Plio-Pleistocene North-South and East-West Extension at the Southern Margin of the Tibetan Plateau

by

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A Dissertation Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy

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ARIZONA STATE UNIVERSITY
August 2012
ABSTRACT

The tectonic significance of the physiographic transition from the low-relief Tibetan plateau to the high peaks, rugged topography and deep gorges of the Himalaya is the source of much controversy. Some workers have suggested the transition may be structurally controlled (e.g. Hodges et al., 2001), and indeed, the sharp change in geomorphic character across the transition strongly suggests differential uplift between the Himalayan realm and the southernmost Tibetan Plateau. Most Himalayan researchers credit the South Tibetan fault system (STFS), a family of predominantly east-west trending, low-angle normal faults with a known trace of over 2,000 km along the Himalayan crest (e.g. Burchfiel et al., 1992), with defining the southern margin of the Tibetan Plateau in the Early Miocene. Inasmuch as most mapped strands of the STFS have not been active since the Middle Miocene (e.g., Searle & Godin, 2003), modern-day control of the physiographic transition by this fault system seems unlikely. However, several workers have documented Quaternary slip on east-west striking, N-directed extensional faults, of a similar structural nature but typically at a different tectonostratigraphic level than the principal STFS strand, in several locations across the range (Nakata, 1989; Wu et al., 1998; Hurtado et al., 2001). In order to explore the nature of the physiographic transition and determine its relationship to potential Quaternary faulting, I examined three field sites: the Kali Gandaki valley in central Nepal (~28°39′54″N; 83°35′06″E), the Nyalam region of south-central Tibet (28°03′23.3″N, 86°03′54.08″E), and the Ama Drime Range in southernmost Tibet (87°15′-87°50′E; 27°45′-28°30′N). Research in each of these
areas yielded evidence of young faulting on structures with normal-sense displacement in various forms: the structural truncation of lithostratigraphic units, distinctive fault scarps, or abrupt changes in bedrock cooling age patterns. These structures are accompanied by geomorphic changes implying structural control, particularly sharp knickpoints in rivers that drain from the Tibetan Plateau, across the range crest, and down through the southern flank of the Himalaya. Collectively, my structural, geomorphic, and thermochronometric studies confirm the existence of extensional structures near the physiographic transition that have been active more recently than 1.5 Ma in central Nepal, and over the last 3.5 Ma in south-central Tibet. The structural history of the Ama Drime Range is complex and new thermochronologic data suggest multiple phases of E-W extension from the Middle Miocene to the Holocene. Mapping in the accessible portions of the range did not yield evidence for young N-S extension, although my observations do not preclude such deformation on structures south of the study area. In contrast, the two other study areas yielded direct evidence that Quaternary faulting may be controlling the position and nature of the physiographic transition across the central Tibetan Plateau-Himalaya orogenic system.
This dissertation is dedicated to my Nana.

Although she was never able to see my passion for geology and teaching, I know she would be proud of me.

She always was.

I love you, I miss you, you are a part of me.
ACKNOWLEDGEMENTS

This work would not have been possible without the help from a small army of advisors, colleagues, logistical experts, mentors and friends. This has truly been an adventure, in every sense of the word, physically, emotionally, spiritually, academically. I suppose following your true passion always is.

To Kip Hodges – thank you for accepting me as your student when I was a serious gamble and I know, a struggle at times. I only hope to make you proud. Thank you for your patience, your insight, your guidance, and for allowing me to find who I am as a scientist.

To Kelin Whipple – you have the rare ability to offer critical academic advice while inspiring your students to improve their work and themselves as scientists at the same time. You truly care about your students. This does not go unnoticed. It was a great comfort at 2 am, when I doubted all my decisions to pursue this degree, to simply know that someone understood and cared.

To Thijs van Soest – I wouldn’t have been able to complete this degree without your help and endless patience teaching me how to pick the worst and most complicated apatites known to science. I owe my expertise on the complications of AHe to you. And the Nepal apatites.

To Brian Monteleone – the best field assistant and “voyage of discovery” leader EVER. Thank you, thank you, for everything, I can’t say it enough. I would also like to thank my other great field assistants: Byron “Fault finder” Adams and Matt Rossi, who listened to me about how to wear a camera in the field and was subsequently, albeit temporarily, kidnapped by Tibetans.
To Frances Cooper – my thank you to you is not making you edit this document. You’re welcome.

To Bhim and Bhairab of Earth’s Paradise Treks, Travels, and Geologistics in Nepal - you are the premier logistical team for geologic work and working with you was not only efficient and easy, but also a pleasure. Thanks also to Rinchin Goshampa of Tibet Wind Horse Adventures and our fabulous Tibetan crew, who may not have understood why we were picking up seemingly random chunks of rock, but who provided all we could need in the field anyway, including music, humor and the best yak fried rice in the Northern Hemisphere. Thank you Erchie Wang for securing us all the permits we needed to complete this exciting work. Fieldwork went smoothly in Tibet thanks to you.

To the Hamilton crew, Sarah, Kristy, Stef, & Amy, thank you for spending countless hours with me over coffee and sometimes tears. You were never shy with your “You got this!”’s, and your unearned belief in me. Thank you!

Finally, my parents, Tom and Judy, who have thoroughly supported and believed in me even when they didn’t know where I was going or what I was doing. Your unquestioning love and devotion to me has allowed me to pursue my dreams and follow a path I am truly passionate about.

Candace – you suffered right along with me in this degree, listening to me complain for years. I’m sure it was hard for you, and it meant the world to me.

And David. You made Phoenix almost tolerable and you made me happy.

Lastly, thank you to the National Science Foundation Tectonics Program (EAR0711140) for funding this work and making it all possible.
TABLE OF CONTENTS

| LIST OF TABLES | xii |
| LIST OF FIGURES | xiii |

CHAPTER

1 INTRODUCTION ................................................................. 1
   MOTIVATION ................................................................. 1
   APPROACH ................................................................. 6
     Chapter 2 ..................................................................... 7
     Chapter 3 ..................................................................... 7
     Chapter 4 ..................................................................... 8
   REFERENCES ..................................................................... 10

2 PLEISTOCENE NORTH-SOUTH EXTENSION AT THE HIMALAYAN CREST, DHULAGIRI HIMALAYA, CENTRAL NEPAL ......... 14
   ABSTRACT ..................................................................... 14
   INTRODUCTION ................................................................ 15
   REGIONAL SETTING ....................................................... 16
   STRUCTURAL CHARACTER OF THE ANnapurna AND DHULAGIRI DETACHMENTS ..................................... 17
     The Annapurna detachment ............................................. 17
     The Dhaulagiri detachment ............................................. 18
## Chapter 2

PREVIOUS THERMOCRONOLOGIC DATA PERTINENT TO DETACHMENT SLIP HISTORIES IN THE KALI GANDAKI VALLEY ................................................................. 20

(U-TH)/He THERMOCRONOLOGY .................................................................. 22

Methods ........................................................................................................ 22

New (U-Th)/He thermochronologic data ...................................................... 24

TECTONIC IMPLICATIONS ............................................................................ 25

REFERENCES ................................................................................................ 29

FIGURE CAPTIONS ....................................................................................... 34

## Chapter 3

EVIDENCE FOR PLIO-PLEISTOCENE NORTH-SOUTH EXTENSION AT THE SOUTHERN MARGIN OF THE TIBETAN PLATEAU, NYALAM REGION ................................................................................. 42

ABSTRACT ..................................................................................................... 42

INTRODUCTION ............................................................................................. 43

STRUCTURAL AND PHYSIOGRAPHIC TRANSITIONS IN THE HIMALAYA ............................................................................................................ 46

CHARACTER OF THE NYALAM REGION, SOUTH-CENTRAL TIBET ..................................................................................................................... 50

Geologic setting ............................................................................................ 51

Geomorphic setting ...................................................................................... 53

THERMOCRONOLOGY ................................................................................ 54
CHAPTER 3

Previous thermochronologic work.................................54
New zircon and apatite (U-Th)/He cooling ages ............56
Methods........................................................................56
Results...........................................................................57

DISCUSSION OF LOW-TEMPERATURE
THERMOCRONOLOGIC DATA...........................................58
TESTING ALTERNATE MODELS........................................62
CONCLUSIONS ...............................................................67
REFERENCES ..................................................................69
FIGURE CAPTIONS ........................................................76

4 MULTI-PHASE EXHUMATION OF THE AMA DRIME RANGE,
SOUTHERN TIBET: EVIDENCE FOR DISTINCT DUCTILE AND
BRITTLE DEFORMATIONAL PHASES ALONG ANAGOLOUS
SHEAR DOMAINS..............................................................95
ABSTRACT ......................................................................95
INTRODUCTION ..............................................................96

THE AMA DRIME RANGE AND EXTENSIONAL FAULTING IN
THE HIMALAYAN-TIBETAN OROGENIC SYSTEM.............97

Structural setting............................................................103

N-DIRECTED EXTENSION ON THE STFS ....................103
DUCTILE EXTENSION ON THE ADSZ AND THE NRSZ ......104

viii
4

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRITTLE EXTENSION ON THE HIGH-ANGLE ADF AND NRF</td>
<td>105</td>
</tr>
<tr>
<td>Geomorphology</td>
<td>106</td>
</tr>
<tr>
<td>THERMAL HISTORY OF THE REGION</td>
<td>107</td>
</tr>
<tr>
<td>Timing of STFS deformation</td>
<td>107</td>
</tr>
<tr>
<td>Timing of ductile deformation on the Ama Drime shear zones</td>
<td>108</td>
</tr>
<tr>
<td>Low-temperature thermal history</td>
<td>109</td>
</tr>
<tr>
<td>Methods</td>
<td>109</td>
</tr>
<tr>
<td>Results</td>
<td>110</td>
</tr>
<tr>
<td>DISCUSSION OF GEOCHRONOLOGIC AND THERMOCRONOLOGIC DATA</td>
<td>113</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>119</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>122</td>
</tr>
<tr>
<td>FIGURE CAPTIONS</td>
<td>129</td>
</tr>
</tbody>
</table>

5 MIOCENE TO QUATERNARY TECTONIC EVOLUTION OF THE HIMALAYAN RANGE CREST: A SUMMARY OF NEW INSIGHTS INTO YOUNG N-DIRECTED EXTENSION AND DEFORMATION AT THE SOUTHERN MARGIN OF THE TIBETAN PLATEAU

BACKGROUND AND MOTIVATION

THE CLASSICAL DEPICTION OF HIMALAYAN TECTONICS AND DEVIATIONS FROM THIS APPROACH

ix
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Out-of-sequence thrust faulting</td>
<td>151</td>
</tr>
<tr>
<td>Lesser Himalayan duplex</td>
<td>153</td>
</tr>
<tr>
<td>N-S extensional structures</td>
<td>153</td>
</tr>
<tr>
<td>Additional important tectonic features of the orogenic system:</td>
<td></td>
</tr>
<tr>
<td>E-W extension</td>
<td>155</td>
</tr>
<tr>
<td>THE ANnapurna-DHAulagiri Himalaya OF CENTRAL NEPAL</td>
<td>157</td>
</tr>
<tr>
<td>Structural evolution of the Annapurna-Dhaulagiri Himalaya</td>
<td>158</td>
</tr>
<tr>
<td>EXHUMATION OF THE GREATER HIMALAYAN SEQUENCE</td>
<td>159</td>
</tr>
<tr>
<td>S-DIRECTED OUT-OF-SEQUENCE THRUSTING</td>
<td>161</td>
</tr>
<tr>
<td>EAST-WEST EXTENSION</td>
<td>162</td>
</tr>
<tr>
<td>LATE-STAGE N-DIRECTED EXTENSION AT THE STRUCTURAL LEVEL OF THE STFS IN THE KALI Gandaki VALLEY</td>
<td>163</td>
</tr>
<tr>
<td>QUATERNARY N-DIRECTED EXTENSION</td>
<td>164</td>
</tr>
<tr>
<td>Constraints on the timing of deformational events across central Nepal</td>
<td>168</td>
</tr>
<tr>
<td>CONSTRAINTS ON EARLY MIocene deformational EVENTS</td>
<td>168</td>
</tr>
<tr>
<td>CONSTRAINTS ON MIDDLE-LATE MIocene deformational EVENTS</td>
<td>169</td>
</tr>
<tr>
<td>CONSTRAINTS ON QUATERNARY deformational EVENTS</td>
<td>171</td>
</tr>
<tr>
<td>THE NYALAM REGION OF SOUTH-CENTRAL TIBET</td>
<td>174</td>
</tr>
</tbody>
</table>
DEFORMATIONAL EVENTS IN THE NYALAM REGION AND

CONSTRAINTS ON THE TIMING OF EVENTS ..................................174

EARLY TO MIDDLE MIocene EXHUMATION OF THE GREATER

HIMALAYAN SEQUENCE ..........................................................174

EAST-WEST EXTENSION – TIMING UNKNOWN .........................175

PLIO-PLEISTOCENE N-DIRECTED EXTENSION ..........................176

THE AMA DRIME REGION OF SOUTHERNMOST TIBET ........177

EARLY TO MIDDLE MIocene EXHUMATION OF THE GREATER

HIMALAYAN SEQUENCE ..........................................................179

MIDDLE TO LATE MIocene EXTENSION ON N-S STRIKING

DUCTILE SHEAR ZONES ..........................................................179

PLIO-PLEISTOCENE EXTENSION ON BRITTLE FAULTS ........181

TECTONIC RECONSTRUCTIONS ...........................................182

Early to Middle Miocene (~22 - 15 Ma) .................................183

Middle to Late Miocene (~14 - 5 Ma) .................................183

Pliocene (~5 – 3 Ma) ..........................................................184

Quaternary ..........................................................185

TECTONIC IMPLICATIONS ....................................................186

FUTURE WORK ..........................................................189

REFERENCES ..........................................................191

FIGURE CAPTIONS ....................................................200
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1.</td>
<td>Apatite and zircon (U-Th)/He data from the Kali Gandaki (A) and Myagdi Khola (B) valleys in central Nepal</td>
<td>36</td>
</tr>
<tr>
<td>3-1.</td>
<td>Approximate sample locations for previous thermochronologic data</td>
<td>81</td>
</tr>
<tr>
<td>3-2.</td>
<td>Apatite and zircon (U-Th)/He data from the Nyalam region</td>
<td>82</td>
</tr>
<tr>
<td>3-2.</td>
<td>Thermochronologic closure temperatures</td>
<td>85</td>
</tr>
<tr>
<td>4-1.</td>
<td>Apatite and zircon (U-Th)/He data from the Ama Drime region</td>
<td>132</td>
</tr>
<tr>
<td>5-1.</td>
<td>Correlation of deformational events between field sites</td>
<td>202</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Geologic and structural map of central Nepal</td>
<td>39</td>
</tr>
<tr>
<td>2-2</td>
<td>Structural and thermochronologic maps of the Kali Gandaki valley (a), and the Myagdi Khola valley (b)</td>
<td>40</td>
</tr>
<tr>
<td>2-3</td>
<td>Comparison of sample cooling age and sample structural distance from the Dhaulagiri detachment</td>
<td>41</td>
</tr>
<tr>
<td>3-1</td>
<td>Geologic and structural map of the Himalaya and simplified structural cross-section</td>
<td>86</td>
</tr>
<tr>
<td>3-2</td>
<td>Relief and geomorphic map of the Himalaya</td>
<td>87</td>
</tr>
<tr>
<td>3-3</td>
<td>Geologic and structural map of the Nyalam region</td>
<td>88</td>
</tr>
<tr>
<td>3-4</td>
<td>Plot of thermochronologic cooling ages versus distance</td>
<td>89</td>
</tr>
<tr>
<td>3-5</td>
<td>Cooling histories for sub-sections of the Nyalam region</td>
<td>90</td>
</tr>
<tr>
<td>3-6</td>
<td>Cooling rates through time for sub-sections of the Nyalam region</td>
<td>91</td>
</tr>
<tr>
<td>3-7</td>
<td>Geomorphic map of the Nyalam region</td>
<td>92</td>
</tr>
<tr>
<td>3-8</td>
<td>Ama Drime Range fluvial knickpoints</td>
<td>93</td>
</tr>
<tr>
<td>3-9</td>
<td>Channel steepness compared to predicted model uplift patterns</td>
<td>94</td>
</tr>
<tr>
<td>4-1</td>
<td>Geologic, and structural map of the central Himalaya</td>
<td>141</td>
</tr>
<tr>
<td>4-2</td>
<td>Geologic, structural and thermochronologic map of the Ama Drime region, southernmost Tibet</td>
<td>142</td>
</tr>
<tr>
<td>4-3</td>
<td>Cross-sections across the ADSZ/ADF and NRSZ/NRF</td>
<td>143</td>
</tr>
<tr>
<td>4-4</td>
<td>ZHe and AHe age-elevation data for the Ama Drime region</td>
<td>144</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>4-5. Thermochronologic cross-section of the Ama Drime Range</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td>4-6. Geochronologic and thermochronologic implied thermal history for the exterior of the Ama Drime Range</td>
<td>146</td>
<td></td>
</tr>
<tr>
<td>4-7. Geochronologic and thermochronologic implied thermal history for the interior of the Ama Drime Range</td>
<td>147</td>
<td></td>
</tr>
<tr>
<td>5-1. Geologic and structural map of the central Himalaya and idealized cross-section through central Nepal</td>
<td>203</td>
<td></td>
</tr>
<tr>
<td>5-2. Geologic and structural map of central Nepal</td>
<td>204</td>
<td></td>
</tr>
<tr>
<td>5-3. Stratigraphic correlations across central Nepal</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>5-4. Correlation of deformational events across central Nepal</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>5-5. Cross-sectional tectonic reconstruction for the central Himalaya</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>5-6. Correlation of deformational events across the central Himalaya</td>
<td>208</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

MOTIVATION

The Himalaya and Tibetan Plateau form one of the most dramatic features on Earth, comprising a high elevation plateau spanning more than 2.5 million km\(^2\) and a mountain range large and high enough to disrupt global climate. Yet, despite more than a hundred years of focused research, the mechanics governing the Tibetan-Himalayan orogenic system remain enigmatic.

Perhaps one of the least understood features within the orogen is the southern margin of the Tibetan Plateau, which defines the boundary between the physiographic plateau and the Himalayan range, and is marked by three unique and poorly understood characteristics. Firstly, the southern plateau margin represents an abrupt morphologic shift from the expansive, high elevation but low-relief Tibetan Plateau to the high relief and rugged topography of the Himalayan realm and will herein be referred to as “physiographic transition 1” or PT\(_1\), following Hodges et al. (2001). Early workers noted a sharp change marking the start of deep gorges on major transverse river systems that drain perpendicularly through the Himalaya from the Tibetan Plateau to the Gangetic Plain (e.g. Wager, 1937). This change in fluvial character manifests as a series of prominent knickpoints at the approximate location of PT\(_1\) across the central Himalaya (e.g., Hodges et al., 2001). One model explains the current margin as
simply a transient stage in the long-term norward retreat of a plateau margin that
was located tens of kilometers to the south in the Early Miocene (e.g. Masek et
al., 1994). An alternate model, put forth by Cattin and Avouac (2000) and
supported by Lavé and Avouac (2001), links the fluvial character to the south of
PT₁ to passive uplift over a ramp in the basal décollement beneath the Himalayan
orogenic wedge. Neither of these models place PT₁ within the current tectonic
framework of the orogenic system, but instead imply the margin is simply
passive. In contrast, a third hypothesis, that of Hodges et al. (2001), links PT₁ to
active deformation. The coupling of surface morphology and tectonics has been
well established (e.g. Wobus et al., 2006; Ouimet et al., 2009; DiBiase et al.,
2010; Kirby and Whipple, in press), and information about differential uplift
patterns can be extracted from the fluvial network and surface landforms. Hodges
et al. (2001) suggested the change in fluvial character is indicative of high uplift
rates to the south of PT₁ compared to the north, consistent with active, or recently
active, faulting at the location of PT₁.

The southern plateau margin also marks the boundary between two crustal-scale,
but contrasting, strain fields: E-W extension accommodated by N-S striking
normal faults that are pervasive across the southern Tibetan Plateau between PT₁
and the Indus-Tsangpo suture zone, and N-directed convergence that is dominant
through the Himalayan zone as a result of ongoing collision between India and
Eurasia. Exactly how far south the N-S striking faults extend into the Himalayan
realm is still in question; all such faults that have been studied in detail either
terminate before reaching PT$_1$ or are truncated by east-west striking extensional faults before crossing into the Himalayan zone (for example, the Dangarzong fault - the principle growth structure for the Thakkhola graben in central Nepal - trends right up to the main Himalayan arc, but is truncated by a young east-west striking extensional fault near the range crest (Hurtado et al., 2001)). In some locations, such as the Ama Drime Range of southernmost Tibet, N-S striking structures cut >30 km into units making up the core of the Himalaya, the Greater Himalayan sequence (e.g., Jessup et al., 2008), although whether these faults are truncated by young structures linked to N-S convergence is uncertain. As is the case with PT$_1$, the mechanism accommodating the transition from one strain field to another is the subject of much debate with some workers describing the transition as diffuse across a wide zone (e.g., Murphy et al., 2010), while others interpret the transition to be sharp and suggest it could be accommodated by a discrete structure (e.g., Hodges et al., 2001).

Finally, the trace of the South Tibetan fault system, a family of predominately top-to-the-north normal faults representing a major lithologic, structural and metamorphic discontinuity that can be traced for nearly 2,000 km along strike near the crest of the range (e.g., Burchfiel et al., 1992), falls roughly in line with the southern plateau margin (Hodges et al., 2001). The STFS has a well-constrained early history, initiating ~ 20-23 Ma (Harrison et al., 1995; Nazarchuk, 1993; Hodges et al., 1996; Coleman, 1996, 1998; Searle et al., 1999), and along with contemporaneous slip on the structurally lower Main Central thrust system
(MCTS), is thought to be responsible for the exhumation of the Greater Himalayan sequence (e.g., Hodges et al., 1992). The duration of activity on the STFS is uncertain; the majority of models for the evolution of the orogenic system limit slip on the fault system to prior to the Middle Miocene (e.g., Searle and Godin, 2003), although Quaternary displacement on strands linked to the system has been documented in several regions spanning a distance of more than 600 km across the central Himalaya (Nakata, 1989; Wu et al., 1998; Hurtado et al., 2001).

The three features described above closely coincide and can be mapped continuously across the central Himalaya within tens of kilometers of each other, not just in one location, but for great distances along strike. This close correspondence prompted Hodges et al. (2001) to suggest a possible causal relationship wherein the STFS acts as an accommodating structure at the strain discontinuity with Quaternary extension setting the form and location of PT$_1$, much as it likely did on the Early-to-Middle Miocene. Early displacement on the STFS was contemporaneous with slip on the MCTS (e.g., Hodges et al., 1992), and coupled with orogenic focused precipitation, resulted in extrusion of a “channel” between the two fault systems (commonly referred to as the Channel Flow-Extrusion hypothesis) (e.g., Beaumont et al., 2001; Hodges et al., 2006 and references therein). Hodges et al. (2001) suggested that continued or episodic activity on the STFS supports the continuation of a similar mechanical process, where the STFS serves as the upper boundary to an extruding channel. One
important requirement for this hypothesis is recently active slip on the fault systems bounding the channel. Quaternary slip on the MCTS is debated; however, thrust faulting at the lower boundary of the channel does not have to be accommodated by the MCTS, but can occur on any structurally lower thrust system, such as the Main Boundary fault system or the Main Frontal thrust system, fault systems known to have been active through the Pliocene and Quaternary (Nakata, 1989; Yeats et al., 1992; Meigs, 1995; DeCelles et al., 1998; Lavé & Avouac, 2000), respectively. The second requirement for this scenario is the existence of active, or recently active extension at PT$_1$, something that, as mentioned earlier, is poorly constrained and controversial.

Given this, an important question emerges: has significant, range-wide extension occurred on the STFS, or similar type faults, during the Quaternary? Regardless of whether the hypothesis of Hodges et al. (2001) is valid, the question of Quaternary activity at PT$_1$ has implications for evaluating all of the models discussed above, as well as for possibly determining the mechanism(s) responsible for the tectonics and topography of the southern margin of the Tibetan Plateau. In the work herein, I examine the nature of the southern plateau margin in three different field sites, central Nepal, south-central Tibet and southeast Tibet, in an attempt to unravel the tectonic significance, or lack thereof, of PT$_1$, and the possible relationship between the strain discontinuity and active faulting there. Since recently active extensional faulting is a strict requirement for the validity of several models while potentially falsifying others, the work focuses on exploring
the evidence supportive of, or against, active deformation at the southern margin of the Tibetan Plateau using a combination of detailed geologic and structural mapping, tectonic geomorphology with an emphasis on the fluvial network, and low-temperature thermochronology.

**APPROACH**

Chapters 2-5 summarize the results of my examination of the southern margin of the Tibetan Plateau in three field sites across the range: the Kali Gandaki and Mygadi Khola valleys in the Annapurna and Dhaulagiri Himalaya of central Nepal, the Tibet-Nepal border region south of Nyalam in south-central Tibet, and the Ama Drime Range and nearby Kharta and Dinggye valleys in southernmost Tibet, ~ 70 km east of Mt. Everest. Field site locations were chosen on the basis of several characteristics: (1) previously documented Quaternary slip on extensional faults, either E-W striking (central Nepal) or N-S striking (central Nepal; Ama Drime Range) in order to constrain the magnitude and timing of that displacement; (2) prominent knickpoints on major transverse rivers as they cross PT₁, a fact suggestive of possible recently active faulting (all three field sites); and (3) close coincidence of N-S striking and E-W striking extensional faults (central Nepal; Ama Drime range) in order to determine the sequence and timing of the orthogonally orientated faulting.
Chapter 2

Hurtado et al. (2001) documented Quaternary brittle displacement on the local strand of the STFS, the Annapurna detachment in the Kali Gandaki valley of central Nepal, and constrained the timing of displacement to more recently than 17.2 ka as the Annapurna detachment truncates the Late Pleistocene N-S striking Dangardzong fault. The amount of displacement during this late-stage activity remained unconstrained. In order to resolve this, a thermochronologic transect was completed across the Annapurna detachment in both the Kali Gandaki valley and the adjacent Myagdi Khola valley ~ 20 km to the west. Although our (U-Th)/He apatite and zircon cooling age data (AHe and ZHe, respectively) allow only minor slip on the Annapurna detachment in the last 3.5 Ma, I describe a second low-angle extensional fault in the hanging wall of the Annapurna detachment, the Dhaulagiri detachment, first documented by Hurtado (2002), which is through-going between the valleys. AHe cooling ages across the Dhaulagiri detachment reveal a dramatic cooling age discontinuity in both valleys, and show that the fault has accommodated > 6.5 km of displacement, with activity continuing into the Pleistocene.

Chapter 3

In order to determine whether young extensional faulting is significant in the evolution of the orogenic system, it is necessary to determine if similar young N-S extensional faults exist across the range crest. As mapping discrete fault traces either in the field or remotely is difficult in this region, to evaluate this, I
examined the nature of the physiographic transition where it is accessible and well-defined in the Nyalam valley of south-central Tibet. On the Bhote Kosi River in the Nyalam region, as is common with large transverse rivers, a prominent knickpoint exists at a location that separates zones of high channel steepness, high local relief and high hillslope gradients to the south from a sharp decrease in all those characteristics to the north. A detailed remote sensing analysis of the region reveals several geomorphic indicators suggesting fault-control on the knickpoint, as well as what appears to be a N-dipping fault outcropping in the high glaciated peaks to the east, trending in line with the knickpoint. A combination of previous (Wang et al., 1998; Wang et al., 2006; Wang et al., 2010) and new thermochronologic data reveal a drastic change in cooling rate at ~ 3.5 Ma. The simplest explanation, consistent with the known thermal and geomorphic data, is differential uplift across a young (Pliocene-Quaternary) extensional fault setting the location and nature of the physiographic transition in this location.

Chapter 4

The Ama Drime Range is a N-S striking transverse feature jutting north of the Himalayan arc, bound on the E and W by high-angle normal faults that display clear Quaternary scarps and are underlain by similarly oriented low-angle ductile shear zones. Previous researchers have interpreted the brittle and ductile shear zones to be related in a single phase of progressive extensional exhumation (e.g., Jessup et al., 2008; Kali et al., 2010; Langille, et al., 2010). To examine the
relationship between the brittle and ductile deformational phases, I coupled existing U-Pb, $^{40}\text{Ar} / ^{39}\text{Ar}$, and AHe thermochronologic data with newly obtained ZHe cooling ages, a chronometer with a closure temperature near the critical range over which the ductile to brittle transition occurs (Stoeckhert et al., 1999). Additionally, AHe samples were collected across the region, both in the footwall of hanging walls of the range-bounding faults to assess differential exhumation on the structures. A compilation of available data and a comparison of footwall and hanging wall thermal histories suggests a multi-phase deformational history on the ductile and brittle shear zones, rather than simple progressive exhumation. Ductile deformation initiated shortly after cessation of the STFS, ~ 11-10 Ma. On the eastern shear zone, rapid exhumation through the 300°C isotherm was followed by a significant period of relatively slow cooling before ZHe data records significant exhumation in the Pliocene. Coupled with structural data, I interpret these data to record two distinct deformational phases. Ductile deformation was longer lived on the western margin, and although two deformational phases is allowed within the data, exhumation on the west may have been progressive through the ductile-brittle domains. Although evidence for young east-west striking, N-directed extensional structures was not found within the limitation of the field site, as PT$_1$ could lie to the south of the studied region, we cannot conclusively rule out its existence at this time.
REFERENCES


CHAPTER 2

PLEISTOCENE NORTH-SOUTH EXTENSION AT THE HIMALAYAN
CREST, DHAULAGIRI HIMALAYA, CENTRAL NEPAL

ABSTRACT

N-S–directed extension on the South Tibetan fault system (STFS) played a critical role in the Himalayan-Tibetan orogenic system in the Miocene Period, but it is generally assumed that orogen-perpendicular extension on this fault system ceased prior to Pliocene time. Previous structural mapping in the Annapurna Range of central Nepal by Hurtado et al. (2001) revealed evidence of Quaternary activity on one N-directed extensional detachment – likely a reactivated basal strand of the STFS – but the amount of displacement on that fault could not be tightly constrained. New (U-Th)/He thermochronology of apatite and zircon from samples collected across the fault suggest no more than a few hundred meters of throw. However, new mapping in this region and in the nearby Dhaulagiri Himalaya has revealed the existence of a new low-angle detachment – described here as the “Dhaulagiri detachment” – sub-parallel to, but structurally higher than, the basal detachment of the STFS. (U-Th)/He apatite and zircon cooling ages across this structure, combined with previous $^{40}$Ar/$^{39}$Ar muscovite and zircon fission track data from the region, demonstrate that the Dhaulagiri detachment likely initiated after significant Miocene STFS activity and has accommodated N-S extension as recently as the Early Pleistocene, with a total Quaternary throw (inferred from the thermochronologic data) of 6.5 km or more.
INTRODUCTION

Although often depicted as the type example of continent-continent collision, the Himalayan-Tibetan orogenic system exhibits several unique characteristics not easily explained by simple critical-wedge models (e.g. Dahlen, 1990). One such feature is the South Tibetan fault system (STFS), a family of top-to-the-north extensional structures located near the crest of the Himalaya (e.g. Burchfiel et al., 1992) (Figure 2-1). The STFS has been linked to exhumation of the metamorphic core of the Himalaya and can be traced for nearly 2000 km along the range crest, suggesting its major significance in the evolution of the orogen (Hodges, 2000).

Across the Himalaya, the initiation age of the STFS is remarkably consistent and well constrained to the Early Miocene (Harrison et al., 1995; Nazarchuk, 1993; Hodges et al., 1996; Coleman, 1996; Coleman & Hodges, 1998; Searle et al., 1999), with ductile activity continuing to the Mid-Miocene in some locations (Edwards & Harrison, 1997; Wu et al., 1998). However, many north-dipping extensional faults that have been mapped as part of the STFS exhibit evidence of late-stage brittle deformation of uncertain age; in most cases only a maximum age of slip is constrained by the fact that the faults in question cut footwall leucogranite bodies of Miocene age. Although some workers have argued for at least limited STFS slip as late as the Quaternary (Wu et al., 1998; Hodges et al., 2001; Hurtado et al., 2001), most currently-popular models restrict activity on the system to the Early-to Mid-Miocene (e.g. Cattin & Avouac, 2000; Beaumont et al. 2001; DeCelles et al., 2001). This paper reports the results of a study aimed at
constraining the post-Miocene activity of well exposed and plausibly Quaternary N-dipping extensional structures that have been mapped previously as part of the STFS in the Annapurna and Dhaulagiri Himalaya of central Nepal (Figure 2-1). We present here, for the first time, thermochronologic evidence for significant displacement on one of these structures more recently than 1.5 Ma.

REGIONAL SETTING
The detachments of the STFS collectively represent a major tectonostratigraphic boundary in the Himalaya. They separate high-grade metamorphic rocks and leucogranites of the Greater Himalayan Sequence footwall from relatively unmetamorphosed Tibetan Sedimentary Sequence hanging wall rocks (Figure 2-1). In central Nepal, the STFS appears to have a complex history including polyphase brittle and ductile deformation on fault strands at several structural levels (Coleman, 1996; Hodges et al., 1996; Vannay & Hodges, 1996; Searle & Godin, 2003). In the Kali Gandaki valley, the basal strand of the STFS is mapped as the Annapurna detachment (Brown and Nazarchuk, 1993), with ductile deformation restricted to the Early Miocene (ca. 22-23 Ma) (Nazarchuk, 1993; Godin et al., 2001). Superimposed brittle deformation fabrics mapped along the fault trace were originally thought to be of Miocene age as well, but Hurtado et al. (2001) demonstrated that the Annapurna detachment – or, perhaps more properly, a late-stage, reactivated segment of the detachment – truncated the principal Quaternary growth fault of the Thakkhola graben (the N-S-striking Dangardzong fault of Colchen, 1980; Figure 2-1) and must have experienced some amount of
Quaternary slip. The inability of Hurtado et al. (2001) to tightly constrain the magnitude of recent slip on the structure was a major motivation for the present study. In addition, we document a structurally higher detachment in the Kali Gandaki and Myagdi Khola valleys, previously only described in the unpublished dissertation of J. Hurtado (2002). We have traced it across the upper Dhaulagiri massif in between the valleys using high-resolution SPOT satellite imagery, and thus refer to it as the Dhaulagiri detachment.

STRUCTURAL CHARACTER OF THE ANNAPURNA AND DHAULAGIRI DETACHMENTS

The Annapurna detachment

Prototypical exposures of the Annapurna detachment occur low in a tributary catchment on the west side of the Kali Gandaki valley (~28°39’54”N; 83°35’06”E) (Figure 2-2A). Footwall amphibolite facies schists and gneisses, with deformed leucogranitic dikes and sills, contain a distinctive mylonitic fabric that is subparallel to the discrete fault surface itself. S-C fabrics and stretching lineations in these rocks indicate normal-sense (hanging wall to the NE) displacement during ductile deformation (Brown and Nazarchuk, 1993; Godin et al., 1999). Within about 5m of the fault surface, the footwall rocks are intensely brecciated, indicative of brittle deformation. Above the brecciated fault zone lie biotite grade calc-silicate rocks and meta-psammites of the Tibetan Sedimentary Sequence, which also contains mylonitic fabrics related to the detachment.
The Annapurna detachment also crops out to the west in the Myagdi Khola valley, ca. 1 km N of Shaulagiri (28°40′23.8″N; 83°25′08.5″E) (Figure 2-2B). The immediate footwall there consists of a highly sheared injection complex of amphibolite facies augen orthogneisses of the Greater Himalayan Sequence with roughly 50% (by volume) leucogranitic dikes and sills. Leucogranitic intrusions persist across the detachment into the lower grade calc-schists of the Tibetan Sedimentary Sequence found in the hanging wall. Mylonitic fabrics, associated with ductile deformation, similar to those observed in the Kali Gandaki valley are well developed in the footwall and hanging wall in the Myagdi Khola valley (Larson & Godin, 2009). Brittle deformation is evidenced by a narrow brecciated zone along the fault that dips ca. 20° to the north.

The Dhaulagiri detachment

The Dhaulagiri detachment is exposed on the west side of the Kali Gandaki valley in a newly excavated road cut ~ 2.5 km north of the village of Larjung (28°42′22.2″N; 83°38′02.9″E) (Figure 2-2A). The fault crops out entirely within the Tibetan Sedimentary Sequence as a discrete shallow-dipping (~25°) fault plane. Footwall rocks are greenschist-facies calcareous gneisses and schists whereas hanging wall rocks are essentially unmetamorphosed limestones. Deformed Miocene leucogranitic dikes and sills (Godin et al., 1999) are relatively abundant in the footwall but are absent from the hanging wall. Both hanging wall and footwall rocks are brecciated in a zone extending up to 200 m away from the discrete fault. Footwall rocks display a strong brittle-ductile shear fabric that dips
subparallel to the fault plane, as well as a down-dip stretching lineation, but no definitive shear sense indicators were found near the detachment in the Kali Gandaki valley. Hanging wall rocks are deformed into macroscale folds that can clearly be traced along the high peaks of Dhaulagiri, Nilgiri and Annapurna (Bordet et al., 1971; Colchen et al., 1981; 1986; Brown & Nazarchuk, 1993; Godin et al., 1999, Godin, 2003). These folds are all truncated by the Dhaulagiri detachment.

Since the Dhaulagiri detachment marks the boundary between north-dipping footwall rocks and flat to shallowly south-dipping hanging wall rocks, the continuation of the structure can be traced relatively easily for a short distance to the east into the Annapurna Range before disappearing into a region of large Quaternary landslides. These very young cover units obscure the region of probable intersection between the Dhaulagiri detachment and the Dangardzong fault, but the traces of the latter structure to the NNE and SSW suggest right-lateral separation of it by the Dhaulagiri detachment (Figure 2-2A).

On the west side of the Kali Gandaki valley, the Dhaulagiri detachment can be clearly traced in the high cliffs above the valley, although the trace is partially obscured by landslide deposits on this side of the valley as well. The dip of the fault there (~ 20°N) is shallower than the dip of the hanging wall sedimentary units, and the fault strikes toward, but does not join, the Annapurna detachment before its trace is lost in the snowfields of Dhaulagiri. We speculate that the fault
forms the boundary of a broad flat region south of the high peak of Dhaulagiri before cutting across to the Myagdi Khola valley to the west.

In the Myagdi Khola valley, the detachment crops out as a discrete brittle-ductile shear zone in the glacial valley just north of Italian base camp (28°42’01.3’’N; 83°26’06.4’’E) (Figure 2-2B). The detachment crops out entirely within calc-schists of the Tibetan Sedimentary Sequence, but as in the Kali Gandaki valley, footwall rocks exhibit a strong foliation sub-parallel to the fault plane while hanging wall rocks display no such ductile fabric. The fault is marked by a ca. 2-m thick zone of fine-grained breccia that dips ~20°N. Subjacent footwall rocks contain well-developed mylonitic fabrics, and pervasive leucogranitic dikes in the footwall exhibit asymmetric extensional boudinage. These and other shear-sense indicators, as well as a ~062/28 stretching lineation, are consistent with hanging wall down-to-the-NE (normal sense) slip. Similar to the Kali Gandaki valley, small discordant leucogranite dikes are disrupted into the zone of brittle deformation, but no leucogranite dikes intrude above the fault zone.

PREVIOUS THERMOCHRONOLOGIC DATA PERTINENT TO DETACHMENT SLIP HISTORIES IN THE KALI GANDAKI VALLEY

Previously published $^{40}$Ar/$^{39}$Ar muscovite data for samples collected on either side of the Annapurna and Dhaulagiri detachments in the Kali Gandaki valley are illustrated in Figure 2-2. Samples collected from the footwall of the Annapurna detachment yielded plateau and isotope correlation dates ranging from 13.0 ± 0.3
to 15.5 ± 0.3 Ma (imprecision quoted at the 2σ confidence level) with no systematic variation as a function of structural level (Vannay and Hodges, 1996; Godin et al., 2001). Two samples from the Tibetan Sedimentary Sequence between the Annapurna and Dhaulagiri detachments were somewhat younger (11.8 ± 0.4 and 12.7 ± 0.4 Ma), a finding that Godin et al. (2001) tentatively attributed to late-stage hydrothermal alteration related to extension of the Thakkhola graben. Perhaps more significantly, Godin et al. (2001) reported a single ⁴⁰Ar/³⁹Ar muscovite isotope correlation date of 18.1 ± 0.7 Ma for a sample collected from the hanging wall of the Dhaulagiri detachment as we have subsequently mapped it in the Kali Gandaki valley. This date is most readily explained by disruption of the ⁴⁰Ar/³⁹Ar muscovite cooling age pattern in the valley by the Dhaulagiri detachment subsequent to 15.5-13.0 Ma. Such an explanation is supported by published fission-track dates from the region. Several zircon fission-track cooling ages from the core of the Greater Himalayan Sequence in the Kali Gandaki are Pliocene or younger (Arita & Ganzawa, 1997), consistent with zircon and apatite fission-track dates from these structural levels in other drainages within the Annapurna Range (Arita & Ganzawa, 1997; Blythe et al., 2007). In contrast, Crouzet et al. (2007) reported zircon fission track ages of 13.3-15.5 Ma from within the Dhaulagiri detachment hanging wall in the Kali Gandaki valley (Figure 2-2).
(U-Th)/He THERMOCHRONOLOGY

We elected to explore the possibility of cooling age discontinuities across the Annapurna and Dhaulagiri detachments further using the apatite and zircon (U-Th)/He thermochronometers (AHe and ZHe, respectively).

Methods

Apatite and zircon were separated using standard gravimetric and magnetic techniques prior to hand picking under a microscope. Only crystals that were euhedral and optically clean – visibly free of inclusions – were selected for analysis. (This last criterion was especially important for picking acceptable apatites; many of the apatite grains in the samples contained high-birefringence micro-inclusions that may be high U-Th minerals, such as zircon or monazite which would render any dates obtained from them effectively uninterpretable.)

The grains were measured prior to analysis in order to enable corrections of the raw (U-Th)/He dates for alpha ejection effects assuming spatially uniform concentrations of U and Th$^{1-3}$. In most cases, single grains of apatite or zircon were analyzed. In some cases, $^4$He measurements on apatite grains were below detection limits, and multi-grain aliquots were analyzed. Multigrain samples are denoted by an “m” after individual grain numbers in Table 2-1.

Samples were encapsulated in Pt or Nb and loaded into a stainless steel sample-holder for $^4$He measurements on an ASI Alphachron in the Noble Gas Geochronology and Geochemistry Lab (NG$^3$L) at ASU. Three age standards
(Durango apatite for apatite samples and Durango apatite and Fish Canyon zircon for zircon samples) and 2 blanks (empty Pt or Nb tubes) together with 20 unknowns were loaded on the sample-holder for each Alphachron run. After pumping down the laser chamber to ultra-high vacuum, helium was extracted from each sample using a 45 Watt, 980 nm diode laser. The gas was spiked with $^3\text{He}$ and cleaned of any reactive gases by exposure to a hot SAES NP-10 getter. The purified gas was analyzed on a Balzers Prisma QMS 200 quadrupole equipped with a Channeltron electron multiplier. $^4\text{He}$ blanks averaged around $0.045 \pm 0.009$ fmol for both apatite and zircon analyses. Total $^4\text{He}$ analytical imprecision for the analyses reported here range from 2.36 to 2.56% (2$\sigma$).

After completion of the Alphachron run, unknowns, age standards, and blanks were extracted from the vacuum system for U and Th analysis by inductively coupled, plasma-source mass spectrometry using a Thermo X series quadrupole instrument in the W.M. Keck Foundation Laboratory for Environmental Geochemistry at ASU. Encapsulated apatite grains were prepared for isotope dilution analysis using 25 $\mu$l of 50% HNO$_3$ containing $\sim$15 ng of $^{235}\text{U}$ and $\sim$5 ng of $^{230}\text{Th}$ (used as a U and Th spike), following the procedure of Evans et al. (2005). Zircon dissolution requires concentrated HF, HNO$_3$ (also containing a $^{235}\text{U}$ and $^{230}\text{Th}$ spike), and HCl and was completed with Parr digestion vessels to reach high temperature and pressure as outlined by ref 3. Total procedural blanks were estimated based on analysis of the empty Pt and Nb tubes used to determine the $^4\text{He}$ blanks. Average Pt tube blanks for the apatite procedure were $0.65 \pm 0.08$
pg (2 SE) U and 0.41 ± 0.10 pg (2 SE) Th, while average Nb tube blanks are higher at 2.6 ± 0.6 pg U and 2.4 ± 1.4 pg Th. Propagated U and Th analytical uncertainties typically ranged from 3 to 5% (2σ).

“Raw ages” were calculated using an iterative process using blank-corrected He, Th, and U values. These values were then corrected for alpha-ejection and the results are reported as “Corrected Ages” in Table 2-1. Following standard procedures in most (U-Th)/He laboratories, we made no attempt to quantify or propagate an uncertainty associated with the alpha-ejection correction. Replicate analyses of Durango fluorapatite apatite in the NG3L yield an average apparent age of 31.77 ± 2.50 (2σ) Ma or 31.77 ± 0.14 Ma (2 SE; n=359). A similar exercise for eighty Fish Canyon zircon crystals yielded an apparent age of 27.92 ± 0.32 Ma (2 SE).

New (U-Th)/He thermochronology data
Samples for this study were collected along transects from the hanging wall of the Dhaulagiri detachment to the footwall of the Annapurna detachment in both the Kali Gandaki and Myagdi Khola valleys. Samples collected in both the Kali Gandaki and Myagdi Khola valleys from the footwall and hanging wall of the Annapurna detachment – but within the footwall of the Dhaulagiri detachment – yield Pliocene to Pleistocene (U-Th)/He dates (Figures 2-2 and 2-3). ZHe dates range from 2.36 ± 0.20 Ma to 3.28 ± 0.24 Ma, while AHe dates range from 0.29 ± 0.10 Ma to 1.380 ± 0.081 Ma. We see no systematic correlation between apparent
ages and structural position or elevation, and conservatively interpret the results to indicate cooling of these structural levels through nominal ZHe closure temperatures (ca. 170-190°C: Reiners, 2004) between 2-4 Ma and nominal AHe closure temperatures (ca. 70-90°C: Farley, 2000; van Soest et al., 2011) between 0.1 and 1.5 Ma.

Although U- and Th-rich accessory phases are far less prevalent in the hanging wall units of the Dhaulagiri detachment, we were able to separate datable (but low U+Th) apatites from one hanging wall sample from each of the two valleys. The results are consistent but dramatically different from AHe results for structurally lower samples: 9.2 ± 2.0 Ma for the Myagdi Khola sample and 10.8 ± 2.5 Ma for the Kali Gandaki sample. Apparently, the immediate hanging wall of the Dhaulagiri detachment cooled through the ca. 70-90°C interval in Late Miocene time, nearly 10 million years earlier than the detachment footwall (Figures 2-2 and 2-3).

TECTONIC IMPLICATIONS

Although the Annapurna detachment in the Kali Gandaki valley is thought to have experienced Quaternary slip, the lack of ZHe or AHe cooling age gradients across the detachment trace demonstrates that the magnitude of that slip was too small to result in a cooling age discontinuity within the limitations of the precision of our AHe and ZHe dates. In contrast, the Dhaulagiri detachment corresponds to an order-of-magnitude change in bedrock AHe cooling ages. The juxtaposition of
much younger (Pleistocene) footwall ages beneath older (Late Miocene) hanging wall ages is consistent with Pleistocene normal-sense displacement along the detachment as the cause of the cooling age pattern disruption (Figure 2-3). We employed the AHe data from the Myagdi Khola valley (where the sampling transect covers a larger range of elevation to estimate a minimum vertical throw of 6.5 km in the last 1.5 Ma on the Dhaulagiri detachment (method from McInnes et al., 1999). Inasmuch as the hanging wall thermal history is constrained by only one sample, this estimate should be taken as preliminary and more work in the region would be necessary to increase our confidence in the result.

Previous work in the Annapurna range established the presence of multiple generations of top-to-the-north, low-angle detachments; several of the identified structures are similar in character to the Dhaulagiri detachment (Caby et al., 1983; Hodges et al., 1996, Coleman, 1996; Hurtado et al., 2001; Godin, 2003; Searle & Godin, 2003). Historically, these structures have been considered as part of the STFS, and many of the “subsidiary” structures of uncertain age in the hanging wall of the basal STFS detachment were presumed to be of Miocene age, only slightly younger than the establishment of the STFS (e.g., Hodges et al., 1996; Searle et al., 2003). Our results demonstrate that at least one of the larger-displacement structures with those characteristics – the Dhaulagiri detachment - is Pleistocene in age.
We anticipate that a structure with this significance would be regional in extent and candidate correlative detachments have been mapped to the east by Hodges et al. (1996), Coleman (1996), and Searle & Godin (2003). In particular, the Machhapuchhare detachment in the Modi Khola drainage is a low-angle, top-to-the-north normal fault entirely within calcareous rocks of the Tibetan Sedimentary sequence, truncates leucogranite melts in its footwall and has crustal-scale folds in its hanging wall, and represents a distinct metamorphic discontinuity, much like the Dhaulagiri detachment (Hodges et al., 1996). Attempts to trace the structure further east toward the well-studied Marsyandi valley using satellite imagery have been unsuccessful; we believe this is largely because the fault strikes parallel to the general fall line of topography, dips only shallowly to the north, and juxtaposes rocks with similar outcrop characteristics. The Phu detachment in the Marsyandi valley (Coleman, 1996; Searle & Godin, 2003) also exhibits similar structural characteristics, but is demonstratively folded, and therefore seems unlikely to be Quaternary in age (Godin et al., 2006). The region to the west of the Myagdi Khola is poorly explored, but the Dhaulagiri Southwest fault of Nakata (1989) is an east-west striking, top-to-the-north normal fault with Quaternary displacement obvious by fault-cut moraines, large triangular facets, sag ponds and offset streams. The structural characteristics of the Dhaulagiri Southwest fault are not well known, and our attempt to extend its known trace using remote sensing imagery cannot unequivocally demonstrate or preclude its correlation with the Dhaulagiri detachment. However, the known length of the Dhaulagiri Southwest fault suggests significant displacement and regional
significance, and makes it a likely candidate for westward continuation of the Dhaulagiri detachment.

The new thermochronologic data presented here, coupled with previous thermochronologic and structural data from central Nepal, indicate that N-S directed extension near the crest of the range played a role in both the Miocene and the Quaternary tectonic evolution of the Himalaya. Whether or not this extension has continued more or less continuously or episodically over the past twenty million years remains unknown.
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FIGURE CAPTIONS

Table 2-1.

A: Apatite (U-Th)/He data from the Kali Gandaki and Myagdi Khola valleys, Dhaulagiri Himalaya, central Nepal

B: Zircon (U-Th)/He data from the Kali Gandaki and Myagdi Khola valleys, Dhaulagiri Himalaya, central Nepal

Figure 2-1.

Simplified geologic and structural map of the central Nepal, modified from Colchen et al., 1986, Vannay & Hodges, 1996, Hurtado et al., 2001, Godin, 2003. Inset map shows location. Boxes show the extent of maps in Figure 2-2 for the Kali Gandaki valley (a - right) and Myagdi Khola valley (b - left). Abbreviations: AD – Annapurna detachment, DD – Dhaulagiri detachment, DZ – Dangardzong fault, KSZ – Kalopani shear zone, MCT – Main Central thrust.

Figure 2-2.

Structural and thermochronologic map of the Kali Gandaki (a) and Myagdi Khola (b) valleys in central Nepal overlain on 90-m DEM shaded relief, modified from Colchen et al., 1986; Vannay & Hodges, 1996; Hurtado et al., 2001; Godin, 2003. In the Kali Gandaki valley, zircon fission track ages from Crouzet et al. (2007), $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite ages from Godin et al. (2001) and Vannay & Hodges (1996). Abbreviations: AD - Annapurna detachment; DD – Dhaulagiri detachment; DZ - Dangardzong fault; KSZ - Kalopani shear zone.
Figure 2-3.

Simplified geologic cross-sections with sample elevations for the Kali Gandaki and Myagdi Khola transects. No vertical exaggeration. Sample symbols are the same as Figure 2-2. Right side of figure illustrates the relationship between structural distance from the Dhaulagiri detachment and cooling age. Abbreviations: AD – Annapurna detachment; DD – Dhaulagiri detachment.
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<td>0.005 g</td>
<td>0.002 g</td>
<td>0.001 g</td>
<td>0.0005 g</td>
<td>0.0002 g</td>
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<td>0.0002 g</td>
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**Sample Description**

- **Sample**: 34.5% Alcohol (v/v)
- **Total Volume**: 2100 ml
Figure 2-1
Figure 2-2
Figure 2-3
CHAPTER 3

EVIDENCE FOR PLIO-PLEISTOCENE NORTH-SOUTH EXTENSION AT THE SOUTHERN MARGIN OF THE TIBETAN PLATEAU, NYALAM REGION

ABSTRACT

The southern edge of the Tibetan Plateau is defined by an abrupt change from the low-relief Tibetan Plateau to the high peaks, rugged topography and deep gorges of the Himalaya. Although the location of this physiographic transition roughly coincides with the predominately normal-sense South Tibetan fault system (STFS), most mapped strands of the STFS ceased activity by the Middle Miocene, and the mechanism controlling the modern plateau boundary has been the subject of much debate. While numerous studies have utilized thermochronology to examine the exhumation history of the Himalaya, few have done so with respect to variations across the Himalaya-Tibetan Plateau transition. In this work, we examine the nature of the transition where it is accessible and well-defined in the Nyalam valley of south-central Tibet. We employ several new and existing thermochronologic datasets (with a closure temperature range of ~ 70°C - 300°C) in conjunction with river incision patterns inferred by the longitudinal profile of the Bhote Kosi River, which flows roughly perpendicular to the transition. The results reveal a change in cooling rate at ~ 3.5 Ma at a location corresponding to a pronounced river knickzone representing a sharp increase in river gradient, and presumably incision rate (a proxy for rock uplift). Margin retreat models cannot
explain the coincidence of these two discontinuities, and uplift over a midcrustal structural ramp does not account for the abruptness of the change. The simplest explanation, consistent with available thermal and geomorphic data, is differential uplift across a young (Pliocene-Quaternary) normal fault, 3.5 km south of Nyalam. Drawing on observations elsewhere along the Tibetan Plateau-Himalaya transition we hypothesize that similar normal faults may define this profound physiographic transition.

INTRODUCTION
The Himalayan mountain chain is arguably the most dramatic landscape on Earth, marked by nine of the ten highest peaks in the world, yet active deformation within the Himalayan realm is widely believed to be restricted to thrusting at the range front, ~150 km south of the high peaks (e.g. DeCelles et al., 1998; Cattin & Avouac, 2000; Lavé & Avouac, 2000; DeCelles et al., 2001; Bollinger et al., 2006). In Early and Middle Miocene time, the range crest was the locus of deformation along a family of normal and transcurrent structures collectively referred to as the South Tibetan fault system (STFS; Hodges, 2000). It seems likely that STFS deformation helped define the active southern margin of the Tibetan Plateau at that time. Most Himalayan researchers hold that the STFS became inactive after the Middle Miocene (e.g. Searle and Godin, 2003), but that perspective presents an interesting conundrum: if the STFS played an active role in defining the plateau margin in Miocene time, and if the STFS has been inactive for over ten million years, is it merely coincidence that the modern plateau margin
(herein referred to as “physiographic transition 1” or PT$_1$, following Hodges et al. (2001)) still lies within only a few tens of kilometers of the trace of the STFS? Or, as hypothesized by Hodges et al. (2001), is it possible that the modern plateau margin remains the locus of recent deformation?

Three fundamentally different interpretations of how PT$_1$ was formed and is maintained have been proposed by various researchers. Masek et al. (1994) and Wang et al. (2010) proposed that the current PT$_1$ reflects headward erosional retreat of a steep plateau margin created by Miocene deformation. In contrast, Cattin and Avouac (2000) and Lavé and Avouac (2001) argued that uplift patterns in the Higher Himalaya do not require active faulting within the range but can be explained by uplift over a ramp-flat geometry in the Himalayan Sole thrust; extrapolation of the ramp-flat model to the north predicts a transition similar to PT$_1$ as uplift rates drop with distance from the mid-crustal ramp. A third interpretation was that of Hodges et al. (2001) and Hurtado et al. (2001) who suggested that PT$_1$ is controlled by top-to-the-north normal faulting on young strands of the STFS. These models make distinct predictions about the spatial and temporal patterns of exhumation associated with the plateau margin, and also imply distinct geomorphic attributes of PT$_1$. In order to test their relative merits, we examine here the thermochronologic, structural and geomorphic characteristics of the margin in the Nyalam region (~86°E) of south-central Tibet (Figure 3-1).
To constrain the thermal history of the southern plateau margin and determine if PT$_1$ represents a marked change in exhumation, we employ a multi-chronometer transect, combining new (U-Th)/He apatite and zircon dates with previously published $^{40}$Ar/$^{39}$Ar and apatite and zircon fission track data. Additionally, we utilize the well-established relationship between surface morphology and tectonics (e.g. Wobus et al., 2006a; Ouimet et al., 2009; DiBiase et al., 2010; Kirby and Whipple, in press) to extract information about differential uplift patterns from the fluvial network and surface landforms. Our analysis follows the example of Wobus et al. (2003; 2006b), who used patterns of landscape morphology with emphasis on analysis of river profiles in conjunction with detrital thermochronology to document an abrupt break in exhumation rate across the physiographic transition that marks the southern limit of the High Himalaya (PT$_2$). Wobus et al. (2003; 2006b) interpreted this coincidence of a dramatic break in exhumation rate with an abrupt physiographic transition as evidence for active out-of-sequence thrust faulting. Although their structural interpretation has been controversial, the identification of an abrupt change in rock uplift and exhumation rate precisely co-located with the physiographic transition has been widely accepted (e.g., Cattin & Avouac, 2000; Bollinger et al., 2006; Robert et al., 2009; Herman et al., 2010). We apply similar tectonic geomorphology tools and a more complete thermochronometric analysis to PT$_1$, specifically to test the relative merits of the three alternative models for the origin and maintenance of PT$_1$ outlined above.
The Nyalam region, and the Bhote Kosi River that cuts across it is an excellent location for this study given that: 1) PT$_1$ is marked by a dramatic knickpoint on the Bhote Kosi longitudinal river profile and a corresponding abrupt increase in local relief, hillslope gradients, and river channel steepness to the south; 2) a north-south trending transect across PT$_1$ is accessible along the Nepal-Tibet Friendship Highway; 3) the Miocene-aged strand of the STFS is highly dissected by young faults and cannot be contributing to the location and nature of PT$_1$ allowing us to eliminate one potentially contributing influence; and 4) several extant thermochronologic datasets can be combined with our new data to constrain the thermal history of the region over a wide range of temperatures and time scales. Here we ask the questions: Is there a change in exhumation rate and history across PT$_1$ as suggested by landform morphology? What structural configuration and deformation pattern best explains the spatial and temporal exhumation patterns? Can PT$_1$, and the associated exhumation patterns, be accounted for by erosional retreat of a Miocene plateau margin as suggested by some researchers (Masek et al., 1994; Wang et al., 2010) or is an additional mechanism required to explain the thermal and geomorphic character of PT$_1$?

STRUCTURAL AND PHYSIOGRAPHIC TRANSITIONS IN THE HIMALAYA

The Himalaya are frequently described in terms of tectonostratigraphic units separated by major north-dipping fault systems (e.g. Gansser, 1964; Le Fort, 1975) (Figure 3-1). The southernmost of these boundaries is the Main Frontal
thrust system, which separates the Gangetic Plains of India to the south from the
Subhimalayan fold and thrust belt to the north and defines the southern extent of
deformation related to the orogenic system. The Main Frontal thrust system is
coincident with the southernmost physiographic transition along the Himalaya
(PT3 of Hodges et al., 2001) (Figure 3-1B), and is believed to represent the
surface expression of the Himalayan Sole thrust, the basal structure along which
the majority of Himalayan shortening has been accommodated since at least
Pliocene time (e.g., Lavé & Avouac, 2000). Quaternary activity is obvious from
deformed river terraces and alluvial fans (Nakata, 1989; Yeats et al., 1992; Lavé
& Avouac, 2000). The Subhimalayan zone is bound to the north by the Main
Boundary thrust system, active in the late Miocene-Pliocene (Meigs, 1995;
DeCelles et al., 1998), which serves as the southern boundary to the Lesser
Himalayan sequence, an 8-10 km thick series of metasedimentary phyllites and
schists (Gansser, 1964; Colchen et al., 1986; Schelling, 1992).

North of the Lesser Himalayan sequence lies the Main Central thrust system
(MCTS) which lies in the vicinity of the second physiographic transition
previously mapped in the Himalaya, PT2 (Figure 3-2). The MCTS is the
structurally highest major thrust system in the Himalayan proper, and the oldest
major Cenozoic structure, with an apparent initiation age of ~ 23-20 Ma (Hubbard
& Harrison, 1989; Hodges et al., 1996). The duration of activity on the MCTS is
unknown but Late Miocene-Pliocene displacement has been documented on out-
of-sequence faults linked to the system in several locations across the range
(Macfarlane et al., 1992; Harrison et al., 1997; Catlos et al., 1999). Wobus et al. (2006b) showed that although PT$_2$ maps near the MCTS in some locations, the two deviate significantly in others. A distinctive feature of PT$_2$ is that the transition marks a pronounced change in fluvial character on major rivers crossing the transition (Seeber and Gornitz, 1983; Lavé & Avouac, 2001; Wobus et al., 2003; 2006b; Meade, 2010). The consistent and abrupt shift from steep, rivers and a high relief, rocky, landscape north of PT$_2$ to much less steep rivers and low relief, soil mantled topography to the south is thought to indicate an abrupt increase in rock uplift rate north of PT$_2$, although whether this activity is due to surface-breaking structures (e.g., Wobus et al., 2003) or growth of a subsurface duplex (e.g. Bollinger et al., 2006) remains controversial (e.g., Robert et al., 2009; Herman et al., 2010; Godard and Burbank, 2011).

The MCTS serves as the lower boundary to the Greater Himalayan sequence, a laterally continuous sequence of upper-amphibolite facies pelitic, calc-silicate, and augen ortho- gneisses often referred to as the “metamorphic core” of the Himalaya (e.g. Le Fort, 1975). Further north, the Greater Himalayan sequence is also bound above by a major fault system, the predominantly low-angle, north-dipping, normal-sense South Tibetan fault system (STFS). The STFS marks a structural, lithologic and metamorphic discontinuity that extends nearly 2,000 km along strike, juxtaposing the high-grade metamorphic rocks of the Greater Himalayan sequence against the low-grade to unmetamorphosed passive margin deposits of the Tibetan Sedimentary sequence to the north. The minimum age of
initiation of the STFS is constrained by U-Pb monazite and zircon dates from deformed and undeformed leucogranite dikes that cross-cut it; for example, U-Pb dates from the central Himalaya demonstrate initiation by ~22-23 Ma (Harrison et al., 1995; Nazarchuk, 1993; Hodges et al., 1996; Coleman, 1996, 1998; Searle et al., 1999) with ductile activity continuing on some strands until 12-13 Ma (Edwards & Harrison, 1997; Wu et al., 1998). Early Miocene displacement on the STFS was coeval with displacement on the MCTS, resulting in the tectonic exhumation of the Greater Himalayan sequence. As is the case for the MCTS, the total duration of activity on the STFS is poorly constrained, with some workers limiting slip on the system to before the Middle Miocene (e.g. Searle & Godin, 2003), while others have proposed continued or episodic activity into the Quaternary (e.g. Hodges et al., 2001; Hurtado et al., 2001). Many previously mapped strands of the STFS are demonstratively inactive (e.g. Burchfiel et al., 1992), yet workers have documented Pleistocene activity on subparallel extensional faults near the crest of the range in several locations (Nakata, 1989; Wu et al., 1998; Hurtado et al., 2001; McDermott et al., submitted-A). The STFS is located near the northernmost physiographic transition in the Himalaya, PT₁, which defines the crest of the range and separates the high elevation but low-relief Tibetan Plateau from the high relief, rugged topography of the Himalayan realm (Figure 3-2). Similar to PT₂, PT₁ is characterized by abrupt river knickpoints that define the southern edge of the Tibetan Plateau (Figure 3-2). The combination of the geomorphic character of PT₁, its rough coincidence with the STFS, and Quaternary activity on structures near the range crest linked to the STFS, suggest
that PT\textsubscript{1} may be a locus of neotectonic activity. Consistent with this hypothesis, a recent study in central Nepal found significant Pleistocene slip on a N-directed extensional fault, located structurally near and subparallel to the basal STFS, at the approximate location of PT\textsubscript{1} (McDermott et al., submitted-A). However, PT\textsubscript{1} does deviate significantly in some areas from the trace of the Miocene STFS, in a relationship similar to that which exists between PT\textsubscript{2} and the MCTS trace. One such deviation is in the Nyalam area; PT\textsubscript{1} is well defined in a narrow zone immediately south of Nyalam, while the Miocene STFS lies in a relatively low relief zone ~ 25 km to the north where it is highly dissected by younger high angle normal faults (Figure 3-3).

CHARACTER OF THE NYALAM REGION, SOUTH-CENTRAL TIBET

For a closer look at PT\textsubscript{1}, we elected to explore the geomorphic and structural nature of the region surrounding the Bhote Kosi River between the towns of Nyalam and Zhangmo/Zham near the border of Tibet and Nepal. A geologic transect was studied from immediately north of the border to 8 km north of Nyalam (Figure 3-3). South of Nyalam, the Bhote Kosi River flows through one of the most dramatic gorges in the Himalaya; due to the extreme relief within the gorge and the political sensitivity in this border region, our transect was restricted to outcrops along the Friendship Highway. Although this was somewhat limiting, the deep road cuts provide good access to unweathered rocks in the near-vertical cliffs above the river.
Geologic setting

Our transect lies entirely within the high-grade para- and augen ortho-gneisses of the Greater Himalayan sequence and associated leucogranitic intrusive bodies (Figure 3-3). The base of that tectonostratigraphic unit, corresponding to the Main Central thrust, lies ~6 km to the south of the border (the southern limit of our transect). The unit’s upper boundary, the STFS, lies ~15 km to the north of our transect, but we refer in this paper to some thermochronologic data from previous studies that extended farther upsection to the immediate footwall of the STFS (Wang et al 1998; Wang et al., 2006; Wang et al., 2010). The southern reach of the field site consists of a thick unit of sillimanite paragneiss overlain by a fine-grained two-mica gneiss. These basal units display evidence for several ductile deformational events, which were contemporaneous with amphibolite facies metamorphism (Hodges et al., 1993). The most prevalent, and oldest, deformation event, $D_{CN-1}$, is characterized by a penetrative foliation ($S_1$) and associated mineral lineation ($L_1$ – defined by the alignment of kyanite, muscovite, and sedimentary quartz aggregates). Shear sense indicators associated with $D_{CN-1}$ and later ductile deformational events, are consistent with top-to-the-south thrusting and have been linked to displacement on the Main Central thrust system (Burg et al., 1984; Burchfiel et al., 1992; Hodges et al., 1993). Near Nyalam, migmatitic gneisses are prevalent and are crosscut by at least two generations of anatetic leucogranites. The structurally lowest leucogranite bodies exhibit weak deformational fabrics consistent with southward thrusting (Burg et al., 1984).
North of our field site, metamorphic units show a greater diversity; in addition to gneissic and leucogranitic lithologies, they include pelitic and psammitic schists, metaquartzites, marbles, and calc-silicate rocks. Leucogranite dikes and sills are prevalent throughout. The basal structure of the STFS in this transect – the Nyalam detachment of Burchfiel et al. (1992) – separates greenschist facies hanging wall Ordovician carbonate rocks from amphibolite facies footwall mafic dolostones, metaquartzites, and psammitic schists of the Cambrian Rouqiecun Group (Myrow et al., 2009). In the top ~1000 m of the footwall, S1 has been transposed into a well-developed S-C fabric (S3-C3 of Hodges et al., 1993) with prominent stretching and mineral lineations (L3). Shear sense indicators including mica “fish” and asymmetric augen structures, are consistent with northward displacement on the overlying STFS (Burg et al., 1984; Burchfiel et al., 1992; Hodges et al., 1993). Leucogranites cross-cutting the Rouqiecun Group also exhibit planar fabrics and shear sense indicators consistent with north-directed slip (Burg et al., 1984). Ductile activity on the Nyalam detachment occurred ~ 17 - 15 Ma (Schärer et al., 1986; Burchfiel et al., 1992; Dougherty et al., 1998) and the consequent tectonic denudation resulted in rapid cooling of the footwall sequence in the Middle Miocene (Wang et al., 2006). Structurally higher strands of the STFS in this area are dissected by north-south striking normal faults of uncertain age and displacement (Burchfiel et al., 1992; Wang et al., 2006), and thus, STF-strands have not experienced significant slip in recent times. Despite this, expansive Holocene hot spring deposits have been mapped near the STFS (Zentmyer et al., 2008), suggesting elevated geothermal gradients and active fluid
flow along avenues of high hydraulic conductivity along these older fault strands. This hydrothermal activity may be related to active deformation at PT\textsubscript{1} as discussed below.

*Geomorphic setting*

The region immediately surrounding and to the north of Nyalam, although once glaciated, is relatively flat, with low hillslope gradients, low relief, and low channel gradients. The Bhote Kosi River flows in a wide, alluviated, sometimes braided, channel. Approximately 1 km south of Nyalam, there is a sudden and dramatic change in the topography. The local relief increases sharply as the river dives into an exceptionally deep gorge; the river channel narrows, steepens, and becomes entrenched in a bedrock canyon, forming near-vertical cliffs at the river and very high hillslope gradients throughout. This change corresponds to a pronounced knickpoint, manifested as a distinct convexity in the longitudinal river profile (Figure 3-2); the river and its tributaries remain steep for ~30 km downstream until it crosses PT\textsubscript{2}. We will refer to this steep reach of the river downstream of the knickpoint near Nyalam as the knickzone. The high relief zone to the south of the knickpoint is characterized by vegetated yet oversteepened cliffs, accessible only along the road cuts of the Friendship Highway. North of the knickzone, where hillslope gradients are low, the vegetative cover diminishes, but is replaced by thick glacial and fluvial deposits. In the knickzone itself, the steep topography is nearly entirely vegetated, and much of the bedrock is covered by large, recent landslides.
THERMOCHRONOLOGY

Several thermochronologic studies (Maluski et al., 1988; Wang et al., 1998; Wang et al., 2006; Wang et al., 2010), including this one, have been completed along the river gorge from the Tibet-Nepal border to north of the Miocene-aged strands of the STFS. Here we combine previous thermochronologic work with our new apatite and zircon (U-Th)/He cooling ages to define the thermal histories of rocks on either side of the physiographic transition.

PREVIOUS THERMOCHRONOLOGIC WORK

Wang et al. (2010) synthesized the results of several studies in the Nyalam region (Wang et al., 1998; Wang et al., 2006; Wang et al., 2010) to produce a densely sampled $^{40}$Ar/$^{39}$Ar biotite (BAr), apatite fission track (AFT), and zircon fission track (ZFT) thermochronologic transect extending from the STFS in the north to the Tibet-Nepal border at Zhangmo/Zham to the south (Table 3-1; Figure 3-3). Location data were not provided for reported samples in these previous studies; sample locations used in this study have been approximated using maps from Wang et al. (1998), Wang et al. (2006) and Wang et al. (2010), known outcrop locations, and road access to outcrops (Table 3-1). Maluski et al. (1988) and Wang et al. (2006) both reported BAr cooling ages from along similar transects; however, the data sets contradict each other south of the knickpoint. The results of Maluski et al. (1988) show a younging trend in cooling ages from 16-15 Ma north of Nyalam to less than 6 Ma near the Nepal border region; Wang et al. (2006) reported no such trend but instead showed that cooling ages consistently
cluster around 16-14 Ma along the entire transect (Figure 3-4). We make no attempt to resolve this conflict in the current work, but include the $^{40}\text{Ar}/^{39}\text{Ar}$ cooling age data from Wang et al. (2006) in our analysis as their work utilizes more up to date analytical techniques. The Wang et al. (2006) data reveal no discernable variation in BAr cooling ages along the transect, indicating that the entire Greater Himalayan Sequence homogeneously cooled through the $^{40}\text{Ar}/^{39}\text{Ar}$ biotite closure temperature ($\sim 300^\circ$C; Harrison et al., 1995) between 16-14 Ma. These data are consistent with BAr data from the Greater Himalayan sequence to the west in central Nepal (Vannay & Hodges, 1996; Coleman, 1998).

The results of two ZFT and AFT studies were summarized in Wang et al. (2010). These data show a cooling age gradient in both thermochronometers, with Middle Miocene ages in the immediate footwall of the STFS younging to Plio-Pleistocene ages in the south (Figure 3-4). These data are not easily explained by the known displacement histories of the MCTS and the STFS, and Wang et al. (2010) interpreted the cooling age patterns as recording climate-enhanced erosion of a topographic front that they argue was located 20-30 km to the south of its current position in the Late Miocene.

ZFT cooling ages show a sharp change in cooling age distribution at the location of PT$_1$ (Figures 3-3 and 3-4). North of PT$_1$, ZFT cooling ages are generally Middle Miocene and show no relationship with elevation, while south of the transition, the ZFT ages are Pliocene and show a strong linear trend with
elevation; this trend is consistent with an apparent exhumation rate of 0.38 mm/yr (Wang et al., 2010). AFT cooling ages also become younger to the south, but do not exhibit the sharp cooling age discontinuity at PT$_1$ observed in the ZFT dataset. Further analysis and more data are required to reach firm conclusions about these data and their relation to the physiographic transition just south of Nyalam.

**NEW ZIRCON AND Apatite (U-Th)/He COOLING AGES**

To further constrain the thermal history of the Nyalam region, and to unlock the most recent exhumation pattern, apatite and zircon (U-Th)/He thermochronologic transects (AHe and ZHe, respectively) were completed along the Bhoti Kosi River gorge, starting just north of the Tibet-Nepal border to the south (at Zhamgmu/Zham, see Figure 3-3) and continuing to ~8 km north of Nyalam.

**Methods**

Apatite and zircon were separated from bedrock samples using standard gravimetric and magnetic techniques prior to hand picking under a binocular microscope. Single euhedral and inclusion-free grains of either apatite or zircon were loaded into Nb micro-crucibles and placed into a stainless steel sample holder for $^4$He measurements on an ASI Alphachron in the Noble Gas Geochronology and Geochemistry Lab (NG$^3$L) at Arizona State University. Three age standards (Durango apatite for apatite samples and Durango apatite and Fish Canyon zircon for zircon samples) and 2 blanks (empty Pt or Nb tubes) together with 20 unknowns were loaded on the sample-holder for each Alphachron run.
After pumping down the laser chamber to ultra-high vacuum, helium was extracted from each sample using a 980 nm diode laser operated at 45W. The gas was spiked with $^3$He and cleaned of any reactive gases by exposure to a hot SAES NP-10 getter. The purified gas was analyzed on a Balzers Prisma QMS 200 quadrupole equipped with a Channeltron electron multiplier.

After completion of the Alphachron run, unknowns, age standards, and blanks were extracted from the vacuum system and prepared for isotope dilution analysis. Encapsulated apatite grains were dissolved using 25 µl of 50% HNO3 containing ~15 ng of 235U and ~5 ng of 230Th (used as a U and Th spike), following the procedure of Evans et al. (2005). Zircon dissolution required concentrated HF, HNO3 (also containing a 235U and 230Th spike), and HCl and was completed with Parr digestion vessels to reach high temperature and pressure as outlined by Reiners (2005). Finally, U and Th measurements were made on an inductively coupled, plasma-source mass spectrometry using a Thermo X-series quadrupole instrument in the W.M. Keck Foundation Laboratory for Environmental Geochemistry at Arizona State University. A more detailed description of AHe and ZHe methods used in this study can be found in van Soest et al. (2011).

Results

Euhedral apatite and zircon grains suitable for (U-Th)/He work were rare in many of the samples collected in the Nyalam region. Nonetheless, we report here 5 ZHe
and 4 AHe cooling ages. Only one sample collected north of PT1 contained a zircon suitable for ZHe analysis; it yielded a date of 14.08 with an analytical imprecision (at the 2σ level) of 0.52 Ma. This date contrasts sharply with ZHe dates for samples collected south of PT1. Mean dates for all other samples (based on analyses of multiple grains from each sample and quoted with an uncertainty corresponding to two standard errors of the mean, or 2SE) range from 2.55 ± 0.11 to 1.415 ± 0.049 Ma (Table 3-2; Figure 3-4). AHe cooling ages below PT1 are Pleistocene, with dates of 1.44 ± 0.10 Ma and 0.380 ± 0.045 (2σ). The latter date is reported on only one grain; two additional euhedral grains were analyzed but their calculated dates (1.73 and 4.08 Ma) are older than ZHe dates from the same sample, suggesting the presence of high U-Th microinclusions, which can lead to an overestimation of cooling age (e.g., Vermeesch et al., 2007). Notably, AHe cooling ages from above PT1 are also Pleistocene (1.079 ± 0.018 Ma and 0.914 ± 0.016 Ma) (Figure 3-4).

DISCUSSION OF LOW-TEMPERATURE THERMOCRONOLOGIC DATA

The combined data sets of Wang et al. (1998; 2006; 2010) with the new (U-Th)/He cooling ages reported in the current study result in a densely sampled transect across PT1 using five different thermochronometers, allowing us to examine the thermal history of the region from ~300°C to ~70°C, over a time period of >16 million years. Although this is a valuable dataset, interpretation of the thermal history from it is complicated by the fact that the transect covers a distance 45 km, an elevation change of over 2.5 km, and a region with variable
topographic relief. Plotting the Nyalam combined thermochronolgoic data in traditional age-elevation or age-distance plots (Figure 3-4) is not particularly revealing. A definitive interpretation of these plots is not possible as they undoubtedly conflate temporal and spatial variations in both exhumation rate and geothermal gradient.

With data from five different thermochronometers arrayed along the transect, however, we can isolate spatial and temporal effects by constructing thermal histories at various positions along the transect as allowed by the distribution of data. To do this, we divided the transect into 7 spatial zones that each encompass data from 3-5 different chronometers (Figure 3-4). We then estimated the cooling rate with time for each spatial zone using given average closure temperature (Table 3-3), cooling age for each chronometer, and simple piecewise linear regression, extrapolating to zero age at 5°C (our best estimate for the average surface temperature at the elevations of interest) (Figure 3-5). We report cooling rates, $\Delta T/\Delta t$ (°C/My), rather than the traditional exhumation rates, $\Delta z/\Delta t$ (km/Ma), as the later require a priori knowledge of the geothermal gradient, which may vary in space and time along the transect. To aid with spatial interpretation of these cooling histories, we plot the cooling rates determined for each zone in five different time periods as a function of position along the transect (Figure 3-6).

The results show higher cooling rates (~ 40 °C/My) in the immediate footwall of the STFS in the Middle Miocene (zones A and B), consistent with rapid
exhumation of footwall rocks (Figure 3-6). The cooling rates in these zones diminishes with time (to ~ 10 °C/My), likely reflecting the cessation of major activity on the Miocene STFS. Cooling rates across the entire region remain low, both north (zones A-C) and south (zones D-F) of the knickpoint, at ~ 10 °C/My until < 4 Ma, when a dramatic increase in cooling rate occurs in all zones south of PT1 (zones D-F). Note that zones G and H record only this young rapid cooling (Figure 3-5). Between ~4 and ~1 Ma, cooling rates remain at ~ 10 °C/My above the knickpoint, but increase to ~ 50 °C/My just to the south, and reach > 120 °C/My at the southern edge of the transect (Figure 3-5 and 3-6). Afterwards (<1 Ma), rapid cooling is recorded north of the knickpoint by two young AHe ages, 8 and 11 km north of PT1 (Figures 3-5 and 3-6).

This cooling rate pattern is consistent with significant slip on the mapped STFS (Figure 3-3) ceasing in the Late Miocene, at least with respect to displacement large enough to be reflected in the low-temperature thermochronologic data. At ~ 3.5 Ma, the cooling rate increases abruptly south of PT1, requiring a mechanism capable of producing distinctly different cooling histories across a narrow zone. While not a unique solution for the thermochronologic data alone, we propose the knickpoint at PT1 and the change in cooling rate may be reflective of recent top-to-the-north normal faulting resulting in significant relative exhumation of the footwall. This interpretation is, however, challenged by two observations: (1) we did not find any clear field evidence of normal faulting near the knickpoint, and (2) the pair of young AHe ages north of the knickpoint imply a recent acceleration
in cooling rate (Figures 3-5 and 3-6) within the proposed hanging wall. Although no candidate fault structures were identified in the field, given the steepness of the river gorge our work was isolated to roadcuts along the Friendship Highway, most of which are obscured by large landslide deposits near the knickpoint. Inspection of satellite imagery on Google Earth, however, reveals a north-dipping contact exposed on a valley side ridge that is on strike (NW-SE) with, and within ~ 5 km of, the knickpoint (at 28°03’23.3”N, 86°03’54.08”E, Figure 3-7). Rotating the 3D view to different perspectives reveals that this contact is a low-angle (< 30°), north-dipping, planar surface. Its position and orientation are consistent with a top-to-the-north normal fault at the position of PT1. Identification of this possible fault contact with the right orientation and on-strike from the knickpoint at PT1 is suggestive, but certainly not definitive, given the lack of exposure of a fault or fault gouge in road cuts.

Most of the thermochronologic data are consistent with the interpretation that PT1 separates areas of differential uplift and exhumation since ~ 3.5 Ma. The two ~ 1 Ma AHe ages to the north of the knickpoint (Figures 3-5 and 3-6) are exceptions. These two data points are also distinct from the rest of our dataset in that replicate analyses on 5 and 6 grains respectively yield by far the most precise ages (~1% uncertainty) we obtained. The internal consistency of the rest of the data and the different character of these precise ages lead us to question whether these samples faithfully reflect cooling due to exhumation or some other near-surface resetting event, such as the circulation of hydrothermal fluids through the upper crust.
(Whipp & Ehlers, 2007). AHe dates are especially susceptible to resetting or partial resetting due to the low closure temperature of He in apatite (~70°C), and the more precise ages may reflect the effects of an abrupt reheating event. As noted earlier, hot spring deposits have been documented to the north of the AHe samples (Zentmyer et al., 2008), although we were unable to conduct a thorough search for travertine at the sample sites due to the political sensitivity of the region. However, the AHe data are also consistent with accelerated young exhumation north of PT1, well into the hanging wall of our hypothesized normal fault. If these dates do reflect exhumation, they imply no difference in exhumation rate on either side of the physiographic transition in the last 1 million years. Moreover, the increase in cooling rate since ~3.5 Ma south of the knickpoint at PT1 could, at least in part, reflect an increase in geothermal gradient associated with the deep canyon rather than simply an increase in exhumation rate. To make further progress, we outline the distinct, testable predictions of three alternate models and turn to the tools of tectonic geomorphology to help evaluate their relative merits.

TESTING ALTERNATE MODELS

As noted earlier, three different models for the formation and maintenance of PT1 have been proposed: (1) retreat of the Miocene-age tectonic margin (Masek et al., 1994; Wang et al., 2010), (2) uplift over a ramp in the Himalayan Sole thrust (Lavé and Avouac, 2001), and (3) active normal-sense displacement at PT1 as proposed above. Each model predicts a distinct relationship among physiography,
modern erosion rates, and exhumation rates implied by cooling ages of surface samples. By combining quantitative measures of the geomorphic character of PT1 (locally and regionally) with the thermal histories determined above, we can more definitively constrain the erosional and tectonic history of the Nyalam region along our transect down the Bhote Kosi River.

The first model proposes that the steep topographic front of the Himalaya existing today can be explained by simple erosional retreat of a mountain front constructed in the Miocene (Masek et al., 1994; Wang et al., 2010). Orographic effects focus precipitation, and thus erosion, along the windward side of the topographic high, removing mass and resulting in a leeward migrating oversteepened plateau margin. In this model, the topographic break at PT1, marks the boundary between high erosion rates to the south and low erosion rates in the rain shadow on the plateau. This should manifest as an abrupt upstream (northward) decrease in channel steepness of rivers flowing across the transition as observed (Figures 3-2 and 3-7), because there is a strong relationship between channel steepness (k_s) - a metric of channel slope corrected for drainage area – and erosion rate (e.g., Wobus et al., 2006a; Ouimet et al., 2009; Cyr et al., 2010; DiBiase et al., 2010; Kirby and Whipple, in press). The margin retreat model, however, does not predict coincidence between the current knickpoint location and the cooling age discontinuity within the thermochronologic data. In order for an increase in erosion rate to be reflected in cooling ages, total erosional relief since the change must be sufficient to exhumate rocks from the depth of closure temperature (~ 3 km
for AHe and 7.5 for ZHe with an average geothermal gradient of 25°C). Even considering an increase in the geothermal gradient to as much as 50°C-75°C/km as a result of isotherm advection, at least 1 km must be eroded before low-temperature thermochronology will record an increase in erosion rate. By definition, for a retreating erosional knickpoint, differential erosion is zero at the knickpoint and increases with distance downstream as erosional relief increases. Consequently, even in regions with rapid erosion-induced exhumation, the thermochronologic cooling age discontinuity will not coincide with the current location of a migrating knickpoint associated with escarpment retreat, but rather, will map at a point downstream where the erosional relief has reached the amount necessary to “reset” the chronometer of interest – at least 20 km in this case (see Figure 3-4, 3-7B). Thus this model is not consistent with the observed increase in exhumation rate as recorded in thermochronometers within 2 km of the knickpoint (where only 200-300 m of differential erosion would be implied by the retreating knickpoint model).

The second model was advocated by Lavé & Avouac (2001) who deduced uplift patterns by examining the incision histories and present-day longitudinal profiles of major transverse rivers in the central Himalaya (where uplift ≈ incision is assumed). They found that, when generalized to fit compiled data from five major rivers, the inferred uplift pattern was roughly consistent with rock uplift across a ramp on the Himalayan Sole thrust (ramp-flat model of Cattin & Avouac, 2000), such that no uplift due to active faults at either the location of PT$_2$ or PT$_1$ would
be required to explain the river profiles. A closer look at the Bhote Kosi, however, reveals that the channel steepness pattern is not consistent with the uplift pattern predicted by the ramp-flat model (Figure 3-8). Around the location of PT₁, the predicted ramp-flat uplift pattern deviates significantly from the uplift pattern implied by the channel profile. The ramp-flat model predicts a gradual decrease in uplift rate to the north and does not explain the abrupt increase in channel steepness at the top of the knickzone - the match between uplift patterns implied by the geomorphology and predicted by the ramp-flat model claimed by Lavé and Avouac (2001) appears to be an artifact of the stacking of 5 river profiles that each imply different uplift patterns with abrupt increases occurring at different positions along their composite profile. These data suggest that an additional mechanism not considered by Lavé and Avouac (2001) is required to explain the fluvial profile at PT₁. Although the Bhote Kosi’s longitudinal profile includes a wide convex zone rather than the “text-book” fault-controlled sharp break (e.g., Wobus et al., 2006), this sort of convexity is commonly seen in reaches above major knickpoint (e.g. Haviv et al., 2006; Berlin and Anderson, 2009) and the abrupt change in geomorphic character at the head of the knickzone is suggestive of a sharp change in the uplift pattern. The rivers bounding the Ama Drime horst in south-central Tibet provide an instructive analog (87º15’-87º50’E; 27º45’-28º30’N). The Ama Drime is bound on the east and west by roughly N-S striking moderate-to-low-angle Quaternary normal faults. The Arun River on the west and the Natang Chu on the east both cross the respective normal faults, both flowing into the uplifting footwall, similar to the hypothesized configuration on the Bhote
Kosi. Although the two rivers cross similar structural configurations, they display distinctly different longitudinal river profiles, with the Natang Chu profile exhibiting the convex form also seen in the Bhotekosi profile (Figure 3-8).

The third hypothesis, put forth by Hodges et al. (2001), proposed that young, N-directed normal faulting may be the mechanism setting and maintaining PT$_1$. These authors also speculated, due to the close coincidence, that the driving faults may be young strands of the STFS. In order to establish the prominent break associated with the transition, the faults would need to accommodate displacement significant enough to drive higher rock uplift rates in the footwall for a sustained period of time. This uplift discontinuity would result in a sharp topographic break coinciding with offset low-temperature thermochronologic cooling ages (AHe, AFT) and likely higher temperature chronometers (ZHe, ZFT) reflecting different exhumation histories across the fault, as well as differential erosion rates likely manifesting as a change in channel steepness (i.e. a knickpoint) on river longitudinal profiles. Our examination of the geomorphic and thermal character of the Bhotekosi at PT$_1$ lends strong support for the fault-control hypothesis of Hodges et al. (2001), although the faulting is not associated with previously mapped strands of the STFS. Both of our independent data sets, geomorphically inferred erosion rates and all thermochronologic data except AHe, indicate discontinuities at PT$_1$. Although we recognize that complicating factors likely exist - for example, perturbations in the geothermal gradient related to changing uplift patterns through time - we make the first-order simplifying
assumptions that channel steepness scales with uplift rate (where uplift \( \approx k_s^2 \), Ouimet et al., 2009; DiBiase et al., 2010) and that cooling rate scales linearly with exhumation rate. When the two data sets are compared with each other given these assumptions, they exhibit consistent patterns (Figure 3-8A), strong evidence that, despite unknown complicating factors, both datasets may scale with exhumation rate. If this is true, then both datasets indicate a sharp and temporally persistent increase in exhumation rate at the location of PT1, something most easily explained by surface-breaking extensional faulting.

The fact that all the compiled geomorphic and thermochronologic data are consistent with fault-control at PT1, with the notable exception of the two AHe dates to the north of the knickpoint leads us to suspect these AHe dates do not reflect cooling history but rather, a resetting event, perhaps related to hydrothermal activity. Alternatively, exhumation could occur on one or more unmapped or previously mapped normal faults of unknown significance (Burchfiel et al., 1992) in the immediate footwall of the STFS, with enough throw to offset the AHe cooling age patterns but not the patterns of higher temperature thermochronometers. This region was not mapped in the course of our study and thus, the possibility cannot be evaluated further at this time.

CONCLUSIONS

The simplest explanation, consistent with a preponderance of the data reviewed in this paper, is that the exhumation discontinuity at PT1 in the Nyalam transect is
set and controlled by recently active extensional faulting, likely initiating at ~ 3.5 Ma. A possible fault contact, striking toward PT₁ as expressed in our transect, can be identified in satellite imagery of the area to the east of our field site. Unfortunately, exposures in the transect are too poor to permit direct field documentation of a fault. The abrupt nature of the physiographic transition and the prominent knickzone on the river profile are geomorphically consistent with recent faulting. The Bhote Kosi channel south of PT₁ displays higher steepness as river incision and erosion work to balance higher uplift rates downstream. The thermochronologic data suggest a sustained difference in exhumation history across the knickpoint since ~3.5 Ma, with very young cooling ages, likely indicating high exhumation rates, to the south of the knickpoint. The coincidence of this prolonged differential cooling over several million years with the geomorphic break representing very recent deformation today lends a significance to this specific location that is best explained by Plio-Pleistocene top-to-the-north normal faulting. Given our findings in the Nyalam region, and the fact that several workers document recently active extension at or near PT₁ in locations that span > 800 km (Wu et al., 1998; Nakata 1989; Hurtado et al., 2001; McDermott et al., in press), we infer that active normal faulting helps define the southern edge of the Tibetan Plateau.
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Wobus, C.W., Whipple, K.X, and Hodges, K.V. (2006b) Neotectonics of the central Nepalese Himalaya: Constraints from geomorphology, detrital $^{40}$Ar/$^{39}$Ar thermochronology, and thermal modeling. Tectonics, 25, TC4011.


FIGURE CAPTIONS

Table 3-1.
Approximate locations of previously published thermochronologic data.

Table 3-2.
A: Apatite (U-Th)/He data from the Nyalam region of south-central Tibet
B. Zircon (U-Th)/He data from the Nyalam region of south-central Tibet

Table 3-3.
Assumed closure temperatures for thermochronometers

Figure 3-1.

a: Geologic and structural map of the central Himalaya, after Hodges (2000).
Rectangle shows the extent of Figure 3-3. b: Idealized and simplified cross-section across the Himalaya showing the location of previously documented physiographic transitions (basic transect location shown in a), modified from Hodges et al. (2001), and Bollinger et al. (2006). Abbreviations: DH – Dhaulagiri; MA – Machhapuchhare; MBTS – Main Boundary thrust fault; MCTS – Main Central thrust system; MFTS – Main Frontal thrust system; EV – Everest; HST – Himalayan Sole thrust; PT$_{1-3}$ – Physiographic transitions 1-3; STFS – South Tibetan fault system; TG – Thakkhola Graben.

Figure 3-2.
Relief map of the central Himalaya (2.5 km circular window) overlain on shaded relief topography data from 90-m DEM. Channel steepness ($k_s$) map created following the procedure in Wobus et al. (2006a). The approximate locations of physiographic transitions 1, 2 and 3 (PT$_1$, PT$_2$, and PT$_3$ respectively) are indicated by dashed white lines; PT$_1$ and PT$_2$ can be traced bounding the high relief and high channel steepness zones. Note the coincidence of the PT$_1$ and PT$_2$ with structures of the South Tibetan fault system (STFS) and Main Central thrust system (MCTS) in some locations but deviating in others. Longitudinal river profiles of transverse Himalayan rivers display prominent knickpoints at the location of PT$_1$ as shown in inset figure. Many of these knickpoints are located near mapped fault traces: the knickpoint on the Kali Gandaki (KG) is located ~ 10 km from a young top-to-the-north normal fault (McDermott et al., in submission), on the Trisuli (T) the knickpoint lies within 20 km of a mapped fault of unknown significance (Burchfiel et al., 1992), the knickpoints on the Arun (A) and Natang Chu rivers correlate exactly with active extensional faults that bound the Ama Drime Range (McDermott et al., in review), and the knickpoint on the Bhote Kosi (BK) is the focus of this study. Bold box indicates extent of Figure 3-7A. Location of Figure 3-9 also indicated.

Figure 3-3.

Geologic and structural map of the Nyalam region, modified in part from Maluski et al. (1988), and Wang et al. (2010). Map shows locations of samples reported for this study as well as samples reported in Wang et al. (1998), Wang et al.
(2006), and Wang et al. (2010). Abbreviations: MCTS – Main Central thrust system; STFS – South Tibetan fault system.

Figure 3-4.
Plot of cooling ages versus distance for the Nyalam region. Cooling age data from this study, Wang et al. (1998), Wang et al. (2006), and Wang et al. (2010). Errors plotted at 2SE. Vertical dashed line denotes the change from low relief to high relief and also coincides with the knickpoint. Vertical grey boxes (A – H) correspond to the spatial zones in Figure 3-5.

Figure 3-5.
Cooling histories (cooling age versus closure temperature) for the individual spatial sections indicated in Figure 3-4 (A-H). Vertical dashed line marks the time of general cooling rate change at ~3.5 Ma as discussed in the text. Cooling age data from this study, Wang et al. (1998), Wang et al. (2006), and Wang et al. (2010). Errors plotted at 2SE. Slopes (cooling rate) for each temporal section are plotted in Figure 3-6.

Figure 3-6.
Cooling rates for each spatial section (compiled from data in Figure 3-5) through time. Cooling rates are non-dimensionalized (τ) for ease of plotting comparison. Displacement on the STFS in the Middle Miocene can be seen in the 16 – 13 Ma and 13 – 10 ma time slots, while displacement likely related to the normal faulting
described in the text is illustrated after ~ 3.5 Ma. Cooling rates for ‘E’ can be calculated several ways after 3 Ma (see Figure 3-5 ‘E’) and therefore a range of possible rates are shown. Since the 1-0 Ma cooling rates for ‘B’ and ‘C’ are based solely on the AHe ages, the specific location of those samples is highlighted within the spatial slots. Numerical values in the final frame (1-0 Ma) represent the time of the significant cooling change in millions of years (see Figure 3-5 for more details).

Figure 3-7.
[A] Relief map of the Nyalam region (2.5 km circular window) overlain on shaded relief topography data from 90-m DEM. River channel steepness calculated as described in text. Abbreviations: MCTS – Main Central thrust system; STFS – South Tibetan fault system. [B] Slope-area data for the Bhote Kosi River (upper right portion of plot) with longitudinal river profile (lower left portion of plot). Location of main knickpoint is indicated. [C] View to the North Google Earth image of proposed fault. [D] Rotated view of same proposed fault on Google Earth as in [C], view to the South-East.

Figure 3-8.
Longitudinal profiles for the Arun (grey) and Natang Chu (black) rivers in southcentral Tibet. Map shows the relationship between Quaternary faults (in bold) and the Arun and Natang Chu Rivers. Both rivers display distinct knickpoints where they cross active normal faults.
Comparison of channel steepness ($k_s$) along the Bhote Kosi River with uplift pattern predicted by the ramp-flat model of Cattin and Avouac (2000). The correlation between the fault proposed in the text and an increase in channel steepness is indicated. Inset map shows relative uplift from channel steepness (where uplift $\approx k_s^2$) [green dots] and apparent exhumation rate from thermochronologic data (assuming exhumation rate scales linearly with cooling rate) [yellow boxes].
Table 3.1. Approximate sample locations for previous thermochronologic data in the Nyalam region

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<th>Sample</th>
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<th>Elevation (m)</th>
<th>Latitude; Longitude</th>
<th>Age (Ma)</th>
<th>2SE (Ma)</th>
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81
<p>| Weighted mean age | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.00             | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |</p>
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Figure 3-2
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CHAPTER 4

MULTI-PHASE EXHUMATION OF THE AMA DRIME RANGE, SOUTHERN TIBET: EVIDENCE FOR DISTINCT DUCTILE AND BRITTLE DEFORMATIONAL PHASES ALONG ANAGOLOUS SHEAR DOMAINS

ABSTRACT

The Ama Drime Range of southern Tibet is a dramatic structural dome developed between two prominent high-angle normal faults with well-developed Quaternary scarps. The immediate footwalls of these faults are ductile shear zones oriented similarly to the brittle faults. As a consequence, the brittle faults and ductile shear zones have been interpreted by previous researchers to be related collectively to a single phase of progressive extensional uplift and exhumation of the range. Here we examine this interpretation in greater detail using existing U-Pb, $^{40}$Ar/$^{39}$Ar, and (U-Th)/He datasets as well as new (U-Th)/He data for samples both internal and external to the horst. The data suggest that exhumation coeval with the development of ductile fabrics was short-lived on the eastern margin of the range and had ceased by ~10 Ma, well before initiation of rapid exhumation along the brittle faults in the Late Pliocene-Quaternary. A significant period of regional, comparatively slow cooling prevailed between the two exhumation events. Distinct deformational phases on the western margin of the range are less certain; although two distinct deformational phases can be delineated within the cooling age data, the duration of the time lag between them is not well-constrained, and thus, the transition from ductile to brittle exhumation may have been continuous.
Across the entire study region, apatite (U-Th)/He cooling ages are Plio-Pleistocene in age, suggesting recent exhumation of the region, likely either through rapid river incision or a regional response to thermal relaxation of advected isotherms due to a reduction in exhumation rates along the Ama Drime boundary faults.

INTRODUCTION

Domal features of extensional origin are found in many of the world’s orogenic terrains (Teyssier and Whitney, 2002), including domes resulting from E-W extension across the Tibetan Plateau (e.g., Pan and Kidd, 1992; Thiede et al., 2006; Jessup et al., 2008; Kapp et al., 2008). With some exceptions, such domes are commonly bound by similarly oriented ductile and brittle shear zones with analogous sense of shear, a characteristic generally inferred to indicate continuous extension as the shear zone evolves through the ductile and brittle domains (e.g., Davis et al., 1986). The Ama Drime Range of southern Tibet is a classic extensional gneiss dome, bound on the east and west by low-angle ductile shear zones and high-angle brittle faults with consistent top-to-the-east (e.g., Burchfiel et al., 1992) and top-to-the-west shear sense (e.g., Jessup et al., 2008), respectively. The origin of the range has been attributed to progressive extensional exhumation along first the ductile shear zones followed by brittle faulting at progressively shallow depths (Zhang and Guo, 2007; Jessup et al., 2008; Cottle et al., 2009; Kali et al., 2010; Langille et al., 2010). However, the published geochronologic and thermochronologic data for the range are based on
mineral-isotopic systems with closure temperatures in excess of 300°C or around 70°C, and they thus do not provide a clear indication of the temporal evolution of Ama Drime tectonite fabrics over the critical temperature range over which the ductile to brittle transition occurs (Stoeckhert et al., 1999). In order to constrain this interval better, we have turned to the zircon (U-Th)/He (ZHe) thermochronometer, which has a nominal closure temperature of ~ 190°C for a cooling rate of 10 °C/Myr (Reiners et al., 2004). In addition, we applied the apatite (U-Th)/He (AHe) thermochronometer, which has a nominal closure temperature of ~70°C for a cooling rate of 10 °C/Myr (Farley, 2000), to a variety of Ama Drime samples to augment existing AHe data for the area (Jessup et al., 2008; Kali et al., 2010). Importantly, the new AHe and ZHe data were obtained for both the core of the Ama Drime Range (footwall of both the eastern and western boundary faults) and the surrounding region (hanging walls of the boundary faults) in order to compare footwall and hanging wall exhumation histories.

THE AMA DRIME RANGE AND EXTENSIONAL FAULTING IN THE HIMALAYAN-TIBETAN OROGENIC SYSTEM

The Ama Drime Range is a roughly N-S trending mountain range, ~ 70 km east of Mt. Everest, jutting north from the main Himalayan crest (Figure 4-1). The most prominent features associated with the range are the clearly defined fault scarps that mark the trace of the high-angle normal faults that bound the range on the east and west (Figure 4-2). Quaternary activity is evidenced from well-preserved
triangular facets, crosscut fluvial and glacial deposits, and abrupt knickpoints, features which can be indicative of active faulting, on rivers crossing the fault traces (e.g., Wobus et al., 2006). The bounding faults have been given various names in the literature; most recently, the eastern and western bounding faults have been referred to as the Ama Drime and Nyönno Ri detachments, respectively (Jessup et al., 2008; Cottle et al., 2009; Jessup and Cottle, 2010; Langille et al., 2010) and the Kharta and Dinggye faults, respectively (Kali et al., 2010; Leloup et al., 2010). As early work in the region referred to an eastern strand of the STFS as the Dinggye detachment (Burchfiel et al., 1992), we prefer the Ama Drime and Nyönno Ri terminology to avoid confusing the N-S striking western boundary fault with the E-W striking detachment of Burchfiel et al. (1992). Within the range, in the immediate footwalls of these faults, ductile shear fabrics are common, and associated kinematic indicators imply a shear-sense that is consistent with the presumed displacement of the range-bounding Quaternary faults. Several previous workers have interpreted this consistency as evidence that the structural architecture of the range is dominated by continuous extension (Jessup et al., 2008; Cottle et al., 2009; Jessup and Cottle, 2010; Kali et al., 2010; Langille et al., 2010). However, we choose to differentiate the distinct structural phases and refer to the shear zones as the Ama Drime and Nyönno Ri shear zones (ADSZ, NRSZ), on the eastern and western boundaries, respectively, and the high-angle brittle structures as the Ama Drime and Nyönno Ri faults (ADF, NRF), again, respectively on the east and west.
The Himalaya are classically partitioned into tectonostratigraphic units bound by major north-dipping fault systems following the pioneering work of Gansser (1964) and Le Fort (1975) (Figure 4-1). Two of these occur in the Ama Drime Range (Figure 4-2). The northernmost of these, outcropping generally between the Indus-Tsangpo suture zone and the Himalayan range crest, is the Tibetan Sedimentary sequence, a nearly continuous Paleozoic to Eocene sedimentary succession of carbonate and siliciclastic rocks recording deposition on the northern margin of India before the Indian–Eurasian collision (Gaetani and Garzanti, 1991). The Tibetan Sedimentary sequence is crosscut by numerous N-S striking grabens bound by high-angle brittle faults (e.g., Armijo et al., 1986), many of which are underlain by ductile fabrics (e.g., Pan and Kidd, 1992; Hurtado et al., 2002; Thiede et al., 2006; Zhang and Guo, 2007; Kapp et al., 2008). Although a single initiation age for E-W extension across the Tibetan Plateau is unlikely, normal faulting on at least some of these faults began by the Middle Miocene (Coleman and Hodges, 1995; Searle, 1995; Blisniuk et al., 2001). There is, however, no doubt of Quaternary activity; faults display dramatic scarps and triangular facets, and crosscut Quaternary moraine and fluvial deposits (e.g., Armijo et al., 1986; Nakata, 1989). The seismic character of southern Tibet also demonstrates that E-W extension dominates modern-day deformation (Molnar and Tapponnier, 1975, 1978; Ni and York, 1978). Southern Tibet also features a series of high-grade metamorphic mylonitic granitic and gneissic domes, known collectively as the North Himalayan gneiss domes (e.g., Burg et al., 1984; Burg and Chen, 1984). Although the origin of the gneiss domes is still debated (Burg et
al., 1984; Le Fort, 1986; Hauck et al., 1998; Chen et al., 1990; Harrison et al., 1997; Lee et al., 2000; Kapp and Guynn, 2004), the majority exhibit structural evidence for roughly N-S extension along the mylonitic shear zone during some phase of their development (e.g., Chen et al., 1990; Lee et al., 2004; Aoya et al., 2006; Quigley et al., 2006), and thus likely represent a different tectonic origin than the Ama Drime Range.

Near the southern margin of the Tibetan Plateau, the structural base of the Tibetan Sedimentary sequence is defined by the South Tibetan fault system (STFS), a family of predominately top-to-the-north normal faults that can be traced for nearly 2000 km along strike (Burchfiel et al., 1992). The STFS played an important role in Himalayan evolution in the Early Miocene, and along with contemporaneous slip on the structurally lower Main Central thrust system (e.g., Hodges et al., 1992), is thought to be responsible for exhumation of the Greater Himalayan sequence, a laterally continuous sequence of middle to upper amphibolite facies paragneiss, calc-silicate gneiss, and augen orthogneiss crosscut throughout by anatctic leucogranites (e.g., Le Fort, 1975). Major displacement on the STFS is widely believed to have ceased by the Middle Miocene (e.g., Searle and Godin, 2003), however Plio-Pleistocene slip on N-directed extensional faults has been documented near the southern margin of the plateau in several locations across the range (Nakata, 1989; Wu et al., 1998; Hurtado et al., 2001; McDermott et al., submitted-A; McDermott et al., submitted-B). In the Ama Drime region, the STFS juxtaposes Greater Himalayan migmatitic garnet-bearing
metapelites, para-amphibolites, and minor orthogneisses in the footwall against unmetamorphosed orange-weathering carbonates and mudstones of the Tibetan Sedimentary sequence in the hanging wall. However, the Ama Drime boundary faults disrupt the “classic” Himalayan tectonostratigraphic divisions, cutting across the Tibetan Sedimentary sequence in the north and the Greater Himalayan sequence in the south, and dissecting the Miocene STFS in the process. To the west of the Ama Drime Range, the STFS has been mapped crossing the Dzakar river (Cottle et al., 2007) before it is cross-cut by the ADF, leaving a preserved klippen within the northern part of the range (Figure 4-2). The ADF may have offset the detachment horizontally by up to 15 km (Leloup et al., 2010), but this interpretation is difficult to evaluate given the low dip angle of the detachment and the significant dip-slip component of displacement on the ADF. To the east, the STFS (the Dinggye detachment of Burchfiel et al., 1992) is cut by several small-scale N-S striking extensional faults of uncertain age. Similarly to the relationship between the klippen within the Ama Drime Range and the STFS strand west of the range, the Dinggye detachment does not project westward to intersect the klippen but instead projects to a point of intersection with the NRF more than 35 km to the south, suggesting possible right-lateral offset (Burchfiel et al., 1992).

Early workers interpreted the Ama Drime rocks as part of the Lesser Himalayan sequence, an 8-10 km thick series of metasedimentary phyllites and schists that make up the footwall of the Main Central thrust system (Gansser, 1964; Colchen
et al., 1986; Schelling, 1992), in part due to a similarity of Sm/Nd model ages (Visonà et al., 2000; Visonà and Lombardo, 2002). This interpretation permits the possibility that Quaternary deformation on the ADF and NRF has obscured a former trace of Main Central thrust system (Lombardo et al., 1998; Lombardo and Rolfo, 2000; Borghi et al., 2003; Groppo et al., 2007; Liu et al., 2007). However, subsequent investigations have revealed no evidence of tectonites in the Ama Drime metamorphic core with shear sense indicators consistent with such a model (Jessup et al., 2008; Cottle et al., 2009; Kali et al., 2010; Leloup et al., 2010; Langille et al., 2010). Given the clear normal sense of shear on all known faults in the region, and the high metamorphic grade found throughout the Ama Drime Range, we prefer the interpretation of workers such as Jessup et al. (2008) who correlate the Ama Drime rocks to the Greater Himalayan sequence. The southern half of the Ama Drime Range, roughly south of 28°15′N, is composed of migmatitic granulite facies augen orthogneiss (the Ama Drime orthogneiss of Jessup et al. (2008)) and contains several well-preserved granulitized eclogite pods (e.g., Lombardo et al., 1998). North of 28°15′N, paragneisses and pelitic schists dominate the unit (the Ama Drime paragneiss of Kali et al. (2010)). Leucogranite dikes and sills are prevalent at all structural levels in both units. Some previous authors have classified the contact between the Ama Drime orthogneiss and the Ama Drime paragneiss as structural (Kali et al., 2010; Leloup et al., 2010), while other authors recognize no such structural boundary (Jessup et al., 2008; Cottle et al., 2009); as the mapping of the structural contact is uncertain and no slip could have occurred in at least the last 30 Ma (Kali et al., 2010), we
disregard this boundary from the following discussions of late Cenozoic-Quaternary tectonics.

**Structural setting**

Within the Ama Drime region as defined by Figure 4-2, three major and distinct deformational events can be identified: top-to-the-north extensional faulting on the STFS; E-W extensional ductile deformation on the Ama Drime shear zones (ADSZ and NRSZ); and E-W extension on high-angle brittle faults (ADF and NRF) overprinting earlier ductile deformation.

**N-directed extension on the STFS**

All structural levels of the Greater Himalayan sequence display a pervasive and well-developed NW-dipping foliation with strongly developed S-C fabric that overprints earlier fabrics of unconstrained origin (Burchfiel et al., 1992; Hodges et al., 1994; Cottle et al., 2007). The strength of the mylonitic fabric increases with proximity to the STFS, and within ~ 500 m of the structure all fabrics are subparallel to the master detachment of the STFS (Burchfiel et al., 1992; Hodges et al., 1994). A mineral and stretching lineation is defined by sillimanite within the Greater Himalayan gneisses, by elongate biotite in the Dzakaa Chu section (Cottle et al., 2007), and by elongate quartz and feldspar grains in intruded leucogranites of the Dinggye area (Burchfiel et al., 1992; Hodges et al., 1994) Calc-silicate gneisses in the Dzakaa Chu section display mesoscopic tight to isoclinal folds (Cottle et al., 2007). In some locations, deformational fabrics are
overprinted by ductile-brittle normal shear zones that may be related to late-stage motion on the STFS (Burchfiel et al., 1992; Hodges et al., 1994).

**DUCTILE EXTENSION ON THE ADSZ AND THE NRSZ**

The Ama Drime Range is bound on the west and east by prominent ductile shear zones, the ADSZ and NRSZ, respectively. The NRSZ strikes NNE-SSW and dips ~20°E. A prominent foliation with associated down-dip stretching lineation is exhibited within a ~ 300-m-thick shear zone (Zhang and Guo, 2007; Jessup et al., 2008; Kali et al., 2010; Langille et al., 2010). Shear-sense indicators, including a well-developed S-C fabric and shear bands around semirigid feldspar grains, record top-to-the-east normal sense of shear (Burchfiel et al., 1992; Zhang and Guo, 2007; Jessup et al., 2008; Langille et al., 2010). The ADSZ strikes NNE-SSW along its southern reach, but curves to the east about halfway along its exposed length before striking north again. Some previous workers have differentiated the northern segment of the normal fault as a separate structure, the Sangkar fault (Kali et al., 2010; Leloup et al., 2010; Langille et al., 2010), although the structural transition in this area remains poorly constrained by field mapping. As on the eastern margin of the Ama Drime massif, rocks on the western margin display a penetrative mylonitic foliation, with down-dip mineral lineation and feldspar shear bands indicating top-to-the-west shear ( Jessup et al., 2008). The dominant foliation shallows to horizontal in the core of the range, and becomes progressively steeper to the east and west. This geometry led some previous authors to interpret the Ama Drime Range as a metamorphic core
complex, although likely kinematically linked to E-W extension on the Tibetan Plateau (Jessup et al., 2008; Cottle et al., 2009; Jessup and Cottle, 2010; Langille et al., 2010), while others have suggested that it may simply be a horst of the Xainza-Dinggye rift system and do not attribute special significance to the domical character of the range (Zhang and Guo, 2007; Kali et al., 2010; Leloup et al., 2010).

**BRITTLE EXTENSION ON THE HIGH ANGLE ADF AND NRF**

Ductile fabrics on both bounding shear zones are offset and truncated by high-angle (≈45º) normal faults with the same sense of shear (top-to-the-west on the ADF and top-to-the-east on the NRF) (Figure 4-3). Abundant fault gouge marks the brittle zone of the ADF and the ductile mylonitic fabric is fragmented and truncated by pseudotachylite veins (Langille et al., 2010). The NRF exhibits clear slickensides suggesting prominent dip-slip motion; just below the fault surface, microbreccia overlie chloritic breccia, and all breccias include fragments of mylonitic gneisses and leucogranites (Zhang and Guo, 2007).

Several high-angle normal faults occur both to the east and west of the Ama Drime Range. To the east, numerous high-angle N-S striking normal faults crosscut the Dinggye detachment in the hanging wall of the NRF (e.g., Burchfiel et al., 1992). The total amount of displacement accommodated by the faults is unconstrained, but throw on any individual fault appears small. To the west, in the hanging wall of the Ama Drime fault, an oblique ~NE-SW top-to-the-NW normal
fault can be traced diverting from the ADF and cutting across the Arun and Kharta Chu, trending SW toward the Everest massif (Kali et al., 2010). No bedrock outcrops of the fault were found, but the fault, the Tsun Cheng fault, displays clear fault scarps across Pleistocene river terraces and glacial features, forming sag ponds in several locations. Fault scarps vary between ~ 5-20 m high.

**Geomorphology**

The ADF and NRF can both be traced for > 70 km and clearly display evidence for Quaternary slip. The faults are easily delineated by a series of sharp, angular, triangular facets; faceted scarps are largest near the center of the range and become smaller to the north and south, suggesting displacement is highest in the center of the range and reduces to near zero to the north. Both faults cut Quaternary moraines, alluvial fans, and colluvial deposits.

The rivers that bound the Ama Drime Range, the Arun and Natang Chu on the west and east sides, respectively, both exhibit prominent knickpoints (defined here as the beginning of a zone of high channel steepness) approximately where the Ama Drime Range meets the crest of the Himalaya (Figure 4-2). As defined, the knickpoints mark a distinct change from wide, low-gradient, alluviated valleys in relatively low relief regions to the north to deep, high gradient, bedrock gorges surrounded by steep, high-relief topography in the south. A close examination of the ADF and NRF, both in the field and with the use of high-resolution digital imagery, reveals the prominent river knickpoints on the Arun and Natang Chu.
rivers coincide with the mapped trace of the faults (Figure 4-2). Based on this new mapping, we link the knickpoint locations on the Arun and Natang Chu rivers to Quaternary activity on the ADF and NRF, respectively. A similar relationship is seen in the Yo Ri gorge, where the Arun River displays abrupt knickpoints at both locations upon crossing the active ADF (Figure 4-2).

THERMAL HISTORY OF THE REGION
The Ama Drime Range and surrounding regions have been the focus of several geochronologic and thermochronologic studies over the past quarter century (Hodges et al., 1994; Cottle et al., 2007; Groppo et al., 2007; Liu et al., 2007; Zhang and Guo, 2007; Jessup et al., 2008; Kali et al., 2010; Leloup et al., 2010). Here we combine previous constraints on the timing of deformational events with new AHe and ZHe data that allow for a more complete and comprehensive examination of the low-temperature thermal history of the region.

Timing of STFS deformation
The timing of STFS initiation in the Ama Drime region is poorly constrained. U-Th-Pb dating of a leucogranite dike crosscutting ductile fabrics in lower parts of the STFS shear zone in the Dzakaa Chu section (to the west of the Ama Drime Range) indicates that STFS slip began prior to ~ 20 Ma (Cottle et al., 2007). $^{40}$Ar/$^{39}$Ar muscovite and biotite cooling ages record rapid cooling of the immediate footwall of the Dinggye detachment (eastern segment of the STFS) between 16 and 13 Ma, and it is generally believed that significant deformation on
STFS structures ceased by the Late Miocene (Hodges et al., 1994; Zhang and Guo, 2007; Leloup et al., 2010).

**Timing of ductile deformation on the Ama Drime shear zones**

Pressure-temperature paths combined with timing constraints for the Ama Drime orthogneiss indicate rocks were at ~ 0.5 GPa and ~ 800°C at 13.5±1.5 Ma (U-Pb monazite date) (Rolfo et al., 2005; Kali et al., 2010). Ductile activity on the NRSZ is constrained by a ~11-10 Ma monazite (U-Th)/Pb crystallization age of a leucogranite dike that cross-cuts the prominent ductile fabric (Kali et al., 2010). $^{40}$Ar/$^{39}$Ar muscovite and biotite cooling ages from the footwall of the NRSZ indicate rocks cooled through ~300-350°C by ~ 9-10 Ma (Zhang and Guo, 2007; Kali et al., 2010) (Figure 4-2), suggesting rapid cooling associated with exhumation on the NRSZ (~400°C in < 2 Ma).

Ductile deformation on the ADSZ is not as well constrained. A leucogranite that cuts a syn-deformational footwall boudin yields a monazite date of 11.6±0.4 Ma (Cottle et al., 2009), similar to crystallization ages from the footwall of the NRF (Kali et al., 2010), suggesting that the structure may have been active by that time. $^{40}$Ar/$^{39}$Ar biotite cooling ages vary significantly in the footwall of the ADSZ (from 23.5 – 6.2 Ma; Kali et al., 2010) (Figure 4-2). The ~ 6 Ma cooling ages and variability within the data suggest the ADSZ did not cool through the $^{40}$Ar/$^{39}$Ar biotite closure temperature (~ 300°C; Harrison et al., 1995) until several million
years after the NRSZ, leading Kali et al. (2010) to suggest ductile deformation occurred over a longer time interval, possibly until ~ 6 Ma.

Low-temperature thermal history

We present new AHe and ZHe dates from both the core of the Ama Drime Range (footwall of the ADF and NRF) and the exterior (hanging wall of the ADF and NRF), to combine with previous AHe datasets from the interior of the range (Jessup et al., 2008; Kali et al., 2010).

Methods

Apatite and zircon were separated from bedrock samples using standard gravimetric and magnetic techniques prior to hand picking on a binocular microscope at 184x magnification to ensure selection of only euhedral and inclusion-free grains. Single grains of either apatite or zircon were loaded into Nb micro-crucibles and placed into a stainless steel sample-holder for 4He measurements on an ASI Alphachron in the Noble Gas Geochronology and Geochemistry Lab (NG3L) at Arizona State University. Three age standards (Durango apatite for apatite samples and Durango apatite and Fish Canyon zircon for zircon samples) and 2 blanks (empty Pt or Nb tubes) together with 20 unknowns were loaded on the sample-holder for each analytical run. After pumping down the laser chamber to ultra-high vacuum, helium was extracted from each sample using a 45 Watt, 980 nm diode laser. The gas was spiked with 3He and cleaned of any reactive gases by exposure to a hot SAES NP-10 getter.
The purified gas was analyzed on a Balzers Prisma QMS 200 quadrupole equipped with a Channeltron electron multiplier.

After completion of the He extraction run, unknowns, age standards, and blanks were extracted from the vacuum system and prepared for isotope dilution analysis. Encapsulated apatite grains were dissolved using 25 µl of 50% HNO3 containing ~15 ng of 235U and ~5 ng of 230Th (used as a U and Th spike), following the procedure of Evans et al. (2005). Zircon dissolution requires concentrated HF, HNO3 (also containing a 235U and 230Th spike), and HCl and was completed with Parr digestion vessels to reach high temperature and pressure as outlined by Reiners (2005). Finally, U and Th measurements were made on an inductively coupled, plasma-source mass spectrometer, a Thermo X-series quadrupole instrument, in the W.M. Keck Foundation Laboratory for Environmental Geochemistry at Arizona State University. A more detailed description of AHe and ZHe methods used in this study can be found in van Soest et al. (2011).

Results

We report here 24 ZHe and 15 AHe cooling ages (Figures 4-2, 4-4 and 4-5). Mean dates for all samples are based on single grain replicate (4 - 7 for zircon, 2 - 6 for apatite) analyses from each sample and are quoted at an uncertainty of two standard errors of the mean (2SE). Note that uncertainties are quoted at 2σ in all figures for easy plotting comparison with previously published data. ZHe dates
range from 2.17 ± 0.29 Ma to 3.504 ± 0.063 Ma in the interior of the range, and 8.620 ± 0.022 Ma to 13.30 ± 0.23 Ma and 2.42 ± 0.20 Ma to 7.23 ± 0.46 Ma in the hanging wall in the east and west, respectively. AHe dates range from 1.067±0.068 Ma to 3.40 ± 0.17 Ma in the interior of the range, and 2.359 ± 0.081 Ma to 7.50 ± 0.18 Ma and 1.067 ± 0.068 Ma to 3.64 ± 0.62 Ma in the hanging wall in the east and west.

ZHe cooling ages within the core of the Ama Drime Range are Pliocene in age, ranging from 2.17 ± 0.29 to 3.504 ± 0.063 Ma (Figure 4-2). Interestingly, ZHe dates in the footwall of the Tsun Cheng fault (immediate hanging wall of the ADF) are also Pliocene in age (2.24 ± 0.11 – 2.72 ± 0.21 Ma) and are equivalent, within error, of cooling ages within the interior of the Ama Drime Range. The ZHe interior data, despite samples covering more than 30 km², show a strong linear relationship between cooling age and elevation, suggesting a steady exhumation of ~ 1 mm/yr in the Pliocene (Figure 4-4). These ages contrast significantly with ZHe cooling ages from the surrounding area (with one exception of 3.77 ± 0.39 Ma on the west side of the Arun river), which are Late Miocene (5.63 ± 0.53 - 7.23 ± 0.46 Ma) in the Kharta valley and Middle to Late Miocene (8.62 ± 0.22 - 13.30 ± 0.23 Ma) in the Riru valley. A comparison of these data on a cross-section running across the region, NW-SE from Kharta to Riru, reveals that the cooling age discontinuity occurs across the NRF and Tsun Cheng fault and does not appear to be correlated with elevation (Figure 4-5). The simplest explanation is that the apparent ages represent cooling of these structural
levels through nominal ZHe closure temperature (ca. 170-190°C; Reiners et al., 2004) by sustained differential exhumation across these structures into the Pliocene. It is important to note here that the cooling age discontinuity occurs across the Tsun Cheng fault and not the southern reach of the ADF, suggesting that, at least in the Late Miocene, throw on the southern ADF was not of a magnitude significant enough to offset ZHe cooling ages within the limitations of their analytical precision.

Our new AHe ages from the interior of the range (including footwall of the Tsun Cheng fault) are consistent with the previously reported ages of Jessup et al. (2008) and Kali et al. (2010) (Figure 4-2). The data follow a general linear trend in age-elevation space, but show considerable scatter (Figure 4-4); we caution over-interpretation of such plots considering the samples span more than 30 km E-W and 65 km N-S and examining the data in this manner likely conflates spatial and temporal variations in exhumation rate.

Surprisingly, AHe cooling ages from the hanging wall of the both the ADF/Tsun Cheng fault and NRF are also Plio-Pleistocene in age. The prominent cooling age discontinuity seen in ZHe cooling ages is substantially less pronounced in AHe cooling ages across the brittle structures, suggesting an offset of only ~ 0.75 Myr (Figure 4-4). Following Kali et al. (2010), we omit samples suggestive of He implantation or microinclusions. These samples include MJAD13 and MJAD14 of Jessup et al. (2008) where individual age replicates negatively correlate with
grain size and MJAD40 where replicate ages are significantly older than expected. In age-elevation space, two roughly linear trends can be distinguished (Figure 4-4) with both trends exhibiting an exhumation rate of ~ 0.5 mm/yr. In the hanging wall, this exhumation rate is similar to the exhumation rate implied for the exterior from higher temperature thermochronometers and suggests generally uniform and consistent exhumation since the Middle Miocene (Figure 4-6). However, the implied interior AHe exhumation rate (~0.5 mm/yr) is approximately half that of the interior ZHe rate (~1 mm/yr), suggesting continued, but reduced, exhumation along the brittle faults into the Pleistocene.

DISCUSSION OF GEOCHRONOLOGIC AND THERMOCHRONOLOGIC DATA

Our examination of the thermal history of the Ama Drime region suggests a multi-stage and multi-phase deformational history on the faults and shear zones that bound the range (Figure 4-7). Initiation of the E-W extensional shear zones, the ADSZ and the NRSZ, occurred prior to ~ 11-10 Ma (Cottle et al., 2009; Kali et al., 2010), shortly after cessation of displacement on the STFS (Hodges et al., 1994; Zhang and Guo, 2007). On the NRSZ, a short period of rapid exhumation followed with ductile displacement likely ceasing by ~ 10-9 Ma (Zhang and Guo, 2007; Kali et al., 2010). The duration of displacement on the ADSZ is not well constrained, but exhumation likely occurred over a longer period of time, possibly into the Late Miocene (Kali et al., 2010). The timing of E-W ductile shearing has been interpreted to mark the transition from N-S extension associated with
ongoing N-directed convergence in the Himalayan realm to E-W extension due to gravitational collapse of the Tibetan Plateau (Jessup and Cottle, 2010; Langille et al., 2010), although whether the exhumation of the Ama Drime Range along the ADSZ and NRSZ is kinematically linked to plateau-wide E-W extension or simply a structural culmination within predominately N-S deformation remains uncertain (Jessup et al., 2008; Cottle et al., 2009).

On the NRSZ, a period of regional relatively slow cooling followed cessation of ductile displacement, at a rate similar to that recorded in the hanging wall of both shear zones (Figures 4-6 and 4-7). ZHe cooling ages indicate that differential exhumation across the boundary faults was once again established by the Late Pliocene, an apparent exhumation rate increase not observed in the hanging wall cooling data where cooling rates remain consistent from the Middle Miocene to the Pleistocene (Figure 4-6). Given the time lapse of 5-6 Ma following NRSZ rocks cooling through 300°C, we propose that the ZHe data records a different thermal episode, likely representing a different deformational phase. This scenario is supported by structural evidence of two clear deformational phases, with high-temperature ductile shearing overprinted and truncated by brittle deformation (Figure 4-3). Thus, we suggest the ZHe data indicate initiation of shallow brittle faulting on the NRF. Brittle fabrics of the ADF also overprint ductile fabrics of the ADSZ, although thermochronologic cooling data suggest the ductile phase was longer lived on the ADSZ and the brittle and ductile fabrics may represent a continuous deformational phase. Previous workers have assumed continuous
ductile–brittle deformation based on the same sense of shear on the shear zones and high-angle brittle faults (e.g., Kali et al., 2010). However, oblique slip on the NRSZ is suggested both by the lateral offset of the STFS (e.g., Burchfiel et al., 1992) and by asymmetric porphyroclasts, S-C fabrics, and foliation-lineation relationships (Zhang and Guo, 2007), while pure dip-slip on the brittle faults is indicated by slickensides (Zhang and Guo, 2007) and by the lack of geomorphic indication of lateral slip. Coupled with the thermal data, this possible shift in deformational style is supportive of a two-phase deformational history for the eastern flank of the Ama Drime Range rather than simple progressive ductile to brittle deformation.

Evidence for two phases of extensional faulting, an early Middle Miocene phase followed by a Plio-Pleistocene phase, is suggested by thermochronologic data for several other extensional systems across Tibet. Biotite and muscovite $^{40}$Ar/$^{39}$Ar cooling ages from the shear zone of the Kung Co half graben, ~70 km to the NW of the Ama Drime Range (Figure 4-1), record rapid cooling from ~11–9 Ma, followed by a period of slow cooling until ~4 Ma when AHe dates indicate a second rapid pulse of exhumation (Mahéo et al., 2007). In the Nyainqentanglha region, low-angle ductile fabrics are overprinted by high-angle brittle faults, similar to the relationship observed on the Ama Drime boundary faults (Pan and Kidd, 1992); while several authors have interpreted extension as continual (Pan and Kidd, 1992; Harrison et al., 1995; Kapp et al., 2005), others have suggested two distinct extensional phases at ~8 Ma and ~4 Ma (Mahéo et al., 2007).
Episodic exhumation has also been recorded on the Tangra Yum Co shear zone (~13 Ma and 6 Ma) (Dewane et al., 2006) and the Shuang Hu graben (> 13.5 Ma and ~ 4 Ma) (Blisniuk et al., 2001), and interpreted by some to represent multiple, distinct, deformational phases (Mahéo et al., 2007).

Although samples were collected over a large spatial region, ZHe cooling ages fit a good linear trend with elevation and suggest exhumation at ~ 1mm/yr throughout the Late Pliocene. A comparison of AHe cooling ages from the footwall of the brittle faults to the hanging walls shows a less pronounced cooling age discontinuity across the faults than is seen in the ZHe data, consistent with a reduction in exhumation rate by the end of the Pliocene. Although there is considerable scatter in the AHe cooling age-elevation relationship, likely enhanced by the spatial scale of the samples, the data fit a general trend of ~ 0.5 mm/yr, half the rate indicated by the ZHe data. Interestingly, AHe data from the exterior of the Ama Drime Range fit a rough, but consistent trend that is subparallel to the interior data (Figure 4-4). Using the parallel trends of the assumed exhumation rates, we can estimate ~ 500-m of vertical displacement on the brittle faults in the last ~ 1 Ma using the method of McInnes et al. (1999).

Brittle extension on the ADF/Tsun Cheng fault is ongoing into very recent times (< 20 ka) based on $^{10}$Be cosmogenic nuclide exposure dating of fault-cut terraces (Kali et al., 2012). Recent exhumation rates are poorly constrained due to large errors in terrace surface dating but range from 0.6-1.4 mm/yr. Recent
displacement is also evidenced in the geomorphology for both boundary faults: clearly defined, angular faceted scarps, fault-cut glacial, colluvial, and fluvial deposits, and prominent knickpoints on the Arun and Natang Chu rivers coinciding with where the fault traces cross the rivers.

The young AHe ages in the hanging walls of the brittle faults are unusual in a region with no known exhumational mechanism and very low precipitation rates, and their exhumation requires an explanation. Given the thermal and deformational history presented here, we deduce two possible factors, likely working simultaneously, that could produce such young cooling ages. As stated above, the cooling age discontinuity in the ZHe dates is indicative of sustained faulting on the Ama Drime bounding brittle faults. If, as the ZHe cooling age data suggest, the NRF and ADF/Tsun Cheng fault accommodated significant displacement through the Miocene-Pliocene, erosion rates within the range would be high compared to the surrounding, tectonically inactive, region. In addition to differential erosion, the faulting likely produced a similar morphological signature to what we see today, producing prominent knickpoints where the faults and river systems interact (e.g., Wobus et al., 2006), and essentially maintaining a high base-level for the upstream reaches of the Arun, the Natang Chu, and their tributaries. When the magnitude of displacement reduced in the Late Pliocene, the river knickpoints would likely begin to migrate upstream. Relative base-level for all upstream reaches of the Arun, the Natang Chu, and their tributaries, would fall, increasing fluvial erosion rates as the rivers adjust to the new boundary
conditions. As the knickpoints migrate upstream, so do the high fluvial erosion rates, resulting in steeper hillslopes, and consequently, high erosion rates on the hillslopes as well. These high erosion rates would affect not only the fluvial systems surrounding the Ama Drime Range, but the interior as well, as the network of drainages crossing the range are tributaries to the two bounding rivers. Thus, erosion rates, and associated exhumation, would be similar in the footwall and hanging walls of the boundary faults, resulting in a fairly uniform exhumation pattern in low-temperature cooling age data recording the event. Re-establishment of higher displacement rates on the brittle faults, (poorly constrained, but likely in the Pleistocene) would once again set up differential exhumation by re-establishing the river knickpoints, essentially raising base-level, and slowing down exhumation rates in the hanging walls of the active faults.

Alternatively, and/or in addition to, the above scenario, if slip rates on the bounding faults were high (≥ 0.2 mm/yr) from the Middle Miocene to the Pliocene, the isotherms in the footwall of the normal faults would be advected into near parallelism with the faults, resulting in an upward curvature of the low-to-moderate-temperature isotherms (Ehlers et al., 2001). ZHe cooling age data from the interior of the Ama Drime Range suggest an average exhumation rate of ~ 1 mm/yr into the Pliocene, a rate sufficient enough to produce warped isotherms; Ehlers et al. (2001) determined the AHe closure isotherm (assuming a closure temperature of 75°C) could be advected ~ 0.8 km closer to the surface (sub-parallel to fault surface) at the these exhumation rates. If, in the Late
Pliocene, slip on the ADF/Tsun Cheng fault and NRF significantly slowed down, the elevated isotherms, no longer advected upwards from high exhumation rates, would relax and migrate vertically down through the subsurface to return to subhorizontal positions. As the 75°C closure isotherm relaxes, apatite grains below the elevated isotherm pass through their closure temperature, recording the time of thermal relaxation, rather than denudation. Given the high exhumation rates suggested by the ZHe cooling data (~1 mm/yr) over a sustained period of time (Late Miocene to Pliocene), cessation of significant displacement on the boundary faults in the Late Pliocene would likely result in concurrent fluvial and thermal responses, as described above.

CONCLUSIONS
The various exhumational origins suggested by previous workers for the Ama Drime Range (Zhang and Guo, 2007; Jessup et al., 2008; Cottle et al., 2009; Jessup and Cottle, 2010; Kali et al., 2010; Leloup et al., 2010; Langille et al., 2010) share the premise that ductile and brittle deformation are explicitly linked and the result of a single deformational phase. Our examination of the time-temperature history of the interior of the range suggests the exhumation history may be the result of several distinct deformational phases. E-W extensional exhumation along low-angle ductile shear zones initiated immediately following cessation on the STFS in the Middle Miocene (Kali et al., 2010; Jessup and Cottle, 2010; Langille et al., 2010). Exhumation on the eastern NRSZ was rapid, occurring over ~11-9 Ma, and cooling age data suggest major displacement on the
shear zone ceased by the Late Miocene. The ductile phase on the western ADSZ was longer lived, likely occurring until ~ 6 Ma. A second phase of brittle faulting was well-established by the Late Pliocene and overprints ductile deformation on both shear zones. On the eastern faults, ductile and brittle deformational events occurred over decidedly different time frames; the short-lived ductile event was followed by a period of relatively slow cooling, indicating a significant time lag before a second phase of deformation we link to faulting on discrete high-angle brittle faults as indicated by a significant ZHe cooling age discontinuity across the brittle structures. Given the time-temperature history indicated by the cooling age data, we suggest the ductile and brittle phases on the eastern margin of the Ama Drime Range represent two distinct deformational phases, rather than a single continuous exhumational event. The duration of ductile and brittle phases on the western boundary of the Ama Drime Range are not as clearly distinctive; while a period of slower cooling between ductile and brittle events is allowed within the data, that period is decidedly shorter than is seen on the eastern boundary, and within the time resolution of the available data, the data are also consistent with continuous ductile-brittle faulting.

Brittle faulting is active into the Holocene, although ZHe and AHe cooling patterns suggest a two-stage exhumation history in the Plio-Pleistocene; exhumation of the core of the Ama Drime Range occurred at ~ 1 mm/yr into the Late Pliocene, but rates slowed in the Late Pliocene-Quaternary. A reduction in the cooling age discontinuity across the brittle structures is reflected in the AHe
data, possibly the result of a combination of rapid regional erosion and thermal relaxation in response to lower slip rates.

Multi-phase exhumation and initiation of Pliocene brittle E-W extension are not unique to the Ama Drime region; a rapid pulse of exhumation has been linked to the initiation of brittle faulting at ~ 4 Ma in the nearby Kung Co half graben (Mahéo et al., 2007), and the possibility of multiple pulses of deformation has been suggested for exhumation along several rift systems on the central plateau, including the Nyainqentanglha horst, the Tangra Yum Co rift, and the Shuang Hu graben (Mahéo et al., 2007), with the youngest phase of rapid exhumation constrained to more recently than 6 Ma (Harrison et al., 1995; Blisniuk et al., 2001; Dewane et al., 2006). Our new results are consistent with a multi-phase exhumational history for the Ama Drime Range, with early Middle to Late Miocene deep-crustal ductile deformation followed by Plio-Pleistocene brittle rifting, possibility linked to a rift phase across the Tibetan Plateau, locally associated with slip on the Xainza-Dinggye rift system to the north.
REFERENCES


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FIGURE CAPTIONS

Table 4-1:
A: Apatite (U-Th)/He data from the Ama Drime region, southernmost Tibet
B: Zircon (U-Th)/He data from the Ama Drime region, southernmost Tibet

Figure 4-1: A: Geologic and structural map of the central Himalaya, after Hodges (2000). Rectangle shows extent of Figure 4-2. B: Map showing location of major extensional features described in text. Maps A and B overlap at the Ama Drime Range and Kung Co graben. Abbreviations: BNS - Bangong shear zone; DH – Dhaulagiri; EV – Everest; ITS – Indus-Tsangpo suture zone; MA – Machhapuchhare; MBTS – Main Boundary thrust fault; MCTS – Main Central thrust system; MD – Machhapuchhare detachment; MFTS – Main Frontal thrust system; NG – Nyainqentanglha shear zone; STFS – South Tibetan fault system; TG – Thakkhola Graben.

Figure 4-2: Geologic, structural, and thermochronologic map of the Ama Drime region, modified from Burchfiel et al. (1992), Cottle et al. (2007), Hodges et al. (1994), Jessup et al. (2008), Kali et al. (2010), and Zhang and Guo, (2007). Cross-sections shown in Figure 4-3 indicated on map (A-A’; B-B’). Transect for data displayed in Figure 4-5 (C-C’’) shown – striped region indicated data included in transect. Inset map shows longitudinal river profiles (bottom) for the Arun and Natang Chu rivers as well as slope-area data (top). Knickpoints marked by known
active faults shown on longitudinal profiles as well as main figure. Abbreviations:

STFS – South Tibetan fault system.

Figure 4-3: Cross-sections across the Ama Drime shear zone and fault zone (A-A’) and Nýonno Ri shear zone and fault zone (B-B’), modified from Kali et al. (2010) and Zhang and Guo (2007). Cross-section locations shown on Figure 4-3. Abbreviations: ADF – Ama Drime fault; ADSZ – Ama Drime shear zone; NRF - Nýonno Ri fault; NRSZ - Nýonno Ri shear zone; STFS – South Tibetan fault system.

Figure 4-4: Age elevation plots for A) ZHe and B) AHe (includes data from Jessup et al. (2008) and Kali et al. (2010)). Regressed line for AHe hanging wall data does not include the >3.5 Ma sample.

Figure 4-5: Thermochronologic (ZHe and AHe) transect across the Ama Drime Range (location and sample ages used shown in Figure 4-2). Dark grey shaded region shows range of ZHe cooling ages for the footwall and hanging wall of the Tsun Cheng fault and NRF; light grey shows same for AHe. Figure shows 2x vertical exaggeration. Abbreviations: ADF – Ama Drime fault; NRF - Nýonno Ri fault.

Figure 4-6: Synthesis of thermochronologic data for the hanging wall of the NRF (eastern samples) and Tsun Cheng fault – ADF (western samples). Data from:
Hodges et al. (1994); Cottle et al. (2007); Zhang and Guo (2007); Kali et al. (2010); Leloup et al. (2010); this study.

Figure 4-7: Synthesis of thermochronologic data for the footwall of the NRF (eastern samples) and Tsun Cheng fault – ADF (western samples). Data from: Rolfo et al. (2005); Liu et al. (2007); Zhang and Guo (2007); Jessup et al. (2008); Kali et al. (2010); this study.
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Figure 4-7
BACKGROUND AND MOTIVATION

The Himalayan-Tibetan orogenic system provides important insights into the possible role of extensional faulting in collisional mountain belts. By the mid-1980’s, researchers recognized the importance of extension on N-S striking fault systems in the late Cenozoic evolution of the Tibetan Plateau (e.g., Armijo et al., 1986), as well as extension on a roughly E-W-striking, N-dipping system of faults near, and roughly parallel to, the Himalayan range crest (e.g., Burchfiel et al., 1992). The first of these classes of extensional structures appears to have initiated in Middle Miocene time and remains active today (Armijo et al., 1986; Coleman & Hodges, 1995; Searle, 1995; Blisniuk et al., 2001). The earliest structures of the second class – belonging to what we refer to here as the South Tibetan fault system (STFS) – developed roughly contemporaneously with structurally lower thrusting on the Main Central thrust system (MCTS) (Hodges, et al., 1992), but are widely assumed to have ceased activity soon thereafter (Harrison et al., 1995; Nazarchuk, 1993; Hodges et al., 1996; Coleman, 1996, 1998; Searle et al., 1999; Searle & Godin, 2003). Despite this, some researchers have provided evidence of more recent extension on some ~E-W-striking faults in the Himalaya, in some
cases as recently as the Quaternary Period (Nakata, 1989; Wu et al., 1998; Hurtado et al., 2001; McDermott et al., submitted-A, -B). In this paper, I review previous work on these and other Miocene-Quaternary structures at the Himalayan range crest in light of new evidence for significant, young, N-directed extension in the Dhaulagiri-Annapurna Himalaya of central Nepal, and the Nyalam region of south-central Tibet. An important outcome of this effort is that the classical tectonostratigraphic schema for the Himalaya – developed by Gansser (1964) and expanded upon by Le Fort (1975) – is of limited value for understanding the late Cenozoic evolution of the Himalaya.

THE CLASSICAL DEPICTION OF HIMALAYAN TECTONICS AND DEVIATIONS FROM THIS APPROACH

The Himalaya are historically described in terms of tectonostratigraphic units separated by major Cenozoic fault systems that can be traced along strike for nearly the entire length of the orogenic front (e.g. Gansser, 1964; Le Fort, 1975; Hodges, 2000) (Figure 5-1). The structurally highest of these fault systems, the STFS, is a family of predominantly top-to-the-north normal faults that lie near the transition from the Tibetan Plateau to the Himalayan realm (Burchfiel et al., 1992; Hodges et al., 2001), and juxtapose unmetamorphosed Indian margin deposits of the Tibetan Sedimentary sequence against middle to upper amphibolite facies paragneisses, calc-silicate gneisses and augen orthogneisses of the Greater Himalayan sequence (e.g., Le Fort, 1975). The STFS initiated in the Early Miocene (Harrison et al., 1995; Nazarchuk, 1993; Hodges et al., 1996; Coleman,
1996, 1998; Searle et al., 1999) broadly coeval with development of the MCTS (Le Fort, 1975), a feature separating the Greater Himalayan sequence from lower amphibolite-greenschist facies quartzites and psammitic phyllites and schists of the Lesser Himalayan sequence in the footwall (Gansser, 1964; Colchen et al., 1986; Schelling, 1992). The MCTS is the oldest of the major Cenozoic thrust systems in the Himalaya ( Hubbard & Harrison, 1989; Hodges et al., 1996). Slip on both of these fault systems ceased by the Middle to Late Miocene (e.g., Searle & Godin, 2003) as the deformation front propagated southward to Main Boundary thrust system (MBTS; Meigs, 1995; DeCelles et al., 1998a), which separates the Lesser Himalayan sequence from unmetamorphosed strata of the Subhimalayan sequence. Conventional wisdom holds that, since Pliocene time, the predominance of N-directed shortening across the Himalaya has been accommodated by the Main Frontal thrust system, a series of thrust faults separating the Subhimalayan fold and thrust belt from the Gangetic Plains of India (Yeats et al., 1992; Wesnousky et al., 1999). The Main Frontal thrust system is thought to project northward beneath the Himalaya orogenic wedge as a basal decollement: the Himalayan Sole Thrust (Molnar, 1984; Hodges, 2000).

Although the STFS is an unusual feature for an orogenic wedge, the progressive southward-propagation (toward the foreland) of major thrust faults systems in the Himalaya are what we would expect based on classical wedge theory (Dahlen & Suppe, 1988). However, a number of field studies over the last two decades have provided evidence for a more complex strain history. In the central Himalaya, key
features not identified in the foundational studies of Himalayan tectonics (Gansser, 1964; Le Fort, 1975) include the following:

*Out-of-sequence thrust faulting*

Out-of-sequence thrust faulting in the hanging wall of the MCTS has been documented in several locations across central Nepal and Bhutan. In the Kali Gandaki and Modi Khola valleys of central Nepal (the Kalopani shear zone and Modi Khola shear zone, respectively, although it is likely the structures are through-going) (Hodges et al., 1996; Vannay & Hodges, 1996) (Figure 5-2) this structurally higher thrusting post-dates Early Miocene ductile slip on both the MCTS and STFS, although likely ceased by the Middle Miocene (Vannay & Hodges, 1996). Ductile deformation fabrics affect rocks of both the upper Greater Himalayan sequence and the lower Tibetan Sedimentary sequence (Vannay & Hodges, 1996), but no constraints on the amount of slip associated with the thrusting event exist. Across Bhutan, the out-of-sequence Kakhtang thrust crops out in several locations (Gansser, 1983; Davidson et al., 1997; Grujic et al., 2002). As in the Annapurna Himalaya, the Kakhtang thrust crosscuts ductile fabrics associated with the MCTS; U-Pb monazite dates reveal a maximum slip age of ~14 Ma, confirming the out-of-sequence thrusting post-dates Early Miocene deformation on structurally lower thrusts. Uniquely, the Kakhtang thrust is believed to be coeval with reactivation of a structurally higher strand of the STFS in the Middle Miocene (Grujic et al., 2002).
Out-of-sequence thrusting has also been documented near the structural level of the MCTS in several locations in central Nepal. Late Miocene-Pliocene reactivation of the MCTS has been documented in the Langtang area (Macfarlane et al., 1992) and a major displacement event occurred around the same time in the upper Lesser Himalayan sequence (Harrison et al., 1997). These thrusting events have been interpreted to be at least partially related to passive transport over the Lesser Himalayan duplex (Macfarlane et al., 1992; Harrison et al., 1997; DeCelles et al., 1998a; 1998b). In the Marsyandi valley, a Pliocene U-Pb monazite age in the MCTS shear zone led Catlos et al. (2001) to estimate >30 km of slip in the last 3 Ma within the zone; however, (U-Th)/He apatite (AHe) cooling ages in the nearby Modi Khola valley show no cooling age discontinuity suggesting no large magnitude (> 4 mm/yr) displacement in the last ~1 Ma (Nadin & Martin, 2012).

The modern uplift pattern of the Greater Himalayan sequence as inferred from fluvial character and surface morphology is suggestive of possible Quaternary out-of-sequence thrusting near its base (the approximate location of the MCTS) (Seeber & Gornitz, 1983; Wobus et al., 2003; 2006). Although a likely Holocene strand was identified ~25 km south of the MCTS in central Nepal based on a sharp change in erosion rates (Wobus et al., 2005), the geomorphic and thermochronologic data are not unique and can also be explained by the growth of a subsurface duplex (e.g. Bollinger et al., 2006).
Lesser Himalayan duplex

Across central and western Nepal, the Lesser Himalayan sequence is repeated in imbricated thrust sheets of the Lesser Himalayan duplex (Schelling, 1992; Srivastava & Mitra, 1994; DeCelles et al., 1998a; 1998b) (Figure 5-1B). Duplex growth is generally believed to be linked to a crustal ramp on the Himalayan Sole thrust (Figure 5-1B). The Lesser Himalayan duplex is considered to be an in-sequence feature, but as constraints on the timing of initiation on the Main Boundary thrust system vary over ~10 Ma (Meigs et al., 1995; DeCelles et al., 1998a), some uncertainty of this exists. Sustained growth within the duplex into the Quaternary is evident from sedimentation patterns in the lower Siwalik Group to the south (DeCelles et al., 1998a). Additionally, a broad pattern of uplift affecting the upper Lesser Himalayan sequence and lower Greater Himalayan sequence as reflected by surface morphology and fluvial profiles has been inferred to represent higher uplift rates (Seeber & Gornitz 1983; Lavé & Avouac, 2001; Wobus et al., 2003; 2006; Meade, 2010) possibly as a result of duplex growth from the transfer of rocks from the footwall to the hanging wall by underplating (Bollinger et al., 2006).

N-S extensional structures

Quaternary N-directed extension has been documented near the Himalayan crest (Nakata, 1989; Wu et al., 1998; Hurtado et al., 2001; McDermott et al., submitted-A, -B) (Figures 5-1, 5-2). One of these young strands crops out near the trace of the older STFS and in part reactivates its basal strand in the Annapurna Himalaya
(Hurtado et al., 2001): the Annapurna detachment of Brown and Nazarchuk (1993). However, other Quaternary extensional structures lie within, rather than bound, the classic tectonostratigraphic domains. The Dhaulagiri Southwest fault of Nakata (1989) is a low-angle, top-to-the-north extensional fault that cuts entirely within the Greater Himalayan sequence southeast of the Dolpo region of west-central Nepal (Figure 5-1). Easily traced for > 35 km in digital imagery (and possibly correlative to the Tibrikot fault, extending its trace to > 65 km (Nakata, 1989)), the fault displays large faceted scarps, offsets fluvial and moraine deposits, and results in the formation of distinctive sag ponds in the hanging wall. Further to the east, several generations of N-dipping normal faults are documented in the hanging wall of the STFS across much of the Dhaulagiri and Annapurna Himalaya. Originally considered to be subsidiary structures to the basal STFS, new data from the Dhaulagiri Himalaya suggest these sub-parallel structures may represent an entirely distinct phase of faulting. Minimum age constraints do not exist for the majority of the structures; however, recent low-temperature thermochronology completed in the Kali Gandaki valley of central Nepal limit the amount of Quaternary slip on the local STFS (the Annapurna detachment named above) while documenting > 6.5 km of slip in the last 1.5 Ma on a structure in its hanging wall, the Dhaulagiri detachment (McDermott et al., submitted-A). The region between the Dhaulagiri Southwest fault and the Dhaulagiri detachment has not been mapped, but given the proximity and similar structural character of the two faults we suggest their possible correlation.
In the Nyalam region of south-central Tibet, recently active (< 3.5 Ma) deformation consistent with N-directed extensional faulting within the Greater Himalayan sequence has been identified as maintaining the abrupt morphological transition between the low-relief Tibetan Plateau and the rugged Himalayan chain (McDermott et al., submitted-B).

Additional important tectonic features of the orogenic system: E-W extension

Structures related to E-W extension have been mapped across nearly the entire Tibetan Plateau, and several of the largest of these structures can be mapped striking into the Himalayan range crest (e.g., Armijo et al., 1986). Although a single initiation age for E-W extension across the Tibetan Plateau is unlikely, normal faulting on at least some of these faults began by the Middle Miocene (Coleman & Hodges, 1995; Searle, 1995; Blisniuk et al., 2001). There is, however, no doubt of Quaternary activity; faults display dramatic scarps and triangular facets, and crosscut Quaternary moraine and fluvial deposits (e.g., Armijo et al., 1986; Nakata, 1989). The majority of N-S striking faults either terminate before reaching the range crest, or are truncated by E-W striking extensional faults. In several locations, N-S striking faults cut south across the STFS and into the Greater Himalayan sequence (Burchfiel et al., 1992; Wu et al., 1998). This is true in the Nyalam region of east-central Nepal (Figure 3-3), though detailed work has shown that a young phase of N-directed normal deformation still lies to the south of all known N-S striking structures (McDermott et al., submitted-B). To the east of 87°E, the N-S striking faults that
bound the Ama Drime Range dominate the landscape, cutting > 30 km south of the STFS into the Greater Himalayan sequence (Figure 4-2). Whether these faults are also truncated by recently active east-west striking extensional faults is uncertain at this time.

Given the above, it seems apparent that the Late Cenozoic tectonic evolution of the orogenic system is more complex than predicted by simple classical wedge theory (Dahlen & Suppe, 1988). Furthering the complexity, the Plio-Pleistocene evolution of the orogenic system does not appear to coincide with the tectonostratigraphic boundaries established during Miocene orogenic growth.

My own work has focused on establishing a better understanding of young extensional faulting along the length of the central Himalayan arc. Below, I describe the structural evolution of three field locations (locations shown in Figure 5-1), within the context of the larger Himalayan tectonic evolution: (1) The Annapurna-Dhaulagiri Himalaya of central Nepal where I have documented significant top-to-the-north normal slip more recently than 1.5 Ma (McDermott et al., submitted-A) and where previous workers have noted post-18 Ma extension, with no minimum constraints, on low-angle, east-west striking normal faults in the hanging wall of the STFS (Coleman, 1996; Hodges et al., 1996; Hurtado et al., 2001; Searle & Godin, 2003), (2) the Nyalam region of south-central Tibet where the geomorphic character and cooling history implied by low-temperature thermochronology is strongly suggestive of young, top-to-the-north extension,
and (3) the Ama Drime Range of southernmost Tibet, a horst block bound on both
the east and west by N-S striking normal faults where N-directed extension has
not been documented. As I have not reported detailed structural observations of
the Annapurna-Dhaulagiri Himalaya elsewhere in this document, I do that here.
Additionally, as the regions of central Nepal to the south of the Annapurna-
Dhaulagiri Himalaya are some of the best-studied regions in the Himalaya, I
extend my examination on the timing of structural events to the range front along
a simplified transect through central Nepal. This transect incorporates data from
all structural levels within the orogen, and although variations invariably occur
along strike, is likely representative of large-scale orogenic structural evolution.
Structural details of the other two field sites are described in previous chapters
(Chapters 3 and 4) and so I report only a summary of pertinent data here. This
chapter serves to summarize structural, geomorphic, and thermochronologic data
of the three field sites, as well as to place this information into the larger context
of Late Cenozoic evolution of the orogen.

THE ANNAPURNA-DHAULAGIRI HIMALAYA OF CENTRAL NEPAL
The Kali Gandaki valley is one of the most easily accessible valleys in the
Himalaya. It forms one of the deepest valleys in the world, lying between the
8000-m peaks of Annapurna and Dhaulagiri, creating a natural north-south cross-
section through the Himalaya. As such, it is one of the best-studied regions of the
Himalaya, having been the focus of nearly four decades of research (e.g., Bordet
et al., 1971; Le Fort 1975; Colchen et al., 1986). The structural history of the
Dhaulagiri and Annapurna Himalaya is complex and the region has undergone numerous episodes of faulting, including top-to-the-south thrusting, out-of-sequence thrusting, N-S directed extension on low-angle normal faults and E-W extension (Figure 5-2). These deformational events span > 20 Ma including several taking place in quick succession in the Quaternary, making it an ideal location to examine the essential character of post-Miocene Himalayan orogenesis.

Structural evolution of the Annapurna-Dhaulagiri Himalaya

The structural history of the region can be subdivided into 5 main deformational events (we correlate our notation with other workers in Table 5-1): D$_{CN-1}$: top-to-the-south thrusting on the MCTS coeval with top-to-the-north extension on the STFS, juxtaposing the Tibetan Sedimentary Sequence on the Greater Himalayan Sequence; D$_{CN-2}$: post-peak metamorphic out-of-sequence thrusts; D$_{CN-3}$: E-W shallow, brittle extension on the N-S striking Dangardzong fault; D$_{CN-4}$: late stage brittle faulting at the structural level of D$_{CN-2}$ faults; D$_{CN-5}$: top-to-the-north extensional deformation on faults sub-parallel to, but structurally higher than, D$_{CN-1}$ normal faults. It is important to note that there are no timing constraints on the order of D$_{CN-4}$ and D$_{CN-5}$ with respect to each other, and these events may in fact be coincident. Correlated stratigraphic sections of the region shown in Figure 5-3.
EXHUMATION OF THE GREATER HIMALAYAN SEQUENCE

D_{CN-1} S-DIRECTED THRUSTING ON THE MAIN CENTRAL THRUST SYSTEM COEVAL WITH N-DIRECTED EXTENSION ON THE SOUTH TIBETAN FAULT SYSTEM

The Greater Himalayan Sequence is dominated by deformational fabrics that are here interpreted as having developed during southward exhumation of the sequence by coeval displacement on the MCTS and the STFS. All structural levels of the Greater Himalayan sequence display a pervasive and well-developed N-dipping foliation. In the structurally lowest sections this foliation is associated with top-to-the-south thrusting on the MCTS, while at structurally higher levels the foliation is linked to top-to-the-north extension on the STFS. The exact location of the MCTS is debated due to disagreement over the criteria that define the shear zone. Some workers have mapped the MCTS-zone as the lithologic contact between the Greater Himalayan Sequence and the underlying Lesser Himalayan Sequence, as is traditional across the Himalaya (Caby et al., 1983; Colchen et al., 1986; Vannay & Hodges, 1996). However, in most of central Nepal, there is no distinct metamorphic discontinuity across this lithologic boundary (Pecher, 1977; Hubbard, 1989; MacFarlane, 1995). Since the metamorphic boundary does not correspond to the lithologic boundary, other workers have mapped the MCTS-zone further to the south, at the base of a >1 km-thick high strain zone (Arita, 1983; Searle & Godin, 2003; Larson & Godin, 2009).
The STFS is known by various local names across central Nepal: the Annapurna detachment in the Kali Gandaki and Myagdi Khola valleys (Brown & Nazarchuk, 1993), the Deorali detachment in the Modi Khola valley (Hodges et al., 1996), the Chame detachment in the Marsyandi valley (Coleman, 1996) and the Dudh Khola detachment in the Dudh Khola valley (Coleman, 1996). As consistent with mapped strands of the STFS across the Himalaya, the local strands in central Nepal juxtapose the Tibetan Sedimentary Sequence directly on the Greater Himalayan Sequence. Although most structural levels of the Tibetan Sedimentary Sequence are relatively unmetamorphosed, the lower sections near the shear zone are generally greenschist facies, and up to amphibolite facies in the Modi Khola (Brown & Nazarchuk, 1993; Coleman, 1996; Hodges et al., 1996). \( D_{CN-2} \) is characterized by a well-developed north-dipping foliation \( (S_2) \), and in most locations, a NE to NNE plunging stretching lineation \( (L_2) \) is prevalent (Brown & Nazarchuk, 1993; Coleman, 1996; Hodges et al., 1996; Searle & Godin, 2003). All fabrics associated with early deformational events in the Tibetan Sedimentary Sequence are transposed parallel to detachment-related fabrics (Brown & Nazarchuk, 1993; Godin 2003). The discrete fault plane is not well-exposed in all transects, but where outcrops are accessible, the detachment crops out as a sharp, low-angle (~15-30\(^\circ\)) structure encased in a 300 m to 1500 m-thick mylonitic or high strain zone that affects both the lower Tibetan Sedimentary Sequence and the upper Greater Himalayan Sequence (Brown & Nazarchuk, 1993; Hodges et al., 1996; McDermott et al., submitted-A). Kinematic indicators are best developed in footwall leucogranite bodies in the Myagdi Khola and Marsyandi valleys, where
S-C fabrics indicate top-to-the-north and oblique top-to-the-west normal sense of shear, respectively (Coleman, 1996; Searle & Godin, 2003; McDermott et al., submitted-A). Footwall rocks preserve extensive ductile fabrics demonstrating extensional shearing, but in the Kali Gandaki valley, these fabrics are overprinted by late-stage brittle deformation suggesting at least two phases of N-directed normal faulting on this structure (Brown & Nazarchuk, 1993; Godin et al., 2001; Hurtado et al., 2001). Several generations of highly deformed to undeformed anatectic leucogranite bodies can be found throughout the shear zone, some of which are truncated by the STFS while some cross-cut the fault zone into the Annapurna Yellow Formation above (Godin et al., 2001; Hurtado, 2002; McDermott et al., submitted-A). Early generations of these leucogranite bodies are highly sheared and extended or shortened depending on orientation, while later generations are only weakly sheared to undeformed, indicating that leucogranite emplacement was synkinematic to post-kinematic with displacement on the STFS (Brown & Nazarchuk, 1993).

S-DIRECTED OUT-OF-SEQUENCE THRUSTING

$D_{CN-2}$ – THE KALOPANI & MODI KHOLA SHEAR ZONES

In the western region of central Nepal, a structural discontinuity identified within the Greater Himalayan sequence represents an out-of-sequence, thrust-sense shear zone that is locally referred to as the Kalopani shear zone in the Kali Gandaki (Vannay and Hodges, 1996) and the Modi Khola shear zone in the Modi Khola valley (Hodges et al., 1996) ($D_{CN-2}$). In the Kali Gandaki valley, $D_{CN-2}$ is defined
by a crenulation cleavage (L_{CN-2c}) and asymmetric micro-kink folds (F_{CN-2}); no new mineral growth is associated with D_{CN-2} deformation, and the event is constrained to post-peak metamorphism developed during D_{CN-1} as L_{2c} overprints S_{1} in the D_{CN-1} high strain zone (Godin, 2003). In the Modi Khola, the shear zone is ~ 1500 m-thick, and is defined by a well-developed schistosity/gneissosity (S_{CN-2}), associated stretching lineation (L_{CN-2s}), asymmetric fold trains (F_{CN-2}), and rare SC fabrics within granitic bodies (Hodges et al., 1996). Previous planar fabrics are transposed parallel to S_{CN-2} and L_{CN-2s} overprints earlier fabrics in the upper Greater Himalayan Sequence. As the shear zone is truncated by D_{CN-5} structures, the original width is unknown (Hodges et al., 1996).

**EAST-WEST EXTENSION**

**D_{CN-3} - N-S STRIKING EXTENSIONAL FAULTS INCLUDING THE DANGARDZONG FAULT**

In the Annapurna-Dhaulagiri region, the most prominent structural feature indicative of E-W extension is the Thakkhola graben, a roughly north-south trending feature that can be traced from near the Indus-Tsangpo suture zone to the crest of the Himalayan range (Fort et al., 1982; Hurtado et al., 2001; Garzione et al., 2003). The principal growth structure for the graben, the Dangardzong fault (D_{CN-3}), forms the western boundary of the graben and can be traced for > 100 km along strike. This high-angle normal fault has accommodated > 4 km of dip-slip displacement in the north, but displacement decreases to the south, and is very small at its termination between the peaks of Dhaulagiri and Annapurna. South of Jomsom, the fault trace is unclear and poorly constrained; the fault crops out
again near the village of Titi, where Hurtado et al. (2001) map a short segment of the fault. The short segment mapped by Hurtado et al. (2001) appears to be offset in a right-lateral sense from the fault trace to the north; the location of this offset coincides with the mapped extension of the Dhaulagiri detachment. Our assertion that the Dhaulagiri detachment is younger than the Dangardzong fault is based on this apparent crosscutting relationship. No trace of the Dangardzong fault is seen south of the Annapurna detachment, leading several workers to suggest the most recent movement on the detachment truncates the Dangardzong fault (Hurtado et al., 2001; Godin, 2003). Several additional N-S striking, sub-vertical normal faults of varying size related to E-W extension have been mapped to the east and west of the Dangardzong fault (Figure 5-2). None of these faults can be traced south of the STFS.

**Late-stage N-directed extension at the structural level of the STFS in the Kali Gandaki valley**

**D_{CN-4} - Late-stage brittle deformation on the Annapurna detachment**

Brittle motion on the Annapurna detachment (D_{CN-4}) occurred post-ductile shearing as evidenced by post-leucogranite emplacement, kyanite field annealing recrystalization, and a brecciated, brittle shear zone with boudinaged dikes that overprints the earlier ductile fabrics (Brown & Nazarchuk, 1993) This phase of late brittle deformation resulted in the truncation of N-S striking normal faults in the Tibetan Sedimentary Sequence, including the Dangardzong fault (Hurtado et al., 2001). The timing of this deformation is constrained by crosscutting
relationships with these N-S striking faults, but the total amount of displacement that occurred during this stage has not been constrained. Previous workers have defined separate fault strands on the east side of the Kali Gandaki River for the ductile and brittle events based in part on the presence of the Larjung Formation, a 200-m-thick amphibolite facies calc-silicate gneiss mapped by Vannay & Hodges (1996) as the uppermost unit in the Greater Himalayan sequence based on lithologic similarities to the underlying Formation II. An examination of the elemental composition of the Larjung Formation using X-ray fluorescence (XRF) suggests the composition more closely resembles the above lying Annapurna Yellow Formation, and thus we prefer the original classification of Colchen et al. (1986) of the Larjung Formation as a high-grade equivalent of the over-riding Tibetan Sedimentary Sequence. This reinterpretation of the Larjung Formation suggests that two fault strands are unnecessary, as an upper strand is no longer required to maintain the juxtaposition of the Tibetan Sedimentary sequence on the Greater Himalayan sequence by the STFS. Therefore, we assert the likelihood that only one strand of the Annapurna detachment exists, and late-stage brittle motion on the detachment occurred as a reactivation of the previously ductile strand.

QUATERNARY N-DIRECTED EXTENSION

D_{CN-5} – N-S EXTENSION ON LOW-ANGLE STRUCTURALLY HIGHER NORMAL FAULTS IN THE TIBETAN SEDIMENTARY SEQUENCE

Low-angle, N-directed extensional structures, sub-parallel to, but structurally higher than the STFS have been mapped across central Nepal, but until recently,
these structures have been considered subsidiary to the basal detachments. The newly documented Quaternary displacement on the Dhaulagiri detachment in the Myagdi Khola and Kali Gandaki valleys (McDermott et al., submitted-A) suggests the possibility that some of the previously recognized low-angle faults of unconstrained age are, in fact, Quaternary.

The Dhaulagiri detachment crops out ~ 2.5 km north of the village of Larjung as a discrete, shallow-dipping (~25°) fault plane surrounded by a brecciated zone approximately 200 m-wide. It can be traced 15 km to the west along strike, across the snowfields of Dhaulagiri to the Myagdi Khola valley near Italian base camp (Figure 5-2). In the Myagdi Khola valley, footwall rocks are dominated by highly sheared leucogranite dikes. Shear sense indicators are absent in the Kali Gandaki valley, but top-to-the-north sense of shear is evidenced in the Myagdi Khola by asymmetric extensional boudinage of leucogranite dikes and a down-dip stretching lineation (062/28) (L$_{CN-5m}$). Footwall rocks display a strong mica-defined foliation which dips parallel to the fault plane (S$_{CN-5}$), while hanging wall rocks are dominated by crustal-scale folds, all of which are truncated by the Dhaulagiri detachment (Figure 5-2). Although the Dhaulagiri detachment lies completely within the Annapurna Yellow Formation, it represents a distinct metamorphic discontinuity; footwall rocks are metamorphosed to greenschist facies while hanging wall rocks are unmetamorphosed. Leucogranite dikes linked to anatexis during displacement on the Annapurna detachment can be found throughout all structural levels of the footwall of the Dhaulagiri detachment,
however, although several dikes can be traced into the fault zone in the Myagdi Khola valley, the highly deformed and ductilely sheared discordant dikes have been overprinted by cataclastic deformation within the brecciated brittle fault zone, and no leucogranite dikes have been identified above the fault zone.

In the Modi Khola, ~ 35 km to the east of the Kali Gandaki, the Machhapuchhare detachment of Hodges et al. (1996) is a low-angle (~25°) west-northwest striking brittle-ductile shear zone, which like the Dhaulagiri detachment, lies sub-parallel to, but structurally above, the basal STFS (Hodges et al., 1996; McDermott et al., submitted-A). Although the discrete fault plane is not well exposed, near-fault rocks are intensely brecciated, and kinematic indicators in the footwall reveal top-to-the-north normal sense of shear. The shear zone marks a sharp metamorphic discontinuity, placing greenschist facies Sanctuary Formation rocks on amphibolite facies rocks of the Annapurna Yellow Formation. The fault serves as the truncating boundary for macroscale folds that dominate the hanging wall, and all leucogranite dikes and sills that cross-cut the footwall. Several younger sub-parallel normal faults, such as the Hiunchuli detachment, have been mapped in the hanging wall of the Machhapuchhare detachment. Hodges et al. (1996) interpreted these faults to be imbricate structures to the Machhapuchhare detachment, but their significance remains unclear. Although detailed field mapping between the Dhaulagiri detachment and the Machhapuchhare detachment does not currently exist, Hurtado (2002) noted a short segment of the Dhaulagiri detachment ~ 10 km to the east of the Kali Gandaki river valley that truncates the macroscale folds.
in the hanging wall, and juxtaposes rocks of the Sanctuary Formation on Annapurna Yellow Formation rocks. This is the same stratigraphic relationship documented in the Modi Khola on the Machhapuchhare detachment (Hodges et al., 1996), and lends support of correlation between the two structures.

Due to poor infrastructure and political sensitivity until very recently, the region to the west of the Myagdi Khola is poorly explored, and little is known about its structural evolution. Nakata (1989) documented a young top-to-the-north low-angle normal fault, the Dhaulagiri Southwest fault. The Dhaulagiri Southwest fault is clearly Quaternary in age, displaying large triangular facets, sag ponds, and offset moraines linked to the last glacial maximum (Nakata, 1989), while the upper fault scarps offset hillslopes, and river drainages, and have persisted in spite of extensive human alteration of the landscape. The Dhaulagiri Southwest fault lies within undifferentiated Greater Himalayan Sequence rocks and has been correlated to the east with both the STFS and the MCTS, despite its clear normal sense (Nakata, 1989; Hurtado, 2002). The Dhaulagiri Southwest fault and Tibrikot fault can be traced for a combined distance of > 100 km, and display obvious young displacement, facts suggestive of significant Quaternary displacement. Inasmuch as the Dhaulagiri Southwest fault strikes toward the Dhaulagiri detachment, and appears to be of similar age and structural character, we note the likely correlation of these structures, but more detailed mapping is needed.
Constraints on the timing of deformational events across central Nepal

Multiple researchers have used geochronologic, thermochronologic, structural and geomorphic methods to constrain the timing and duration of deformational events in central Nepal. Here we summarize the results of that work, incorporating new low-temperature thermochronologic data for the Dhaulagiri Himalaya (Figure 5-4) produced as part of my dissertation research. Additionally, as the region to the south of the Dhaulagiri-Annapurna Himalaya has been the focus of numerous studies, we extend our discussion on the timing of deformational events from our field site to the front of the range, therefore covering a complete cross-section through the Himalaya (Figure 5-1B).

Constraints on Early Miocene deformational events

Ductile displacement on the MCTS \((D_{CN-1})\) is constrained by U-Th-Pb zircon and monazite dating of amphibolite-facies rocks within the \(D_{CN-1}\) shear zone to ~ 22-18 Ma (Coleman & Parrish, 1995; Hodges et al., 1996; Catlos et al., 2001; Coleman, 1996). Ductile slip on the STFS is constrained to similar ages, ~ 23-18 Ma based on U-Th-Pb zircon and monazite ages from deformed and undeformed crosscutting leucogranites in the \(D_{CN-1}\) shear zone (Nazarchuk, 1993; Coleman & Parrish, 1995; Hodges et al., 1996; Searle & Godin, 2003), and is believed to be coeval with the MCTS. It is commonly held that significant slip on both of these structures ceased by the Middle Miocene (e.g., Searle & Godin, 2003).
Constraints on Middle to Late Miocene deformational events

$^{40}$Ar/$^{39}$Ar muscovite cooling dates have been published for samples collected from the upper Greater Himalayan Sequence and lower Annapurna Yellow Formation, including transects across $D_{CN-1}$, $D_{CN-2}$, and $D_{CN-5}$ structures (Vannay & Hodges, 1996; Coleman, 1998; Godin et al., 2001). Cooling ages within the Greater Himalayan Sequence across central Nepal consistently range from ~17-12 Ma with no correlation with structural position or distinct age discontinuity across the $D_{CN-2}$ Kalopani shear zone in the Kali Gandaki valley. These data led Vannay and Hodges (1996) to conclude that the entire Greater Himalayan sequence cooled homogeneously through the muscovite closure temperature (~350°C) during that time period. The $^{40}$Ar/$^{39}$Ar muscovite cooling ages, thereby, provide a minimum age for deformation on the Kalopani shear zone, and perhaps the Modi Khola shear zone as well if the two structures are correlated.

The upper structural boundary for the Middle Miocene cooling ages varies along strike in central Nepal. In the Marsyandi river valley, the upper limit is the Chame detachment (Figure 5-2), which represents a sharp cooling age discontinuity between Middle Miocene ages in the footwall and Oligocene cooling ages in the hanging wall (Coleman, 1998). In the Kali Gandaki valley, muscovite cooling ages across the Annapurna detachment and into the lowermost Annapurna Yellow Formation are slightly younger, although within error of the 15-13 Ma cooling ages in the Greater Himalayan Sequence, at 12.7±0.4 and 11.8±0.4 Ma (Vannay & Hodges, 1996; Godin et al., 2001). They are, however, significantly different
from the one sample in the hanging wall of the Dhaulagiri detachment (D_{CN-5}) at 18 Ma (Godin et al., 2001), making the upper boundary of this cooling pattern a D_{CN-5} structure.

An $^{40}$Ar/$^{39}$Ar muscovite cooling age from a roughly north-south striking extensional fault in the Marsyandi valley constrains the initiation of east-west extension on D_{CN-4}-type faults to \(~14\) Ma in central Nepal (Coleman & Hodges, 1995); basin fill deposits suggest slip on the Dangardzong fault (D_{CN-4}) likely began \(~11\) Ma (Garzione et al., 2003).

The growth of the Lesser Himalayan duplex (Figure 5-1B) likely occurred over a sustained period of time, and therefore the timing of initiation is difficult to define with geochronologic constraints. In western Nepal, the duplex dissects sections of the Dumri Formation, and thus, must post-date \(~15\) Ma (DeCelles et al., 1998a); detrital zircons of the granitic provenance of the northern part of the duplex record \(~12-11\) Ma (DeCelles et al., 1998b), while carbonate nodules similar to those in the southern portion of the duplex suggest an erosional influx \(~9-8\) Ma (Quade et al., 1997). Within the Himalayan literature, the Lesser Himalayan duplex has been inexplicitly linked with the Main Boundary thrust system and the Himalayan Sole thrust to which it roots (e.g., DeCelles et al., 2001; Pearson & DeCelles, 2005; Bollinger et al., 2006). However, due to some discrepancy in age constraints on the Main Boundary thrust system, there is some question as to the sequence between the two. In western Nepal, crosscutting relationships allow for
displacement on the Main Boundary thrust system from ~ 15 – 2 Ma (DeCelles et al., 1998a), while provenance age data in India support an active structure by ~ 9 Ma, possibly as early as ~ 11 Ma (Meigs et al., 1995). In the model proposed by Pearson & DeCelles (2005), the Main Boundary thrust system acts as the duplex floor structure, and thus, would initiate late in the stage of duplex growth, constraining possible initiation of the Main Boundary thrust system ~ 5 Ma. Given the uncertainties on the initiation age of the thrust system, the common assumption that the Lesser Himalayan duplex is an in-sequence feature is open to question. Sedimentation patterns indicate duplex growth is ongoing, although likely due to ramp-uplift related to the Main Frontal thrust system rather than the Main Boundary thrust system, in more modern times (e.g., Bollinger et al., 2006).

Late Miocene-Pliocene brittle reactivation of the MCTS has been documented in the Langtang area of central Nepal (Macfarlane et al., 1992). Given the diachronous nature of ductile and brittle thrusting on the MCTS in this region, Macfarlane et al. (1992) suggested the brittle phase may be related to a deeper crustal ramp. This interpretation, of course, is dependent on initiation of the Main Boundary thrust system prior to ~ 8 Ma.

*Constraints on Quaternary deformational events*

The Main Frontal thrust system, the southernmost structure in the fold-and-thrust belt, displays clear Holocene slip, cutting young alluvial and fluvial deposits across the front of the orogen (Nakata, 1989; Lavè & Avouac, 2000), and is
usually inferred to have initiated in Late Pliocene time, although that date is poorly constrained (DeCelles et al., 2001).

As discussed above, several Miocene structures exhibit evidence of ongoing activity into the Quaternary, including the Lesser Himalayan duplex (DeCelles et al., 1998a; Bollinger et al., 2006), out-of-sequence thrusting (Wobus et al., 2005), east-west extension on the Tibetan Plateau (the Dangardzong fault (D_{CN-3}) in our field area) (e.g., Armijo et al., 1986; Godin, 2003).

Quaternary slip on east-west striking, N-directed extensional faults has been documented across central Nepal (Nakata, 1989; Hurtado et al., 2001; McDermott et al., submitted-A). At its southernmost termination, the Dangardzong fault is truncated by brittle deformation on the Annapurna detachment (Figure 5-2), suggesting brittle reactivation of the Annapurna detachment (D_{CN-4}) occurred more recently than 17 ka (Brown & Nazarchuk, 1993; Hurtado et al., 2001; Godin, 2003). A zircon (U-Th)/He (ZHe) transect across the Annapurna detachment yielded no cooling age discontinuity within the precision of the method, constraining the maximum amount of slip to be ~ 2 km in the last 3.5 Ma (assuming a geothermal gradient of 30°C/km) (McDermott et al., submitted-A). The minimum age of deformation on the Annapurna detachment has not been constrained.
AHe and ZHe ages across the $D_{CN-5}$ Dhaulagiri detachment reveal an abrupt cooling age discontinuity of ~ 10 million years, juxtaposing rocks with Late Miocene cooling ages in the hanging wall directly on rocks with Pleistocene cooling ages in the footwall, and indicating the Dhaulagiri detachment has accommodated significant top-to-the-north normal displacement (estimated at > 6.5 km of vertical throw) in the last 1.5 Ma (McDermott et al., submitted-A). AHe and apatite and zircon fission track ages (AFT and ZFT, respectively) from similar structural levels in the Marsyandi valley to the east range from 0.3 – 0.9 Ma (AHe), 0 – 3.8 Ma (AFT) and 0.8 – 1.9 Ma (ZFT) (Blythe et al. 2007). In all regions with low-temperature thermochronologic constraints, young cooling ages are found across the basal STFS and into the lower structural levels of the Annapurna Yellow Formation (Blythe et al., 2007; McDermott et al., submitted-A). As no thermochronologic data exist across the $D_{CN-5}$ Machhapuchhre detachment in the Modi Khola valley, and fabrics related to $D_{CN-5}$ crosscut 18 Ma leucogranites, a maximum age of 18 Ma with no minimum constraints is applied to these structures (Hodges et al., 1996). If, as we propose, the Dhaulagiri detachment is correlative with the Machappuchhare detachment in the Modi Khola, then Quaternary slip on that structure is likely as well. As minimum ages on $D_{CN-3}$, $D_{CN-4}$, and $D_{CN-5}$ structures are very difficult to constrain, our notation of slip on the Dhaulagiri detachment as the most recent deformational event in the region is based on possible right-lateral offset of the Dangardzong fault by the Dhaulagiri detachment as reported by McDermott et al. (submitted-A).
THE NYALAM REGION OF SOUTH-CENTRAL TIBET

Deformational events in the Nyalam region and constraints on the timing of events

The structural evolution of the Nyalam region (Figure 3-3) is dominated by three distinct deformational events: $D_{NY\text{-}1}$: top-to-the-south thrusting on the MCTS coeval with top-to-the-north extension on the STFS; $D_{NY\text{-}2}$: E-W shallow, brittle extension on roughly north-south striking faults; $D_{NY\text{-}3}$: differential uplift at PT$_1$, most consistent with N-directed extension on east-west striking faults. There are no timing constraints on the order of $D_{NY\text{-}2}$ and $D_{NY\text{-}3}$ with respect to each other and the order implied here is solely based on deformational events in other locales that may not be representative of the Nyalam region.

EARLY TO MIDDLE Miocene exhumation of the Greater Himalayan sequence

$D_{NY\text{-}1}$ - S-DIRECTED THRUSTING ON THE MAIN CENTRAL THRUST SYSTEM COEVAL WITH N-DIRECTED EXTENSION ON THE SOUTH TIBETAN FAULT SYSTEM

Fabrics related to the most prevalent deformational event, $D_{NY\text{-}1}$ ($D_3$ of Hodges et al., 1993), are pervasive throughout the Greater Himalayan sequence. $D_{NY\text{-}1}$ is characterized by a penetrative foliation ($S_{NY\text{-}1}$) and associated mineral lineation ($L_{NY\text{-}1}$) defined by the alignment of kyanite, muscovite, and sedimentary quartz grains (Hodges et al., 1993). Near the base of the sequence, shear sense indicators record top-to-the-south thrusting and have been linked to displacement on the MCTS (Burg et al., 1984; Burchfiel et al., 1992; Hodges et al., 1993). Near the
top of the sequence, in the footwall of the Nyalam detachment (the basal structure of the STFS, Burchfiel et al., 1992), $S_{NY-1}$ has been transposed into a well-developed S-C fabric which intensifies with upward structural level (Hodges et al., 1993). Mica “fish” and asymmetric augen structures indicate northward shearing on the STFS (Burg et al., 1984; Burchfiel et al., 1992; Hodges et al., 1993).

Ductile deformation on the Nyalam detachment occurred ~ 17-15 Ma (Schärer et al., 1986; Burchfiel et al., 1992; Dougherty et al., 1998). Several generations of strongly deformed to undeformed leucogranites are mapped within the Nyalam detachment shear zone; the least deformed of these yielded a monazite U-Pb crystallization age of 16.8 ± 0.6 Ma, leading Hodges et al. (1993) to interpret the initiation of ductile deformation to before this date. $^{40}\text{Ar}/^{39}\text{Ar}$ biotite dates cluster around 16-14 Ma throughout the Greater Himalayan sequence (Figure 3-3), suggesting the entire sequence cooled rapidly through the biotite closure temperature (~ 300°C; Harrison et al., 1995) in the Middle Miocene (Wang et al., 2006).

**EAST-WEST EXTENSION – TIMING UNKNOWN**

$D_{NY-2}$ – EAST-WEST EXTENSION ON N-S STRIKING NORMAL FAULTS

The Nyalam detachment is dissected by roughly north-south striking normal faults that cut from the lower Tibetan Sedimentary sequence into the uppermost Greater Himalayan sequence (Figure 3-3). These structures appear to be shallow, brittle
features and no ductile deformation has been observed (Burchfiel et al., 1992). The faults cut both ductile and brittle deforma-
tional fabrics associated with $D_{NY-1}$ (Wang et al., 2006). The total amount of slip associated with this extension is unknown, but $^{40}\text{Ar}/^{39}\text{Ar}$ biotite dates in the footwall and hanging wall of individual faults reveal no discontinuity in cooling age (Wang et al., 2006), suggesting either that the faulting occurred post-exhumation of the Greater Himalaya sequence or that the slip on the N-S striking faults was insufficient to produce a discontinuity in $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages within the limit of analytical precision, or both. No other constraints on the timing of faulting exist.

**PLIO-PLEISTOCENE N-DIRECTED EXTENSION**

Although no discrete structure linked to N-S extension has been mapped in the Nyalam region, significant N-directed extension at PT$_1$ is inferred from the geomorphic character of PT$_1$ and a distinct break in the cooling histories of the rocks to the north and south of the transition (Figure 3-7). This deformation initiated at $\sim 3.5$ Ma, and given the abrupt nature of the morphologic break, is likely active or recently active. Unlike the young, N-directed extensional structures in central Nepal which lie within the Tibetan Sedimentary sequence, structurally above the STFS, this inferred deformation lies well to the south of the STFS, entirely within the Greater Himalayan sequence.

No constraints on the relative timing between E-W extension and N-S extension exist in the Nyalam region. All mapped N-S striking extensional faults die out
well to the north of PT₁, and thus, no potential cross-cutting relationships can be evaluated. The categorization of D_{NY-2} and D_{NY-3} is solely based on initiation of E-W extension on the Tibetan Plateau: Middle Miocene in several known locations near the range crest (Coleman & Hodges, 1995; Searle, 1995; Blisniuk et al., 2001). As E-W extension continues into Recent times, the faulting in the Nyalam region could have occurred prior to, synchronously with, or, given the fact that no minimum age constraints exist on either set of structures, postdate deformation on N-directed extensional faults.

THE AMA DRIME REGION OF SOUTHERNMOST TIBET

Although the Ama Drime region has been the focus of research for nearly 100 years, much controversy exists over the structural evolution of the region and what geodynamical processes are responsible for Ama Drime Range itself. The Ama Drime Range is a domical feature, bound on both the eastern and western margins by low-angle ductile shear zones (N̄yonno Ri shear zone (NRSZ and Ama Drime shear zone (ADSZ) on the east and west, respectively) overprinted by high-angle brittle faults (N̄yonno Ri fault (NRF) and Ama Drime fault (ADF), again on the east and west, respectively) (Figures 4-2, 4-3); some workers interpret the Ama Drime Range as a metamorphic core complex, although likely kinematically linked to E-W extension on the Tibetan Plateau (Jessup et al., 2008; Cottle et al., 2009; Jessup & Cottle, 2010; Langille et al., 2010), while others have suggested that it may simply be a horst of the Xainza-Dinggye rift system and do not attribute special significance to the domical character of the range (Zhang &
Guo, 2007; Kali et al., 2010; Leloup et al., 2010). Given the consistent sense of shear observed through both the ductile and brittle phases, previous workers have considered the bounding faults to represent progressive exhumation through the ductile and brittle zones (e.g., Kali et al., 2010). Our new low-temperature thermochronologic data, combined with high- and low-temperature geochronometry and thermochronometry of previous workers indicates a significant period of regional slow cooling occurred between higher temperature and low-temperature chronometry on the eastern margin of the range, suggesting the ductile and brittle fabrics represent two distinctly different deformational events. This period of relatively slow cooling is present on the western margin, but as the time lag is significantly smaller, deformation may have been progressive on the western faults. Following this, we recognize three deformational phases: $D_{AD-1}$: top-to-the-north extension on the STFS presumed to be coeval with S-directed thrusting on the MCTS, $D_{AD-2}$: E-W extension on low-angle ductile shear zones, and $D_{AD-3}$: several generations of N-S striking, high-angle brittle normal faults that overprint ductile fabrics associated with $D_{AD-2}$. Unlike in Nyalam and central Nepal, no evidence for post-Miocene N-directed extension has been documented in the Ama Drime region; however, as there is some possibility that $PT_1$ may lie to the south of the field site explored in the current work, we do not conclusively rule out its existence.
EARLY TO MIDDLE MIocene exhumation of the Greater Himalayan sequence

$D_{AD-1}$ - S-directed thrusting on the Main Central thrust system coeval with N-directed extension on the South Tibetan fault system

Deformational fabrics associated with $D_{AD-1}$ are pervasive throughout the Greater Himalayan sequence and have been linked with the exhumation of the sequence by coeval displacement on the STFS and the MCTS (Burchfiel et al., 1992; Hodges et al., 1994). $D_{AD-1}$ is defined by a NNE striking foliation ($S_{AD-1}$), down-dip mineral lineation ($L_{AD-1}$), and well-developed S-C mylonitic fabric ($S_{AD-1}$-$C_{AD-1}$) (Burchfiel et al., 1992; Hodges et al., 1994). Ductile deformation on the Dinggye detachment (local strand of the STFS in the Dinggye region, to the east of the Ama Drime massif) occurred between ~ 16 and 13 Ma (Hodges et al., 1994; Zhang & Guo, 2007; Leloup et al., 2010) while ductile slip on Dzakaa Chu strand (STFS to the west of the Ama Drime massif) occurred < 20 Ma (Cottle et al., 2007).

MIDDLE TO LATE MIocene extension on N-S striking ductile shear zones

$D_{AD-2}$ – E-W extension on the Ama Drime and Nyonno Ri shear zones

Within the core of the Ama Drime massif, fabrics related to $D_{AD-1}$ are nearly entirely obscured by overprinting of $D_{AD-2}$ fabrics, with rare exceptions in the core of the range and along the western limb where polyphase folding suggests an earlier deformational event (Jessup et al., 2008). The NRSZ is marked by a NNE-SSW striking ~ 300-m-thick shear zone (Zhang & Guo, 2007; Jessup et al., 2008;
Kali et al., 2010; Langille et al., 2010). The shear zone dips ~20°E and displays a prominent foliation ($S_{AD-2}$) with associated down-dip stretching lineation ($L_{AD-2}$). Shear-sense indicators, including a well-developed S-C fabric and shear bands around semirigid feldspar grains, record top-to-the-east normal sense of shear (Burchfiel et al., 1992; Zhang & Guo, 2007; Jessup et al., 2008; Langille et al., 2010). The dominant foliation shallows to horizontal in the core of the range, and becomes progressively steeper to the east and west. Thus, on the western side, the ADSZ displays a penetrative mylonitic foliation ($S_{AD-2}$), with down-dip mineral lineation ($L_{AD-2}$) and feldspar shear bands indicating top-to-the-west shear (Jessup et al., 2008).

Monazite (U-Th)/Pb apparent ages constrain ductile displacement on the NRSZ to ~ 11-10 Ma (Kali et al., 2010) while $^{40}$Ar/$^{39}$Ar muscovite and biotite cooling ages from the footwall are ~ 10-9 Ma (Zhang & Guo, 2007; Kali et al., 2010) suggesting rapid exhumation perhaps associated with ductile deformation on the NRSZ (~400°C in < 2 Ma) (Figure 4-6). Ductile deformation on the ADSZ is not as well constrained; an amphibolite boudin-cutting leucogranite yields a monazite date of 11.6±0.4 Ma (Cottle et al., 2009), but $^{40}$Ar/$^{39}$Ar muscovite and biotite cooling ages vary significantly in the footwall of the ADF (from 23.5 – 6.2 Ma; Kali et al., 2010), suggesting ductile deformation may occurred over a longer time interval (Figure 4-2).
Plio-Pleistocene extension on high-angle brittle faults

DAD-3 – Brittle E-W extension on the Amadrime and Nyonno Ri faults

The NRSZ and ADSZ are both truncated and offset by high-angle (~45°) normal faults with the same sense of shear (top-to-the-west on the ADF and top-to-the-east on the NRF) (Figure 4-3). The brittle fault zone of the ADF is marked by abundant fault gouge and fragmented ductile mylonitic fabrics (Langille et al., 2010), while the NRF zone exhibits slickensides and microbreccia overlying chloritic breccia (Zhang & Guo, 2007).

A period of regional relatively slow cooling followed the rapid exhumation on the shear zones, although is more prevalent on the NRSZ (Figure 4-6). ZHe cooling ages indicate significant differential exhumation was once again well-established by the Late Pliocene; given the time lapse of 5-6 Ma following shear zone rocks cooling through 300°C, we propose that the ZHe data records a different thermal episode, likely representing initiation of brittle extension as a distinct deformational phase from ductile deformation. This scenario is supported by structural evidence of two clear deformational phases, with high-temperature ductile shearing overprinted and truncated by brittle deformation. Although samples were collected over a large spatial region, ZHe cooling ages from within the range fit a good linear trend with elevation and suggest exhumation at ~1mm/yr throughout the Late Pliocene (Figure 4-4). A comparison of AHe cooling ages from the footwall of the brittle faults to the hanging walls shows a less pronounced cooling age discontinuity across the faults than is seen in the ZHe
data, consistent with a reduction in exhumation rate by the end of the Pliocene. Although there is considerable scatter in the AHe cooling age-elevation relationship, likely enhanced by the spatial scale of the samples, the data fit a general trend of ~ 0.5 mm/yr, half the rate indicated by the ZHe data. Brittle extension is ongoing into very recent times (< 20 ka) based on $^{10}$Be cosmogenic nuclide exposure dating of fault-cut terraces on the west (Kali et al., 2012) and clearly defined, angular faceted scarps, fault-cut glacial, colluvial, and fluvial deposits, and prominent knickpoints on the Arun and Natang Chu rivers coinciding with where the fault traces cross the rivers.

TECTONIC RECONSTRUCTIONS
My recent work in the Dhaulagiri – Annapurna Himalaya of central Nepal, and the Nyalam region of south-central Tibet suggests the significance of N-directed extensional faulting near the Himalayan range crest may not be limited to the Early Miocene (McDermott et al., submitted-A, -B). Evidence for young N-directed extension was not found in the Ama Drime region, but as its existence cannot be ruled out with certainty at this time, I do not address the lack of such in this reconstruction.

Here, I take a closer look at the sequence of structural development throughout the orogen. As a transect across central Nepal yields the most complete structural data, the cross-section shown (Figure 5-5) is directly applicable there and contains details known about central Nepal that may not transfer to other regions, although
many structural events shown can be correlated along strike. Correlated deformational events between the three field sites are shown in Figure 5-6.

*Early to Middle Miocene (~ 22 – 15 Ma) - Active structures: STFS and MCTS*

Contemporaneous slip on the STFS and MCTS initiated ~ 22-20 Ma in central Nepal and likely slightly later (~18-16 Ma) to the west, resulting in exhumation of the Greater Himalayan sequence (e.g., Hodges et al., 1992). Significant slip on both fault systems ceased by the Middle Miocene.

*Middle to Late Miocene (~ 14 - 5 Ma) – Active structures: Main Boundary thrust system, Lesser Himalayan duplex and E-W extension on the Tibetan Plateau*

After a short duration of out-of-sequence thrusting on the Kalopani/Modi Khola shear zones in central Nepal (~ 18 – 15 Ma) (Vannay & Hodges, 1996), the significance of which remains unknown, the thrust front migrated to the south. Shortening initiated on the Ramgarh thrust, the roof thrust of the Lesser Himalayan duplex that can be traced at least across Nepal (Pearson & DeCelles, 2005), on a similar time frame as initial east-west extension began on the Tibetan Plateau. It is possible that east-west extension evolved to dissipate excess orogenic gravitational potential energy (e.g., Molnar & Lyon-Caen, 1988) in a role similar to that played by the STFS in the Early Miocene (Hodges et al., 2001). Several N-S striking structures linked to E-W extension cut south of the STFS into the Greater Himalayan sequence, as seen in Nyalam and the Ama Drime region (e.g., Burchfiel et al., 1992; Wu et al., 1998; Hintersberger et al.,
suggesting this tectonostratigraphic distinction may be invalid in the recent evolution of the orogenic system.

Shortening-related deformation continued to propagate outwards to the south, with the Middle Miocene growth of the Lesser Himalayan duplex over a mid-crustal ramp on the Himalayan Sole thrust (DeCelles et al., 1998a, 2001; Robinson et al., 2003; Pearson & DeCelles, 2005), likely aided by accretionary underplating (Bollinger et al., 2006). It is apparent duplex growth was well-established by ~10 Ma, but as thrusting on the Main Boundary system must have initiated after duplex growth and could have initiated any time between ~15 to 5 Ma (DeCelles et al., 1998a) the timing of duplex growth is somewhat unclear given the current chronologic constraints.

\textit{Pliocene (~5-3 Ma) – Active structures: Main Boundary thrust system, accretionary growth on the Himalayan Sole thrust, out-of-sequence thrusting on the MCTS, E-W extension on the Tibetan Plateau}

By Pliocene time, thrusting on the Main Boundary thrust system was well-established (Meigs et al., 1995), likely serving as the surface expression of the Himalayan Sole thrust. Ramp geometry in the décollement at mid-crustal depths (Cattin & Avouac, 2000), resulted in accretionary growth and uplift of rocks well to the north of active thrusting as a result of accretion of material from the footwall of the Himalayan Sole thrust to the hanging wall (Bollinger et al., 2006),
possibly resulting in re-activation of brittle faulting near the structural level of the MCTS to the north (Macfarlane et al., 1992).

*Quaternary – Active structures: Main Frontal thrust system, accretionary growth on the Himalayan Sole thrust, out-of-sequence thrusting on the MCTS, N-directed extension near the range crest, and E-W extension across the Tibetan Plateau*

The thrust front migrated to the Main Frontal thrust system prior to the Holocene and this ongoing thrusting is believed to accommodate the majority of crustal shortening related to the collision of India with Eurasia today (e.g., Lavé & Avouac, 2000). Paradoxically, the region experiencing the most rapid uplift rates, as inferred from topographic profiles, low-temperature thermochronology, and fluvial character, is located ~ 50-120 km to the north, in a zone comprising the upper Lesser Himalayan sequence and the Greater Himalayan sequence (Seeber & Gornitz, 1983; Lavé & Avouac, 2001; Wobus et al., 2006; Bollinger et al., 2006; McDermott et al., submitted-B). Some researchers cite accretionary underplating beneath the Lesser Himalayan duplex as sufficient for concentrating uplift across the northernmost hanging wall of the duplex (Lavé & Avouac, 2001; Bollinger et al., 2006), while others acknowledge the contribution of duplex related uplift, but postulate additional active faulting is required to explain the patterns displayed in the geomorphic and thermochronologic data (Wobus et al., 2006; McDermott et al., submitted-B). Consistent with the latter suggestion, out-of-sequence thrusting in the upper Lesser Himalayan sequence has been documented in central Nepal, although whether this slip is independent of a shallow ramp at depth is questioned.
(Harrison et al., 1997). Recently active N-directed extension at the upper boundary of the high uplift zone has, however, been documented across central Nepal ($D_{CN-5}$ structures; Nakata et al., 1989; McDermott et al., submitted-A) and the Nyalam region ($D_{NY-3}$; McDermott et al., submitted-B). These Quaternary structures lie entirely within tectonostratigraphic domains (Dhaulagiri Southwest fault – Greater Himalayan sequence (Nakata et al. 1989); Dhaulagiri – Machhapuchhre detachments – Tibetan Sedimentary Sequence (Hodges et al., 1996; McDermott et al., submitted-A); unnamed extensional structure south of Nyalam – Greater Himalayan sequence (McDermott et al., submitted-B)), and if they are correlated, as suggested in this article, crosscut tectonostratigraphic boundaries. These N-directed extensional structures appear to be active on a similar time scale as structures related to E-W extensional faults to the north on the Tibetan Plateau, but appear to mark the transition from plateau extension and Himalayan convergence, at least across central Nepal.

TECTONIC IMPLICATIONS
The regional extent of N-directed extensional structures, including the Dhaulagiri detachment, and the estimated magnitude of displacement into the Late Quaternary requires a re-evaluation of the late-stage evolution of the Himalayan range crest, and inasmuch as the range crest is connected to the overall tectonic regime, the orogen as a whole. Our characterization of N-directed extensional structures within the context of the continued evolution of the orogen reveals several key features for consideration. First, although $D_{CN-5}$ structures from the
Kali Gandaki to the Marsyandi were previously linked to the STFS, and believed to merely be subsidiary structures to the basal detachment, recent evidence suggests this is likely not the case. Second, in the context of classic tectonostratigraphic boundaries, N-directed extensional structures near the range crest do not remain at constant structural levels, or mark the boundary between tectonostratigraphic domains. Rather, these structures cut across the Miocene-established tectonostratigraphic domains, tracing from the Greater Himalayan Sequence to the Tibetan Sedimentary Sequence. An examination of the evolution of Late Miocene - Quaternary structures throughout the orogen reveals this cross-boundary pattern appears to be the norm post-Miocene.

Larson & Godin (2009) proposed that the structurally higher N-directed extensional structures may represent an outward growth of the core of the orogen; basal thrust faults propagate southward away from the initial thrust, the MCTS, and upper boundary extensional faults propagate to the north away from the STFS. However, as discussed above, Quaternary N-directed extensional structures do not lie solely in the hanging wall of older extensional fault systems, rather some of the faults are mapped in the Tibetan Sedimentary sequence (structurally higher than the STFS) while others lie entirely within the Greater Himalayan sequence (structurally lower than the STFS). If these young east-west striking extensional faults are significant to orogenic evolution, and more than simply local phenomena, as suggested by the magnitude of their displacement and their existence in several locations along strike of the Himalayan range crest, then the
structures cut across tectonostratigraphic domains; this structural geometry is not consistent with the outward growth model of Larson & Godin (2009).

We speculate that Quaternary extensional faulting near the crest of the range may represent a young phase of Himalayan evolution. In its ~50 Ma history, the Himalayan-Tibetan orogenic system has undergone several tectonic phases, and in each phase, different tectonic domains defined the type and location of deformation. In the Eocene, the focus of deformation was the Indus-Tsangpo suture zone, defining the boundary between the converging Indian and Eurasian plates. By the Early Miocene, the Tibetan Plateau, and the gravitational potential within it, built-up enough to shift deformation to the south, resulting in the extrusion of the core of the Himalaya along the STFS and the MCTS. The Middle to Late Miocene was dominated by gravitational collapse of the Tibetan Plateau through E-W extension across the physiographic plateau while crustal shortening continued within the core of the Himalayan range. Based on the distribution of young features that appear to dominate the most recent evolution of the orogenic system, the Plio-Pleistocene may represent yet another structural reorganization within the orogenic system.

This work verifies young N-directed extensional faults at the range crest, but finds that they do not correlate with classically defined tectonostratigraphic domains set-up by Miocene tectonic regimes. This appears true for other Quaternary structures as well: the Main Frontal thrust system, although clearly
active, does not correlate with the zone of highest uplift within the Himalaya, the Lesser Himalayan duplex sustains young faulting within the Lesser Himalayan and Greater Himalayan sequences, affecting several tectonostratigraphic domains. We speculate these out-of-sequence deformational features imply an episodic reorganization of the Himalayan orogenic wedge through time that is inconsistent with simple models of Himalayan evolution that emphasize only a southward progression of deformation with time. Although the total length of Quaternary N-directed extensional faults is uncertain at this time, the existence of such structures across > 500 km of the southern margin of the Tibetan Plateau suggests orogenic significance. Although the Quaternary structures do not appear to be directly linked to the STFS, they accommodate the extrusion of material in a similar sense as the STFS in the Early – Middle Miocene. Given this, it is possible the southward extrusion of material along east-west striking normal faults near the Himalayan range crest is not simply a singular event, but may be an episodic feature in the evolution of the orogenic system.

FUTURE WORK

Several important questions remain unanswered upon completion of this dissertation. The examination of the Annapurna-Dhaulagiri Himalaya described in Chapter 2 reveals the existence of young, N-directed extension structurally above the STFS (the Dhaulagiri detachment) which can be traced for > 25 km. We infer in this chapter, based on structural similarities, that the Dhaulagiri detachment may be correlated to the Machhupuchhare detachment in the Modi Khola to the
east and the Dhaulagiri Southwest fault to the west, however no low-temperature thermochronologic data exists across these structures to confirm or disprove this suggestion. If these structures are correlated to the Dhaulagiri detachment, they should exhibit the same cooling age discontinuity observed in the Kali Gandaki and Myagdi Khola valleys, especially in AHe. Second, although the geomorphologic and thermochronologic data from the Nyalam region are compelling, due to high relief, Quaternary cover, and political sensitivity, I was unable to locate the discrete fault structure accommodating the extension. Finally, the evaluation of young, N-directed extension defining PT$_1$ across the Himalaya is incomplete without a thorough investigation of the location and nature of PT$_1$ in the Ama Drime region. I propose PT$_1$ may lie to the south of Ama Drime Range, but was unable to evaluate the relationship between possible N-directed extension and the E-W extension composing the Ama Drime massif within the limitations of our field access. An investigation of PT$_1$ in this region, as well as in other PT$_1$ locations along the range would greatly aid in our understanding of the role of young N-directed extension at the crest of the Himalaya.
REFERENCES


Hubbard, M.S., and Harrison, T.M. (1989) $^{40}$Ar/$^{39}$Ar age constraints on deformation and metamorphism in the Main Central thrust zone and Tibetan slab, eastern Nepal Himalaya. *Tectonics*, 8, p. 865-880.


FIGURE CAPTIONS

Table 5-1: Correlation of deformational events across central Nepal

Figure 5-1: A: Geologic and structural map of the central Himalaya, after Hodges (2000). Rectangles shows the extent of Figures 3-3 (Chapter 3), Figure 4-2 (Chapter 4), and Figure 5-2 (this chapter). B: Idealized and simplified cross-section across the Himalaya (basic transect location shown in A), modified from Hodges et al. (2001), Pearson & DeCelles (2005), and Bollinger et al. (2006). Abbreviations: BKF – Bhote Kosi fault; DD – Dhaulagiri detachment; DH – Dhaulagiri; DSW – Dhaulagiri Southwest fault; KT- Kakhtang thrust; LNP – Langtang National Park; MA – Machhapuchhare; MBTS – Main Boundary thrust fault; MCTS – Main Central thrust system; MD – Machhapuchhare detachment; MFTS – Main Frontal thrust system; EV – Everest; HST – Himalayan Sole thrust; LH duplex – Lesser Himalayan duplex; STFS – South Tibetan fault system; TF – Tibrikot fault; TG – Thakkhola Graben; YCS – Yadong cross-structure.

Figure 5-2: Simplified geologic and structural map of the central Nepal, modified from Colchen et al., 1986, Vannay & Hodges, 1996, Hurtado et al., 2001, and Godin, 2003. Abbreviations: AD – Annapurna detachment; CD – Chame detachment; DD – Dhaulagiri detachment; DiD – Deorali detachment; DZ – Dangardzong fault; HD – Hiunchuli detachment; IBC – Italian base camp; KSZ – Kalopani shear zone; MCTS – Main Central thrust system; MD –
Machhupuchhare detachment; MKSZ – Modi Khola shear zone; PD – Phu detachment.

Figure 5-3: Correlated simplified general stratigraphic sections of valley transects across central Nepal. Data used to construct sections: Myagdi Khola – Hurtado (2002), this study; Kali Gandaki – Vannay & Hodges (1996), Godin (2003), this study; Modi Khola – Hodges et al. (1996); Marsyandi – Coleman (1996), Searle & Godin (2003).

Figure 5-4: Age constraints on deformational events across central Nepal. Deformational events 1-5 as described in text are correlated based on structural similarity.

Figure 5-5: Structural evolution of the Himalaya from the Early Miocene to the Quaternary. Although most deformational events can be correlated across significant distances in the orogen, the relationships shown are specific for central Nepal. See text for detailed descriptions of structural evolution.

Figure 5-6: Timing constraints on deformational events for the three field studies presented in this study. Correlated events are shown with shaded boxes.

All other figures cited in this chapter (Figure 2-x; Figure 3-x; Figure 4-x) can be found in their respective chapters (Chapter 2; Chapter 3; Chapter 4).
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**Notes:**
- Data provided by Brown, A., A.
- Additional data by Varnum, K.
- Further data collected in 1998 by Chen, M.
- Updated in 2001 by Chen, M. and Cohen, J.
Figure 5-1

203
Figure 5-5