, 4.11,
4.14, 4.17, 4.20, 4.23, 4.26), which suggests they are derived from a crustal source (Rubatto et al., 2006; Mottram et al., 2014b; Holder et al., 2015).

**Figure 5.1.** A) Five samples of melts plotted on a simplified alumina saturation diagram indicating peraluminous composition (Manaslu - purple, Deniel et al., 1987; Everest - blue, Visona et al., 2012). Diagram produced with ioGAS (v.7.2). B) The REE chondrite normalized spider plot for sample AM-01, stromatic metatexite ± schist. This spider plots shows REE La to REE Lu, with the exception of REE Pm, chondrite normalized after McDonough and Sun (1995), and displays a negative Eu anomaly.

The stromatic metatexite melts, leucogranitic dyke and sill network, and Chuwa granite all yield coeval ages. The stromatic metatexite samples analysed are the structurally lowest samples in the Chuwa Khola section (Fig. 5.2A, B, C). Both stromatic metatexite samples yield peak monazite crystallization ages at 18.5 Ma (Fig. 5.2D, E). The two stromatic metatexite samples also record minimum monazite crystallization ages of ca. 13 Ma (Fig. 5.2D, E). Both metatexite samples show an increase in Y as the system decreases in age, indicate monazite crystallization could be linked with retrograde metamorphism (Fig. 5.2D, E) (Spear and Pyle, 2002; Kohn et al., 2005).
Figure 5.2. A) Simplified cross section showing the seven U-Th/Pb sample locations within the study area. AM-01, AM-08, AM-11, AM-12, AM-15, and AM-19, highlighting the migmatite samples: AM-01 and AM-08B. B) Outcrop AM-01, showing the leucosome and restite portions of the migmatite. C) Outcrop AM-08B, showing the leucosome and restite portions of the migmatite. D) Date histogram and probability density curve for sample AM-01, peak is 18.5 Ma and minimum is 13.2 Ma, relative amounts of Y shown. E) Date histogram and probability density curve for sample AM-08B, peak is 18.5 Ma and minimum is 12.8 Ma, relative amounts of Y shown.
The leucogranitic dyke and sill complex is found at an intermediate structural level in the Chuwa Khola (Fig. 5.3A, B, C). The leucogranitic dyke samples yield peak monazite crystallization ages of 20 Ma (Fig. 5.3D) and 18.5 Ma (Fig. 5.3E) and minimum monazite crystallization ages of 19.1 Ma (Fig. 5.3D) and 15.8 Ma (Fig. 5.3E). The dyke and sill complex is affected by top-to-the-southwest shear (Fig. 5.3B, C); consequently, the shearing must have persisted since approximately 19 Ma until at least 16 Ma.

**Figure 5.3.** A) Simplified cross section showing the seven U-Th/Pb sample locations within the study area. AM-01, AM-08, AM-11, AM-12, AM-15, and AM-19, highlighting the leucogranitic dyke samples: AM-11B and AM-19B. B) Outcrop AM-11B, showing a sheared leucogranite boudin. C) Outcrop AM-19B, showing the sheared leucogranitic dyke sample. D) Date
The Chuwa granite is located at the structurally highest levels of the Chuwa Khola (Fig. 5.4A, B, C). Dated granite samples yield peak monazite crystallization interpreted ages at 18 Ma (Fig. 5.4D, E) with monazite crystallization occurring until ca. 16.5 Ma (Fig. 5.4D, E). This crystallization seems to have operated in an Y rich environment, with Y potentially coming from the country rocks where the garnet grains have all be resorbed and have released their Y (Fig. 5.4D, E). This increasing Y content could be linked with retrograde metamorphism/decompression (Spear and Pyle, 2002; Kohn et al., 2005) and would support coeval activity on the South Tibetan detachment above the Chuwa granite. The coeval monazite crystallization ages in the Chuwa Khola are summarized in Figure 5.5 and 5.6 below. All of the presented results lead to the conclusion that the various melts within the Chuwa Khola are genetically linked.
In summary, the migmatization operated in the structurally lowest position in the Chuwa Khola within the pelitic units, and probably provided the melt source for the leucogranitic dyke and sill network, ultimately feeding the Chuwa granite at the structurally highest level (Fig. 5.5), with migmatization beginning around 35 Ma to 25 Ma (Fig. 5.2D, E). Although the magmatic rock system is pervasively sheared in a top-to-the-south/southwest reverse sense, it is speculated...
that the granite is capped by the South Tibetan detachment (top-to-the-north normal sense) system farther north (Fig. 5.5), meaning the STD has been eroded from over this section. This scenario is similar to the magmatic rock system associated with the Manaslu leucogranite in central Nepal (Searle and Godin, 2003; Godin et al., 2006b) and the Everest region in eastern Nepal (Searle, 2013).

**Figure 5.5.** Geometry of the coeval magmatic rock system in the Chuwa Khola. Peak monazite crystallization ages of the stromatic metatexite, dyke and sill network, and the Chuwa granite. Diagram is not to scale. STD: South Tibetan detachment, MCT: Main Central thrust.

### 5.2 Chuwa Khola magmatic rock system implications

The various different magmatic rocks observed in the Chuwa Khola are interpreted to be genetically related (Fig. 5.6). Based on results presented in this thesis, I propose that the stromatic metatexite, leucogranitic dyke and sill network, and Chuwa granite were produced by the same thermal event. The 20 Ma to 18 Ma peak melt crystallization ages as well as the ca. 20 Ma to <16 Ma top-to-the-southwest reverse sense of shear (Fig. 5.5) are consistent with typical southward extrusion of the Himalayan metamorphic core observed across the Himalaya (e.g. Grujic et al., 1996; Beaumont et al., 2001; Godin et al., 2006b; Larson et al., 2010; Law et al., 2011; Xu et al., 2013), which ceased ca. 16 Ma in NW Nepal (Antoln et al., 2013; Godin et al., 2021). The melt crystallization ages and dominant top-to-the-southwest sense of shear are inconsistent with Gurla Mandhata core complex evolution (Murphy et al., 2002; Murphy and Copeland, 2005; Murphy, 2007; McCallister et al., 2014; Nagy et al., 2015), in which E-W
The magmatic rocks in the Chuwa Khola are coeval, with only the migmatites yielding minimum monazite crystallization age of ~13 Ma. The histograms are arranged from north (top) to south (bottom).

**Figure 5.6.** Summary of monazite crystallization ages. The magmatic rocks in the Chuwa Khola are coeval, with only the migmatites yielding minimum monazite crystallization age of ~13 Ma. The histograms are arranged from north (top) to south (bottom).

extension and exhumation initiated ca. 15 Ma to 13 Ma (Nagy et al., 2015). I suggest that the three manifestations of magmatic rocks within the Chuwa Khola are the product of a thermal event coeval with southward extrusion of the Himalayan metamorphic core, prior to doming and west-directed extension associated with the Gurla Mandhata core complex (Fig. 5.6). The meta-
It is predicted that the Himalayan metamorphic core rocks extruded along a decompression/retrogressive path (e.g. Godin et al., 2006a; Larson et al., 2016; Soucy La Roche and Godin, 2019; Godin et al., 2021). The rare earth element data (highlighted in detail in Chapter 4) is compatible with this interpretation of southward extrusion of the Himalayan metamorphic core in the Chuwa Khola. Five out of the seven U-Th/Pb monazite petrochronology samples show trends in the rare earth element data consistent with retrograde metamorphism. For example, the structurally lowest sample analysed in the Chuwa Khola (AM-01) indicates that Y increases slightly with younger ages, indicating garnet breakdown and therefore retrograde metamorphism (Fig. 4.8A) (Spear and Pyle, 2002; Kohn et al., 2005). Furthermore, these same U-Th/Pb monazite samples display decreasing Gd/Yb with younger monazite crystallization ages, also suggesting garnet breakdown and retrograde metamorphism. (Fig. 4.8C) (Zhu and O'Nions, 1999). This retrograde metamorphism is interpreted to be linked with southward extrusion of the Himalayan metamorphic core and exhumation (e.g. Godin et al., 2006a). This process is recorded in the garnet breakdown as a result of retrograde metamorphism, and therefore increased Y and decreased Gd/Yb in the monazite as the system decreases in age. Lastly, the trend in Eu* when plotted against the monazite crystallization ages for the analysed magmatic rock samples are also compatible with the thermal event associated with southward extrusion of the Himalayan metamorphic core. This trend is observed in five of the seven analysed samples, in both stromatic metatexite samples (AM-01, AM-08B), one leucogranitic dyke sample (AM-19B), and both granite samples (AM-12, AM-15B). In all five of these samples, the Eu* decreases as the system decreases in age, suggesting feldspar growth and therefore melt crystallization as a result of southward extrusion of the Himalayan metamorphic core (Rubatto et al., 2006; Mottram et al., 2014b; Holder et al., 2015). An example of the Eu* decreasing as the system decreases in age can be seen again in the structurally lowest sample in the Chuwa Khola, AM-01 (Fig. 4.9B).

S-type granites often result from anatexis of crustal rocks, and the subsequent segregation, aggregation, ascent, and emplacement of the resultant magma (Crawford and Windley, 1990; Brown, 2001; King et al., 2011). I interpret the source of all the melts to come
from a similar package of rocks, because the magmatic rocks found within the Chuwa Khola all have the same mineralogical and geochemical characteristics (Fig. 5.1). The melts in the Chuwa Khola are therefore locally-derived, and were likely formed by nearby in situ melting of the structurally lower Greater Himalayan sequence rocks. The leucogranitic dyke and sill network is interpreted as a feeder system for the structurally higher Chuwa granite (Fig. 5.4A), based on mineralogy, geochemical characteristics, observed field relationships, and coeval ages.

The magmatic rocks in the Chuwa Khola, do, however, record varying minimum monazite crystallization ages. The stromatic metatexite (structurally lowest samples) record minimum monazite crystallization ages of ca. 13 Ma (Fig. 5.2D, E), in contrast with the four other samples from the middle and upper portions of the Chuwa Khola that yield a minimum monazite crystallization age of ca. 17 Ma (Figs. 5.3D, E, 5.4D, E). The young ca. 13 Ma age for the structurally lowest sample can be explained by its close proximity to the active West Nepal (strike-slip) fault system (Fig. 2.6) (McCallister et al., 2014; Murphy et al., 2014; Silver et al., 2015). The dextral shear (e.g. Fig. 3.1) may explain the young migmatite ages in the southern Chuwa Khola. One possibility is that the dextral shear is kinematically linked with doming of the Gurla Mandhata core complex, which generated decompression melts at its edges (and structurally higher levels) (McCallister et al., 2014; Murphy et al., 2014; Silver et al., 2015).

Ages of melt crystallization within the Chuwa Khola are coeval with the melt crystallization ages found within the central part of the Gurla Mandhata core complex (Godin et al., 2021) but not with the melt crystallization ages determined at the western limit of the Gurla Mandhata core complex (Fig. 5.8) (Murphy et al., 2002; Murphy, 2007). Melts at the western edge of the core complex are structurally higher and younger, while melts in the central part of the core complex are structurally lower and older. The melts found in the west of the core complex have been related with decompression along the Gurla Mandhata detachment (Fig. 5.8) (Murphy et al., 2002; Murphy, 2007). The >15 Ma coeval ages found within the Chuwa Khola (Fig. 5.6) and the central part of the core complex, therefore contrast with the 11 Ma to 7 Ma Th-Pb monazite ages from the western termination of the Gurla Mandhata core complex (Murphy et al., 2002). This suggests that decompression melting may only be occurring proximal to the Gurla Mandhata detachment and also proximal to the dextral shear zone of the West Nepal fault system (Fig. 5.8) (Godin et al., 2021). Based on these results, I suggest that the Chuwa Khola,
along with the Gurla Mandhata core complex, experienced high-T metamorphism and anatectic melting during crustal thickening and southward extrusion from 40 Ma to 16 Ma, prior to the initiation of orogen-parallel extension and top-to-the-NW shearing at ca. 15 Ma to 13 Ma (Nagy et al., 2015).

5.3 Chuwa granite characterization

The structurally highest manifestation of the magmatic rocks observed in the Chuwa Khola is the Chuwa granite (Figs. 5.4, 5.5). The Chuwa granite is a medium to coarse grained, equigranular, quartz + plagioclase + alkali-feldspar + biotite ± muscovite ± sillimanite granite and covers an extensive amount of the field area. Although the Chuwa granite had been preliminarily mapped (Murphy and Copeland, 2005; Yakymchuk and Godin, 2012), it hadn’t been studied and characterized in detail until now. The southern limit of the Chuwa granite is the only part that has been mapped in the Chuwa Khola (Fig. 3.2). The Mugu granite, about 100 km east of the Chuwa Khola, has been recognized as one of the largest single granite bodies in the Himalaya (~ 1600 km2) and has monazite crystallization ages (ca. 20 Ma to 18 Ma) coeval with the Chuwa granite (e.g. Harrison et al., 1997; Hurtado, 2002). I suggest that the Chuwa granite might be the eastern termination of the Mugu granite (Fig. 5.7).

I interpret the Chuwa granite to be a North Himalayan granite based on mineralogy, rare earth element concentrations, monazite crystallization ages, and structural position. (e.g. Burchfiel et al., 1992; Leech, 2008; Larson et al., 2010; Pullen et al., 2011; Guo and Wilson, 2012; Liu et al., 2016; Weinberg, 2016; Xie et al., 2018). Mineralogically, the Chuwa granite could be characterized as either a North or High Himalayan granite. However, the presence of > 5% biotite (visible in outcrop, Figs. 3.4H, 4.1D, E) and the lack of tourmaline and muscovite is more consistent with North Himalayan granite mineralogy rather than High Himalayan leucogranites (Debon et al., 1986; Guillot and Le Fort, 1995; Zhang et al., 2004). The Chuwa granite also contains high heavy to light rare earth element ratios and yttrium contents (Table E2 – supplementary material), which typically characterize North Himalayan granites (Debon et al., 1986; Schärer et al., 1986; Montel, 1993; Harrison et al., 1997; King et al., 2011; Wu et al., 2020). The Chuwa granite yields peak monazite crystallization ages of ca. 18 Ma, consistent with North Himalayan (18 Ma to 9 Ma) granite emplacement (Harrison et al., 1997; Leech, 2008; Larson et al., 2010; Guo and Wilson, 2012; Weinberg, 2016; Jessup et al., 2019).
The interpretation of the Chuwa granite as a North Himalayan granite implies specific melt source and exhumation history (e.g. Schärer et al., 1986; Le Fort et al., 1987; Guo and Wilson, 2012; Weinberg, 2016; Yang et al., 2019). Common to other North Himalayan granites, the Chuwa granite is likely sourced uniquely from Greater Himalayan sequence rocks (typically biotite-bearing pelite) (e.g. Guo and Wilson, 2012), in contrast to High Himalayan leucogranites that are often sourced from both Greater and Lesser Himalayan sequence rocks (typically slates) due to Lesser Himalayan sequence underplating (e.g. Guo and Wilson, 2012). Similar to North Himalayan granites, exhumation of the Chuwa granite is likely related to rock uplift associated with folding of the North Himalayan antiform combined with erosion. Because the Chuwa granite is characterized as a North Himalayan granite, the North Himalayan antiform trace is possibly extending to the Xiao Gurla complex, north of the study area, where foliation measurements dip to the southeast/southwest and northeast (Pullen et al., 2011).

**Figure 5.7.** Simplified geologic map of the Nepal, Bhutan, and North Indian Himalaya, showing the extension of the North Himalayan antiform into the Gurla Mandhata core complex (from Godin et al. (2021), modified from Murphy and Copeland (2005); McQuarrie et al. (2008); Antolín et al. (2013); Soucy La Roche et al. (2018a)). MFT: Main Frontal thrust, MBT: Main Boundary thrust, MCT: Main Central thrust, STD: South Tibetan detachment, IYZS: Indus-Yarlung Zangpo suture zone, NHA: North Himalayan antiform, NHGD: North Himalayan gneiss domes.
5.4 The eastern limit of the Gurla Mandhata core complex

The Gurla Mandhata core complex has been the subject of limited geochronology, thermochronology and isotopic studies over the last two decades (e.g. Murphy et al., 2002; Murphy and Copeland, 2005; Murphy, 2007; Pullen et al., 2011; Yakymchuk and Godin, 2012; McCallister et al., 2014; Nagy et al., 2015; Godin et al., 2021). These studies have concentrated in the central part of the core complex, as well as near the western Gurla Mandhata detachment, the Gurla Mandhata-Humla fault system that bounds the core complex to the south, and West Nepal fault system. Despite these past studies, there remains a significant gap in the understanding of what constitutes the eastern limit of the Gurla Mandhata core complex.

In the Chuwa Khola, monazite crystallized at ca. 24 Ma to 16 Ma, coeval with top-to-the-south/southwest reverse shear (Domain I) (Fig. 5.8). In the center of the Gurla Mandhata core complex, monazite crystallized between 35 Ma to 16 Ma, while the dominant top-to-the-west/northwest shear (Domain II) operated at ca. 15 Ma to 13 Ma (Fig. 5.8) (Nagy et al., 2015; Godin et al., 2021). The 15 Ma to 13 Ma time also marks a fundamental change from south directed extrusion of the Himalayan metamorphic core to east-west extension (Fig. 5.8) (Nagy et al., 2015). North of the Chuwa Khola, in the Xiao Gurla complex, leucogranite bodies yield an average U/Pb crystallization age of ca. 19 Ma (Fig. 5.8) (Pullen et al., 2011), suggesting that intrusions in this area predate the initiation of east-west extension along the Gurla Mandhata-Humla fault system (Fig. 5.8) (Nagy et al., 2015; Godin et al., 2021). In the Karnali River south of the Chuwa Khola, the dominant sense of shear is reverse top-to-the-south (Domain I) (Fig. 5.8) (Yakymchuk and Godin, 2012). This shearing in the Karnali River is dated at 18 Ma to 11 Ma (Braden et al., 2017).

Based on these constraints, I propose that the structurally deeper level of the Gurla Mandhata core complex and the Chuwa Khola rocks have been affected by similar thermal pulses compatible with southward extrusion of the Himalayan metamorphic core. Both regions yield monazite crystallization ages older than 16 Ma, antecedent to the hypothesized transition to east-west extension at ca. 15 Ma to 13 Ma (Nagy et al., 2015). I further suggest that the leucogranites in the Xiao Gurla complex are also the products of the older than 16 Ma thermal pulse as they too do not yield monazite crystallization ages younger than 16 Ma. However, only the central and western portions of the Gurla Mandhata core complex and the Xiao Gurla complex have been overprinted by the top-to-the-west sense of shear associated with orogen
parallel extension (Fig. 5.8) (Murphy et al., 2002; Murphy, 2007; Nagy et al., 2015). The Xiao Gurla complex has been interpreted as a northeastward continuation of the Gurla Mandhata detachment fault because it shows similar top-to-the-west sense of shear as the Gurla Mandhata core complex (Pullen et al., 2011).

The question therefore remains: why does the Chuwa Khola record a different top-to-the-south sense of shear than what is seen in both the Gurla Mandhata core complex to the west and the Xiao Gurla complex to the north? I postulate that this is a result of ~ N-S strain partitioning boundary separating the two strain domains, Domains I and II (Fig. 5.8). The top-to-the-south reverse sense of shear in the Chuwa Khola and Karnali River (Domain I) is overprinted by a strike-slip shear zone (Domain III) highlighted by east plunging mineral lineations associated with ductile activity along the West Nepal fault system (Fig. 5.8).
Figure 5.8. Compilation map showing all previous work done in the Gurla Mandhata core complex and the Chuwa Khola, showing the melt crystallization ages (pink tear drop) and the timing of ductile flow (in the black arrows) and proposed strain partitioning boundary (from Godin et al. (2021), modified from Murphy et al. (2002); Murphy and Copeland (2005); Murphy and Burgess (2006); Pullen et al. (2011); McCallister et al. (2014)). TSS: Tethyan sedimentary sequence, GHS: Greater Himalayan sequence, LHS: Lesser Himalayan sequence, STD: South Tibetan detachment, GMD: Gurla Mandhata detachment, MCT: Main Central thrust, GMH: Gurla Mandhata-Humla fault system, WNFS: West Nepal fault system.
5.4.1 Evolutionary model of the Gurla Mandhata core complex and the Chuwa Khola

In this section, I present a model modified from Soucy La Roche et al., 2018a, Braden et al., 2020, and Godin et al., 2021, for the temporal evolution of the Gurla Mandhata core complex and the Chuwa Khola (Fig. 5.9). From the onset of continental collision at ca. 55 Ma to 50 Ma to ca. 16 Ma (prior to initiation of E-W extension), the Gurla Mandhata and the Chuwa Khola rocks are interpreted to have undergone similar evolution. Initial crustal thickening occurred from 40 Ma to 30 Ma in central and western Nepal (Godin et al., 2001; Stübner et al., 2014; Larson and Cottle, 2015; Soucy La Roche et al., 2018a), which led to limited partial melting at mid-crust depth and kyanite-grade metamorphism (Fig. 5.9A) (Godin et al., 2001; Soucy La Roche et al., 2018a).

From 30 Ma to 25 Ma, continued crustal thickening led to partial melting and weakening at mid-crustal depths, ultimately culminating in strain localization and extrusion of the Himalayan metamorphic core and coeval activation of the Main Central thrust and the South Tibetan detachment (Fig. 5.9B) (Grujic et al., 1996; Jamieson et al., 2006; Godin et al., 2006a; Braden et al., 2020; Godin et al., 2021).

From 25 Ma to 15 Ma the Himalayan metamorphic core in the foreland was subjected to exhumation and cooling, while the hinterland sustained sillimanite-grade metamorphism. This second metamorphic pulse is linked to extensive partial melting and a decrease in pressure associated with tectonic denudation at the structurally highest levels (South Tibetan detachment) (e.g. Guillot et al., 1994; Hodges et al., 1998; Beaumont et al., 2001; Searle and Godin, 2003). Part of the Lesser Himalayan sequence is also interpreted to have accreted to the immediate hanging wall of the Main Central thrust in the foreland during this time, while the Chuwa granite was emplaced at higher structural level in the hinterland (Fig. 5.9C).

The combination of the mid-crustal channel and the ongoing contraction of the entire orogen causes colder rheologically stronger lower plate in the hinterland mid-crust to develop a ramp at its leading edge, deflecting the melt-weakened Himalayan metamorphic core mid-crustal channel upwards (Beaumont et al., 2004; Jamieson et al., 2006; Warren et al., 2008). This upward deflection of the mid-crustal channel in turn generates the Gurla Mandhata core complex above the ramp (Fig. 5.9C) (Godin et al., 2021). I propose that it is in this time period, the eastern limit of the Gurla Mandhata core complex and associated ramp-flat geometry (e.g. Hauck et al., 1998; Gao et al., 2016) was segmented by the activation of a strain partitioning boundary (Fig. 5.9C).
This segmentation requires the presence of a tear fault between the Gurla Mandhata core complex and the Chuwa Khola (e.g. Soucy La Roche and Godin, 2019).

From 15 Ma to 7 Ma the transition from southward extrusion of the Himalayan metamorphic core to E-W extension occurs in this part of the Himalaya (approximately 15 Ma to 13 Ma; Nagy et al., 2015). The initiation of E-W extension generated extensional features across the Himalaya (e.g. Murphy et al., 2002; Murphy and Copeland, 2005; Hintersberger et al., 2010; Antolín et al., 2012; Nagy et al., 2015; Larson et al., 2020), coeval with the Karakoram fault system overprinting the South Tibetan detachment and ultimately kinematically linking with the Gurla Mandhata-Humla fault system between 14 Ma and 11 Ma (Fig. 5.9D) (Searle et al., 1998; Murphy et al., 2000; Murphy and Burgess, 2006; Leech, 2008). During this time, it is speculated that the Chuwa Khola region was not affected by the transtensional strain of the Gurla Mandhata-Humla fault system (Figs. 5.8, 5.9D). The strain isolation may have been accommodated by the formation of a dilational jog bound to the east by the strain partitioning boundary between Domain I and II and to the south by the E-W Gurla Mandhata-Humla fault system of Domain III, which eventually fed into the West Nepal fault system (Fig. 5.9D). Activity along the Main Central thrust and South Tibetan detachment ceased in the foreland, while out-of-sequence hinterland thrusting coeval with orogen-parallel transtensional deformation along the Gurla Mandhata-Humla fault system was initiated (Fig. 5.9D).

The Gurla Mandhata core complex, the Xiao Gurla complex, and the Chuwa granite are interpreted to have exhumed in the last 7 Ma (Fig. 5.9E). Greater Himalayan sequence rocks and accreted Lesser Himalayan sequence rocks are now exposed in the Gurla Mandhata core complex (Fig. 5.9E) (Godin et al., 2021). Surface exposure of the foreland klippe also takes place in this time period (Fig. 5.9E) (Soucy La Roche et al., 2018a).
Figure 5.9. Evolutionary model of the Chuwa granite, the Himalayan metamorphic core, and the Gurla Mandhata core complex in the NW Nepal Himalaya. See text for full description of the temporal evolution (from Godin et al. (2021), modified from Soucy La Roche et al. (2018a) and Braden et al. (2020)). STD: South Tibetan detachment, MCT: Main Central thrust, MBT: Main Boundary thrust, MHT: Main Himalayan thrust, OOST: Out-of-sequence thrust, TSS: Tethyan sedimentary sequence, GHS: Greater Himalayan sequence, LHS: Lesser Himalayan sequence, HMC: Himalayan metamorphic core, GMH: Gurla Mandhata-Humla fault system, WNFS: West Nepal fault system, GMCC: Gurla Mandhata core complex, KFS: Karakoram fault system, XG: Xiao Gurla complex.

5.4.1.2 The N-S strain partitioning boundary

The ~ N-S strain partitioning boundary (Fig. 5.9C, D, E) separates two different shear sense domains (Domains I and II) (Figs. 5.8). The location of this boundary, and resultant partitioning of E-W and N-S kinematics, is interpreted to coincide with the eastern limit of the dilational jog that formed to accommodate E-W extension in this part of the Himalaya (Fig. 5.9D). The location of the ~ N-S strain partitioning boundary is also interpreted to coincide with the trace of a pre-Himalayan India lithospheric structure that was reactivated as thrust sheets propagated southward (in the 25 Ma to 16 Ma time period; Fig. 5.9C) (e.g. Godin et al., 2019; Soucy La Roche and Godin, 2019).

In the foreland, the tear fault is interpreted to be active at ca. 30 Ma, segmenting the Himalayan metamorphic core into two distinct pressure-temperature paths (Soucy La Roche and Godin, 2019). This tear fault has been interpreted to coincide with an underlying basement fault, inherited from the Indian lithosphere (Soucy La Roche and Godin, 2019). This postulated basement fault aligns with the eastern limit of a dilational jog within the strike-slip system of the Karakoram fault which feeds into the West Nepal fault system (Fig. 5.9C, D, E) and the location of the proposed strain partitioning boundary.

Inherited (pre-orogenic/basement) structures undeniably have a significant influence on the development of the orogenic architecture during collision and eventual collapse (e.g. Godin et al., 2019; Soucy La Roche and Godin, 2019). Such orogen perpendicular cross structures have been observed across the Himalaya (e.g. Godin and Harris, 2014; Gibson et al., 2016; Godin et al., 2019; Soucy La Roche and Godin, 2019). In the Chuwa Khola, strain partitioning is
occurring at approximately 82°0’ E, with the shear sense to the west of this strain partitioning boundary being ~ top-to-the-west and the shear sense to the east of this being ~ top-to-the-south (Figs. 5.7, 5.8). I propose that this cross structure at 82°0’ E is an extension of the Lucknow basement fault that bounds the west side of the Faizabad Ridge in the Indian craton (Fig. 5.10) (e.g. Godin and Harris, 2014; Soucy La Roche and Godin, 2019). I propose that this feature may stair step, as seen in Fig. 5.10.

The location and northward extension of the Lucknow basement fault towards the Chuwa Khola is supported by a variety of data sets in western Nepal, which highlight major along-strike changes at ~ 82°0’E (e.g. Murphy et al., 2014; Harvey et al., 2015; Silver et al., 2015; Soucy La Roche and Godin, 2019; Fan and Murphy, 2020). The Gurla Mandhata core complex (at ~ 82°0’E) marks a change of thickness in the orogenic core (Fan and Murphy, 2020). West of the Gurla Mandhata core complex the thickness of the Himalayan metamorphic core is approximately 25-26 km, while east of the Gurla Mandhata it is approximately 34-42 km (Fan and Murphy, 2020, Fig. 2, Fig. 4). Furthermore, microseismicity and earthquake hypocenters show significant differences from east to west across west Nepal (Fig. 5.10) (Soucy La Roche and Godin, 2019). In particular, more spatially scattered and distributed microseismic events occur west of 82°0’E compared to more concentrated events to the east of ~ 82°0’E (Fig. 5.10) (e.g. Murphy et al., 2014; Harvey et al., 2015; Silver et al., 2015; Soucy La Roche and Godin, 2019). This stark difference in earthquake localities has been attributed to different flat/ramp configurations along the Main Himalayan thrust, which resulted in significant along-strike changes in topographic profiles (Harvey et al., 2015). These changes have been interpreted to be related to the location of an inherited basement faults underlying the Himalayan system (Soucy La Roche and Godin, 2019), and/or to a change from oblique to orthogonal convergence of the orogen (Silver et al., 2015; Fan and Murphy, 2020).
Figure 5.10. Geologic map of the northwest Nepal Himalaya, showing the Gurla Mandhata core complex, the Chuwa granite, and Indian basement features (the Lucknow basement fault, the Faizabad Ridge, and the Pokhara basement fault) (modified from Soucy La Roche and Godin (2019)). MFT: Main Frontal thrust, MBT: Main Boundary thrust, MCT: Main Central thrust, STD: South Tibetan detachment, IYZS: Indus-Yarlung Zangpo suture zone, KFS: Karakoram fault system.
CHAPTER 6

GENERAL CONCLUSIONS AND SUGGESTIONS FOR FUTURE STUDIES

The main objective of this thesis was to date and characterize the rocks in the Chuwa Khola and to answer the following questions:

- Are the three manifestation of magmatic rocks found within the Chuwa Khola, namely the migmatite, the dyke and sill network, and the Chuwa granite genetically related to one another?
- Is the Chuwa granite a North Himalayan or a High Himalayan granite?
- Are the melt crystallization ages within the Chuwa Khola compatible with the Gurla Mandhata core complex evolution or with typical southward extrusion of the Greater Himalayan sequence?
- What is the nature of the eastern boundary of the Gurla Mandhata core complex?

These questions were addressed through detailed field mapping, petrographic and microstructural analysis, geochemical analysis and finally in situ U-Th/Pb monazite petrochronology. In this concluding chapter, I summarize results of this study and propose future research considerations related to unresolved questions.

6.1 Conclusions

The Chuwa Khola exposes five major mappable units and three types of magmatic rock. The magmatic rocks within the Chuwa Khola share very similar mineralogy and geochemical characteristics. The stromatic metatexite, leucogranitic dyke and sill complex, and Chuwa granite are all mineralogically similar, containing quartz + plagioclase + alkali-feldspar + biotite (± muscovite ± sillimanite ± garnet ± tourmaline). Geochemical analyses indicate all magmatic rocks are peraluminous. The seven analysed samples yield a negative Eu anomaly, which suggests they are derived from a crustal source. In situ U-Th/Pb monazite petrochronology yields similar ages of ca. 20 Ma to 18 Ma to (Fig. 5.5). Consequently, the three different types of magmatic rocks are interpreted to be genetically linked. I therefore interpret that the source of the magmatic rocks in the Chuwa Khola are the same, being the Greater Himalayan sequence rocks.
The genetic link between the three different magmatic rocks imply that they are most likely the result of the same thermal event. The ca. 20 Ma to 18 Ma peak melt crystallization ages (Fig. 5.5) are coeval with the ca. 20 Ma to <16 Ma top-to-the-south/southwest reverse sense of shear, which is consistent with southward extrusion of the Himalayan metamorphic core in the NW Nepal Himalaya. Although the magmatic rock system is pervasively sheared in a top-to-the-south/southwest reverse sense, it is speculated that the Chuwa granite is capped by the South Tibetan detachment (top-to-the-north normal sense) system farther north (Fig. 5.5). The ages determined for monazite crystallization and the dominant top-to-the-south/southwest reverse sense of shear in the Chuwa Khola contrast with the ages and structural measurements observed in the Gurla Mandhata core complex, where the monazite crystallization ages are ca. 35 Ma to 16 Ma and the dominant sense of shear is top-to-the-west (Godin et al., 2021). I therefore suggest that the crystallization of the magmatic rocks in the Chuwa Khola predate doming and west-directed extension associated with the Gurla Mandhata core complex. Finally, the migmatization in the southern and structurally lowest part of the Chuwa Khola records a minimum monazite crystallization age as young as ca. 13 Ma, associated with pervasive E-W mineral elongation lineation, interpreted to represent mid-Miocene ductile shearing along the West Nepal fault system in this area.

The Chuwa granite is a medium to coarse grained, equigranular, quartz + plagioclase + alkali-feldspar + biotite ± muscovite ± sillimanite granite and covers an extensive amount of the field area. The boundaries of the Chuwa granite remain somewhat unknown. The southern limit has been mapped in the Chuwa Khola, and I suggest that to the east the Chuwa granite may connect with the Mugu granite (e.g. Hurtado, 2002). The Chuwa granite is interpreted to be a North Himalayan granite based on the mafic mineralogy (specifically biotite), rare earth element concentrations, monazite crystallization ages, and structural position. Most distinguishingly, North Himalayan granites are usually richer in dark minerals and the Chuwa granite has a significant amount of biotite in it. Classifying the Chuwa granite as a North Himalayan granite implies that it is sourced from Greater Himalayan sequence rocks (e.g. Guo and Wilson, 2012). The Chuwa granite is interpreted to have exhumed through a combination of southward extrusion and folding of the North Himalayan antiform, combined with erosion and tectonic exhumation along a postulated South Tibetan detachment farther to the north. The
characterization of the Chuwa granite as a North Himalayan granite implies that the North Himalayan antiform is potentially influencing the observable geology near the study area.

Three distinct structural domains are defined: Domain I in the Chuwa Khola, Domain II in the Gurla Mandhata core complex region, and Domain III along the southern edge of the Gurla Mandhata core complex and the Chuwa Khola (Fig. 5.8). In the Chuwa Khola and the upper Karnali Valley (Domain I), the dominant shear sense is top-to-the-south/southwest with partial melting interpreted at ca. 18 Ma. In the Gurla Mandhata core complex and the Xiao Gurla complex (Domain II), the sense of shear is dominantly top-to-the-west-directed. The age of monazite crystallization in the central part of the Gurla Mandhata core complex has been documented between ca. 35 Ma and 16 Ma (Godin et al., 2021). In order to account for these different tectonic domains, I propose that there must be a N-S oriented zone between the Gurla Mandhata core complex and the Chuwa Khola where strain is partitioned, referred to as the strain partitioning boundary at ~ 82°0’E (Fig. 5.8). The top-to-the-south reverse sense of shear in the Chuwa Khola (Domain I) is overprinted by ductile activity along the West Nepal fault system in Domain III (Fig. 5.8).

The proposed ~ N-S strain partitioning boundary at ~ 82°0’E coincides with other significant along-strike variations observed in west Nepal, such as microseismicity and earthquake hypocenters (e.g. Murphy et al., 2014; Harvey et al., 2015; Silver et al., 2015; Soucy La Roche and Godin, 2019), thickness of the Himalayan metamorphic core (e.g. Fan and Murphy, 2020), and changes in across-strike topographic profiles (e.g. Harvey et al., 2015). These changes spatially coincide with the location of the Lucknow inherited Indian basement fault (Godin et al., 2019; Soucy La Roche and Godin, 2019).
6.2 Unanswered questions and future research directions

The protolith of the metamorphic rocks within the Chuwa Khola is still unknown. The protoliths of the Greater Himalayan sequence and the Lesser Himalayan sequence have contrasting ages, which can be assessed with Sm-Nd isotope analyses. In the Himalaya, $\epsilon_{Nd(0)}$ values below -19 are assigned to the Lesser Himalayan sequence, whereas values above -19 are typically Greater Himalayan sequence (e.g. Murphy, 2007; Godin et al., 2021). Differentiating the metamorphic rocks in the Chuwa Khola as either Greater Himalayan sequence or Lesser Himalayan sequence will help understand the overall geometry of the eastern limit of the Gurla Mandhata core complex (Fig. 5.8). Therefore, I suggest Sm-Nd isotope analyses be done on samples from the Chuwa Khola. The same samples used for U-Th/Pb monazite petrochronology can be used as there are still large hand samples, in addition to a range of other hand samples from the Chuwa Khola in the archives of the Queen’s Tectonics Research Laboratory. The timing of exhumation of the rocks in the Chuwa Khola is also still unknown. It has been predicted that exhumation occurred within the last 7 Ma (Fig. 5.9E). This hypothesis should be tested, using thermochronology, for the rocks in the Gurla Mandhata core complex, Chuwa Khola, and the Xiao Gurla.

The Chuwa granite is defined as a North Himalayan granite, allowing for interpretations to be made about the source and the exhumation history of the Chuwa granite. If the Chuwa granite is in fact a North Himalayan granite, then structural mapping to the east and north of the Chuwa Khola should reveal a domal geometry (both south and north dipping foliations) in the Chuwa granite. I therefore suggest that structural mapping be undertaken to explore north of the surface exposure of the Chuwa Khola. Furthermore, I suggest that Sm-Nd analyses be carried out on the Chuwa granite to test the melt source. North Himalayan granites should only show traces of Greater Himalayan sequence source rocks, whereas High Himalayan leucogranites would show traces of both Greater and Lesser Himalayan sequence source rocks (e.g. Guo and Wilson, 2012).

The question still remains if the Chuwa granite does in fact connect with the Mugu granite to the east. I suggest that preliminary site investigation be conducted using Google Earth and complementary satellite imagery. Advances in remote sensing technology and satellite data have allowed for the mapping of the Himalayan granites, applied to domes along the North Himalayan antiform (e.g. Watts and Harris, 2005; Larson et al., 2010; Wang et al., 2020). These
principles can be applied to the Chuwa granite to determine the extent of this granite body. I further suggest that in conjunction with remote sensing technology, geologic mapping be conducted to search for the eastern limit of the Chuwa granite. This could prove very significant as large batholiths are fertile targets for Tungsten-Tin skarn deposits in the Himalaya (e.g. Cao et al., 2020).

The nature of the proposed strain boundary at ~ 82°0’E remains unclear. I suggest efforts be made to traverse across this proposed strain partitioning boundary to see if there are any observations that can support/test the nature and location. There is still significant area between the Gurla Mandhata core complex and the Chuwa Khola that remains unmapped where I predict to see the eastern termination of the dilational jog, manifest as east plunging lineations, high angle active normal faults, and/or seismic activity. The presence of active structures can be tested with tectonic geomorphology, microseismicity, and stress modeling. In addition to mapping, seismic profiles across this strain partitioning boundary would add enormous value to the understanding of what is occurring in the subsurface. A seismic reflection study has already been conducted on the western limit of the Gurla Mandhata core complex where the Main Himalayan thrust was imaged (Gao et al., 2016). A seismic study on the eastern limit of the Gurla Mandhata core complex would therefore complement this study.

The location of the South Tibetan detachment with respect to the study area is also still unclear. Therefore, I suggest exploring for any record of the South Tibetan detachment to the north of the study area. Lastly, the question also remains as to whether the proposed strain partitioning boundary at ~ 82°0’E extends farther south and connects with features in the foreland (e.g. Soucy La Roche and Godin, 2019). In order to investigate this, preliminary studies should be done using Google Earth to locate field areas around 82°0’E where offset surface features or distinct surface geology can be seen juxtaposed against one another. Targeted mapping in these areas can then be undertaken to find more evidence for a strain partitioning boundary at ~ 82°0’E.
REFERENCES


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Appendix A

Field station locations and structural measurements

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Structure</th>
<th>Azimuth</th>
<th>Dip/Plunge</th>
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<td>Foliation</td>
<td>289</td>
<td>24</td>
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<td>AM-01</td>
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<td>E 81°53.698’</td>
<td>Foliation</td>
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<td>22</td>
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<td>Foliation</td>
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<td>50</td>
</tr>
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<td>AM-17</td>
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<td>E 82°02.447</td>
<td>Foliation</td>
<td>155</td>
<td>25</td>
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<tr>
<td>AM-17</td>
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<td>AM-19</td>
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<td>20</td>
</tr>
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<td>Fold Hinge</td>
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Appendix B

Supplementary monazite backscattered electron (BSE) imagery and x-ray microprobe chemical maps

AM-01
AM-01 mnz 05
AM-01 mnz 16
AM-08B
| Y  | U  | Co  | Ni  | Cu  | Fe  | Pb  | Zn  | Ca  | Mg  | Si  | Al  | Mn  | Cr  | Co  | Ni  | Cu  | Fe  | Pb  | Zn  | Ca  | Mg  | Si  | Al  | Mn  | Cr  |
|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1  | 2  | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | 21  | 22  | 23  | 24  | 25  | 26  | 27  | 28  | 29  |
| 30 | 31 | 32  | 33  | 34  | 35  | 36  | 37  | 38  | 39  | 40  | 41  | 42  | 43  | 44  | 45  | 46  | 47  | 48  | 49  | 50  | 51  | 52  | 53  | 54  | 55  | 56  | 57  | 58  |
| 59 | 60 | 61  | 62  | 63  | 64  | 65  | 66  | 67  | 68  | 69  | 70  | 71  | 72  | 73  | 74  | 75  | 76  | 77  | 78  | 79  | 80  | 81  | 82  | 83  | 84  | 85  | 86  | 87  | 88  |

AM-12 mnz 12
AM-15B mnz 07
AM-15B mnz 15
AM-15B mnz 17
AM-19B mnz 10
AM-19B mnz 14
AM-21B mnz 12
AM-21B mnz 14
AM-21B mnz 16
**Appendix B, Table 1.** A complete summary list of the monazite grains examined on the microprobe at Queen’s Facility for Isotope Research (QFIR).

<table>
<thead>
<tr>
<th>Thin Section</th>
<th>Monazites Probed</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM-01</td>
<td>01a, 01b, 02, 04, 05, 07, 08, 09, 10, 11, 13, 16, 17, 19 (14 total)</td>
</tr>
<tr>
<td>AM-08B</td>
<td>01, 02, 04, 05, 07, 08, 09, 10, 16 (9 total)</td>
</tr>
<tr>
<td>AM-11B</td>
<td>01/02, 03, 05 (3 total)</td>
</tr>
<tr>
<td>AM-12</td>
<td>01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 14, 15 (15 total)</td>
</tr>
<tr>
<td>AM-15B</td>
<td>01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 15, 16, 17, 18, 19 (18 total)</td>
</tr>
<tr>
<td>AM-19B</td>
<td>01, 02, 03, 04, 05, 06, 08, 09, 10, 12, 13, 14, 16, 20 (14 total)</td>
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<tr>
<td>AM-21B</td>
<td>01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 12, 13, 14, 15, 16, 17, 19, 22 (18 total)</td>
</tr>
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</table>
Appendix C

Supplementary monazite x-ray microprobe chemical maps (Y) with laser spot locations and Pb\textsuperscript{208}/Th\textsuperscript{232} dates (Ma)

The scale bar seen below applies to all figures that can be found in this appendix. The dark blue/green colours on the spectrum represent relatively low values of yttrium (Y) while the red/pink colours represent relatively high values of Y. Relative concentrations as opposed to absolute values have been used to allow comparison between samples.

Finally, the dates that are reported in these figures are in millions of years (Ma). The error shown is the 2 SE absolute values.

AM-01

AM-01 mnz 01a
AM-01 mnz 19

1: 18.9 Ma
2: 17.6 Ma
3: 20.4 Ma
4: 18.9 Ma
AM-08B mnz 16

1: 20.8 Ma
2: 20.6 Ma
5: 20.1 Ma
6: 19.1 Ma
7: 18.8 Ma
AM-12 mnz 15

1: 17.9 Ma
2: 18.5 Ma
3: 20.7 Ma
4: 21.5 Ma

Y —— 10 µm
AM-15B mnz 09

1: 17.4 Ma
2: 17.5 Ma
3: 17.9 Ma
4: 17.7 Ma
5: 17.9 Ma
6: 17.5 Ma
7: 18.0 Ma
8: 17.9 Ma
9: 17.5 Ma

AM-15B mnz 10

1: 18.2 Ma
2: 18.3 Ma
3: 18.7 Ma
4: 23.1 Ma
5: 21.4 Ma
6: 18.2 Ma
7: 20.3 Ma
AM-15B mnz 18

1: 17.1 Ma
2: 17.9 Ma
3: 17.8 Ma

Y  5 um
AM-19B

AM-19B mnz 01

1: 18.8 Ma 19: 18.9 Ma
2: 20.4 Ma 20: 19.3 Ma
3: 20.8 Ma 21: 18.9 Ma
4: 23.3 Ma 22: 40.1 Ma
5: 20.6 Ma 23: 341.6 Ma
6: 21.7 Ma 24: 24.9 Ma
7: 19.2 Ma 25: 19.6 Ma
8: 19.2 Ma 26: 21.1 Ma
9: 19.2 Ma 27: 19.4 Ma
10: 19.8 Ma 28: 189.1 Ma
11: 19.5 Ma 29: 209.5 Ma
12: 20.3 Ma 30: 21.5 Ma
13: 19.4 Ma 31: 22.9 Ma
14: 19.0 Ma 32: 19.5 Ma
15: 18.9 Ma 33: 20.5 Ma
16: 20.3 Ma 34: 21.0 Ma
17: 22.9 Ma 35: 20.3 Ma
18: 19.7 Ma 36: 18.7 Ma
AM-19B mnz 16

1: 17.9 Ma
2: 18.4 Ma
3: 18.6 Ma
### Appendix C, Table 1

A complete summary list of the monazite grains examined at the University of California, Santa Barbara (UCSB).

<table>
<thead>
<tr>
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<th>Monazites Probed</th>
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<td>01a, 01b, 02, 04, 05, 07, 08, 09, 10, 11, 13, 16, 17, 19 (14 total)</td>
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<td>AM-08B</td>
<td>01, 02, 04, 05, 07, 08, 09, 10, 16 (9 total)</td>
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<tr>
<td>AM-11B</td>
<td>01/02, 03 (2 total)</td>
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<td>AM-12</td>
<td>01, 02, 03, 04, 05, 06, 07, 08, 09, 11, 12, 13, 15 (13 total)</td>
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<td>AM-15B</td>
<td>01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 15, 16, 17, 18 (17 total)</td>
</tr>
<tr>
<td>AM-19B</td>
<td>01, 02, 03, 04, 05, 06, 08, 10, 12, 13, 14, 16 (12 total)</td>
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<td>AM-21B</td>
<td>01, 03, 05, 06, 08, 09, 10, 12, 13, 14, 15, 16, 17 (13 total)</td>
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**Appendix C, Table 2.** The laser spots that were excluded from analyses, and the reason for their exclusion.

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<th>Exclusion Justification</th>
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<td>Laser spot hit a zircon grain not a monazite</td>
</tr>
<tr>
<td>AM01-05-12</td>
<td>Laser spot half off the monazite</td>
</tr>
<tr>
<td>AM08B-07-1</td>
<td>Laser spot half off the monazite</td>
</tr>
<tr>
<td>AM08B-16-3</td>
<td>Laser spot on a crack</td>
</tr>
<tr>
<td>AM08B-16-4</td>
<td>Laser spot on a crack</td>
</tr>
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<td>AM12-05-1</td>
<td>Laser spot missed the monazite</td>
</tr>
<tr>
<td>AM12-12-1</td>
<td>Laser spot part not on the monazite</td>
</tr>
<tr>
<td>AM15B-01-16</td>
<td>Laser spot hit on a large crack</td>
</tr>
<tr>
<td>AM15B-01-18</td>
<td>Laser spot hit on a large crack</td>
</tr>
<tr>
<td>AM15B-04-5</td>
<td>Laser spot is partly on a large pit/crack of this monazite</td>
</tr>
<tr>
<td>AM15B-11-5</td>
<td>Laser spot hit on a crack</td>
</tr>
<tr>
<td>AM15B-11-7</td>
<td>Laser spot partly re-shot AM15B-11-6</td>
</tr>
</tbody>
</table>
Appendix D

Supplementary data tables

**TABLE D1.** Complete geochemical analysis results available in a separate Excel file.

**TABLE D2.** U-Th/Pb monazite petrochronology data available in a separate Excel file.