Exhumation Mechanisms of the Greater Himalayan Sequence, Garhwal Region, India

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Exhumation Mechanisms of the Greater Himalayan Sequence,
Eastern Garhwal Region of India

Christopher J. Spencer

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Masters of Geological Sciences

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Graduate Committee Approval

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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ABSTRACT

Exhumation Mechanisms of the Greater Himalayan Sequence,
Eastern Garhwal Region of India

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Geothermobarometric, micro- and macro-structural data indicate that peak metamorphic pressure and temperature of the Greater Himalayan Sequence (GHS) of the Garhwal Region of India increase dramatically across the Main Central Thrust (MCT). Metamorphic pressure and temperature increase from ~5 kbar and ~550 °C in the Lesser Himalayan Crystalline Sequence (LHCS) in the footwall to ~14 kbar and ~850 °C at ~3 km above the MCT in the hanging wall (GHS). Pressures decrease slightly upsection to ~8 kbar and temperatures remain nearly constant at ~850 °C to the structurally overlying South Tibetan Detachment (STD). The LHCS exhibits a high temperature-depth gradient (30 °C/km) whereas the lower GHS has a much lower temperature-depth gradient (18 °C/km) that increases to ~28 °C/km near the STD. The pressure-temperature pattern is consistent with conduction of heat from the hotter (initially deeper) GHS into the colder (initially shallower) footwall of LHCS and conductive cooling of the hotter hanging wall of GHS along the STD.

Numerical “channel flow” models predict a pressure-temperature pattern for the exhumation of the GHS similar to what is observed in the Garhwal Region of India. However, observed pressures (~10-14 kbar) are higher than predicted in the models (~10-12). The higher pressure of the GHS is likely due to the greater exhumation from displacement along the Munsiari Thrust (MT). In other words, the GHS in the Eastern Garhwal region provides a deeper view of the channel material than elsewhere in the range. The temperature-depth ratios of the Eastern Garhwal region also exhibit a very different pattern of conductive heating and cooling of the LHCS and GHS respectively, than elsewhere in the range.

Ductile features within the GHS exhibit sheath fold geometries, indicative of high degrees of ductile flow. Overprinting the ductile structure are two populations of extensional conjugate fractures oriented both parallel and perpendicular to the orogen. These fractures crosscut major tectonic boundaries in the region such as the MCT and STD, and are found throughout the LHCS, GHS, and Tethyan Sedimentary Sequences (TSS). The crosscutting of these brittle structures across the major tectonic boundaries in the area indicate that the various tectonolithic sequences were exhumed during widespread extensional deformation as one coherent block.
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INTRODUCTION

The metamorphic core of the Himalayan Orogen found in the Eastern Garhwal region of northwest India consists of a ~26 km thick sequence of upper amphibolite facies medisedimentary rocks known as the Munsiari Formation and the Vaikrita Group or Greater Himalayan Sequence (Virdi, 1986) (Figures 1 and 2). The Munsiari Formation is truncated at the base by the Munsiari Thrust, which places this formation over the unmetamorphosed Mandhali Formation of the Lesser Himalayan Crystalline Sequence. The Main Central Thrust places the Greater Himalayan Sequence over upper greenschist - lower amphibolite facies rocks of the Munsiari Formation, which is the uppermost part of Lesser Himalayan Crystalline Sequence. The South Tibetan Detachment juxtaposes unmetamorphosed Tethyan Sedimentary Sequence over the high-grade metamorphic rocks of the Greater Himalayan Sequence (Gururajan and Choudhuri, 1999).

The Greater Himalayan Sequence represents the highest grade rocks found in the Himalayan orogen, and therefore is key to understanding the metamorphic evolution and degree of exhumation of the orogen (Kohn and others, 2005). The 5 to 30 km thick package of medium to high grade metasedimentary rocks extends nearly 2500 km (Figure 1a) along the strike of the Himalayan Orogen and comprises its metamorphic core (Vannay and others, 1996; Godin and others, 2001; Kohn and others, 2005; Yin, 2006; Jessup and others, 2008). During the India-Asia collision, the Greater Himalayan Sequence was thickened to 20-50 km before being exhumed to the surface (Vannay and others, 1998; Stephenson and others, 2001; Catlos and others, 2001; Daniel and others, 2003; Goscombe and others, 2006 Kohn and others, 2008). Exhumation is most often
associated with the uplift associated with a major intercontinental thrust system and erosion of the material exposed at the surface (Daniel and others, 2003). The South Tibetan Detachment is also thought to have contributed to the exhumation of the Greater Himalayan Sequence (Cottle and others, 2007; Jessup and others, 2008). It is unclear whether the South Tibetan Detachment merges with the Main Central Thrust and Main Himalayan Thrust (Gansser, 1964; Schelling & Arita, 1991; Zhao and others, 1993; Hauck and others, 1998; Burchfiel and others, 1992; Grujic and others, 1996) or makes up the upper boundary of the extruding channel (Beaumont and others, 2004; Jamieson and others, 2004).

Various mechanisms proposed for the exhumation of the Himalayan metamorphic core have been the foci of many empirical studies (for example Searle and others, 2005; Carosi and others, 2006; Robinson and Pearson, 2006; Cottle and others, 2007; Kohn, 2008; Jessup and others, 2008; Patel and others, 2009; Long and others, 2010), some of which have been described by numerical thermal-mechanical models (Beaumont and others, 2001, 2006, 2008; Jamieson and others, 2004; Célérier and others, 2009b). There is still little consensus about which mechanisms best explain the metamorphic conditions observed. Some of the problems in identifying various orogenic processes stem from applying unrealistic interpretations or relying too heavily on simple numerical models (for example Harrison, 2006; Kohn, 2008; Beaumont and Jamieson, 2010).

Simplified first-order processes are often modeled numerically to gain greater understanding of orogenic evolution. However, some of these have been inappropriately applied to specific details in various transects across the range (see Hodges, 2000 for examples). Ironically, this is specifically cautioned against by the authors of the models (Jamieson and others, 2004). As Jamieson and others (2004) and
Beaumont and others (2004) demonstrate, minor changes in the model parameters creates significant variations in model results. They continue to warn that numerical models lack the spacial resolution for detailed comparisons with geological data and do not include several potentially important parameters (for example, lithology, precipitation, shear heating, and strain partitioning).

Few detailed investigations of exhumation mechanisms of the Greater Himalayan Sequence are published, and those that are rarely integrate metamorphic petrology and geochemistry (thermobarometry, phase equilibria, geochronology) with detailed structural measurements. Without a structural construct, various geochronologic and thermobarometric data can be misleading (Jessup and others, 2008).

This study investigates the peak metamorphic conditions and deformation mechanisms associated with the exhumation of the Greater Himalayan Sequence in the Eastern Garhwal Region of India (Figure 1a) through an integration of structural field mapping and thermobarometry along transects of two major rivers (Alaknanda and Dhauliganga rivers). Because the Alaknanda and Dhauliganga rivers dissect the Greater Himalayan Sequence nearly perpendicular to the strike of the range, they provide natural cross-sections through the Greater Himalayan Sequence.

Hodges and Silverberg (1988) performed a thermobarometric study along the same transects of this study. However, phase equilibria constraints of Kohn (2008) and Holland and Powell (1998) show mineral assemblages in nine of the eleven samples of Hodges and Silverberg (1988) violate phase equilibria. This is because the mineral compositions used to calculate pressure and temperature conditions were not equilibrated at peak conditions (Kohn, 2008). Farther to the west, Metcalfe (1993) also
reported pressures and temperatures from the Munsiari Formation and the Greater Himalayan Sequence. However, the mineral assemblages reported from the upper part of the section also violate phase equilibria.

TECTONOSTRATIGRAPHY

The crystalline rocks of the Eastern Garhwal region are divided in two suites. 1) the Munsiari Formation of the Lesser Himalayan Crystalline Sequence and 2) the Greater Himalayan Sequence (or Vaikrita Formation after Gururajan and Choudhuri, 1999) (Figures 2 and 3). These are underlain by the Mandhali Formation (after Valdiya, 1980) of the Lesser Himalayan Crystalline Sequence and overlain by the Martoli Formation of the Tethyan Sedimentary Sequence.

Munsiari Formation

The Munsiari Formation includes garnet bearing-mica schists, calc-silicate lenses, and quartzite (Gururajan and Choudhuri, 1999). Pelitic samples within the Munsiari Formation have quartz + biotite + plagioclase + garnet ± staurolite ± muscovite ± graphite ± andalusite. Garnet within the Munsiari Formation has a synkinematic fabric near the rim with respect to the earlier schistosity near the core (Figure 2a). The base of the Munsiari Formation is bounded by the Munsiari Thrust, which places the Munsiari Formation on top of the unmetamorphosed Mandhali Formation of the Lesser Himalayan Crystalline Sequence (Valdiya, 1980). Célérier and others (2009b) report an average 40Ar/39Ar cooling age for white mica of 8.5 Ma for the footwall of the Munsiari Thrust.

Main Central Thrust (Vaikrita Thrust)
The Main Central Thrust in the Eastern Garhwal Region is defined as the ductile shear zone between the micaceous quartzites and chlorite-biotite schists of the Munsiari Formation and the kyanite gneisses of the Joshimath Formation of the Greater Himalayan Sequence (Figure 1ab) (Valdiya, 1973, 1977, 1978, 1980). This boundary also coincides with the Nd-isotopic boundary between the Greater Himalayan Sequence and the Lesser Himalayan Crystalline Sequence defined by Ahmad and others (2000). Intense mylonitization is pervasive for tens of meters above and below the Main Central Thrust (Valdiya, 1980). However, no brittle contractional deformation structures are observed associated with the Main Central Thrust.

Greater Himalayan Sequence

Within the Eastern Garhwal region, the Greater Himalayan Sequence is divided in three formations (after Valdiya, 1979, 1989): a lower augen-kyanite gneiss (Joshimath Formation); a thick micaceous arkose quartzite (Pandukeshwar Formation); and an upper augen-sillimanite gneiss (Badrinath Formation). The dominant foliation throughout the Greater Himalayan Sequence is primarily defined by aligned mica (biotite and muscovite) and is generally isoclinally folded. A secondary foliation is locally axial-planar, it is weakly developed where micro- to mesoscale assymetric to isoclinal folds dominate the sequence.

Joshimath Formation

The Joshimath Formation is a series of pelitic gneisses with schistose interlayers that has a typical mineral assemblage of quartz + biotite + plagioclase + garnet ± staurolite ± muscovite ± kyanite ± chlorite ± calcite ± graphite ± titanite ± opaques (rutile, ilmenite). The base of the Joshimath Formation is defined by the Main Central Thrust and the
Munsiari Formation, whereas the top of the Joshimath Formation is gradational from pelitic metasediments to arkosic and quartzose metasediments of the Panudkeshwar Formation. Farther to the east, Paul (1998) reported migmatites in the upper portion of this Formation.

**Pandukeshwar Formation**

The Pandukeshwar Formation grades from the metapelites of the Joshimath Formation to metapsammites and quartzites of the Pandukeshwar Formation. It consists primarily of medium- to fine-grained arkosic quartzite interlayered with minor amounts of kyanite-bearing schist (Paul, 1998). Throughout the formation inverted and right-side-up low angle cross beds are found, defining original horizontality and sedimentary origin. The Pandukeshwar Formation typically has quartz + K-feldspar ± plagioclase ± muscovite ± biotite ± garnet ± chlorite ± opaques (rutile, ilmenite, chromite).

**Badrinath Formation**

The Badrinath Formation grades from the arkosic quartzose Pandukeshwar Formation to the metapelites and calc-silicates of the Badrinath Formation. The pelitic layers have a similar mineral assemblage to the Joshimath Formation with the addition of sillimanite (quartz + biotite + plagioclase + garnet ± staurolite ± muscovite ± kyanite ± sillimanite ± cordierite ± chlorite ± calcite ± graphite ± rutile ± ilmenite). Calc-silicate layers generally contain calcite + diopside + quartz ± hornblende ± biotite ± scapolite ± actinolite ± tremolite (Paul, 1998). Migmatitization of the Badrinath Formation occurs roughly 16 km up structural section from the Main Central Thrust and increases upward to the South Tibetan Detachment. The upper Badrinath Formation is intruded by small leucogranite bodies that include dikes, sills, and tabular bodies up to 5 km2 with quartz
+ K-feldspar + plagioclase + muscovite ± biotite ± garnet ± tourmaline ± sericite (secondary) ± chlorite (secondary). The Badrinath Formation is bounded at the top by the South Tibetan Detachment and structurally overlying unmetamorphosed Martoli Formation.

Virdi (1986) concludes that the Badrinath and Joshimath Formations are equivalent units that are repeated vertically by a series of isoclinal folds. However, this hypothesis predicts that the highest grade of metamorphism should be exposed in the core of the anticline, which is contrary to our observations of the highest grade rocks in the uppermost Badrinath Formation. The same relationship is also found to the east in the Kumaun Region (Paul, 1998).

*Martoli Formation*

The Martoli Formation consists primarily of Cambrian age greywacke and slate with minor amounts of sedimentary quartzite (Kacker and Srivastava, 1996; Valdiya and others, 1999). This formation is juxtaposed against the Greater Himalayan Sequence by a low-angle (~30°), north dipping normal fault (the South Tibetan Detachment). The angle of the South Tibetan Detachment follows very closely the angle of the dominant foliation of the underlying Badrinath Formation (Figure 2). Bedding in the Martoli Formation dips slightly into the steeper dipping South Tibetan Detachment. West of the studied section, Metcalfe (1993) described the same relationship between the upper Greater Himalayan Sequence and the Martoli Formation.

**ANALYTICAL METHODS**
21 samples were selected for detailed thermobarometric analyses to constrain peak metamorphic conditions across the Greater Himalayan Sequence. Electron microprobe analyses and X-ray compositional maps were made by using the fully automated Cameca SX-50 at the Department of Geological Sciences, Brigham Young University. Backscatter electron images and element maps of Fe, Mg, Ca, Mg were made of various phases selected for probe analyses. X-ray maps were used to determine appropriate locations for analyses and were collected with an acceleration voltage of 15kV, a current of 40 nA, a time per pixel of 20 ms. Point analyses and/or transects were conducted across garnet, biotite, muscovite, and plagioclase compositions to further characterize internal zoning and to find appropriate areas for thermobarometric calculations. For quantitative analyses of silicates, operating conditions were 15 kV acceleration voltage, 20 second count time, and 10-20 nA current. Natural minerals were used as standards.

**PETEROGRAPHY/GARNET ZONING**

Because garnet is stable over a wide range of pressures, temperatures, and bulk compositions, it can preserve compositional zones that reflect its growth and reaction history (for example, Chakraborty and Ganguly, 1991; Spear, 1993). Garnet X-ray element maps and compositional traverse across these garnets indicate unique burial and exhumational histories across the Vaikrita and Muniari thrusts. Electron microprobe analyses of various minerals used in this study are found in Appendix A.

**Munsiari Formation**

Garnet porphyroblasts are mostly sieve garnets and primarily contain quartz inclusions. Sieve garnets are confined to distinct quartz-rich and mica-poor domains whereas euhedral garnets are found in mica-rich domains. Most euhedral garnets have inclusion
rich cores with inclusion free rims. Two different types of inclusion patterns are also found: 1) Sigmoidal inclusion trails oriented at an oblique angle to the dominant foliation and spiral inclusion trails or “snowball” garnets (Figure 2a); 2) Muscovite fish and porphyroblast sigma-tails define a top-to-the-southwest shear sense (Figure 2b). Some samples also preserve syn- and post-kinematic mica growth where post-kinematic mica crosscuts the dominant foliation.

Compositional maps and point transects of garnet porphyroblasts (sample GH4b-4) (Figure 3 and 5) show Fe concentration decreases slightly from core (Xalm = 0.72) to rim (Xalm = 0.80), Ca is depleted in the core (Xgrs = 0.08) and oscillatory with a slight increase at the rim (Xgrs = 0.10), Mg is relatively homogeneous (Xpyr = 0.07 average), and Mn decreases from core (Xsps = 0.13) to rim (Xsps = 0.04). These bell-shaped chemical zoning profiles are characteristic of growth zoning that has remained unaltered by subsequent diffusion (Tracy, 1976; Yardley, 1977). In non-spherical and sieve garnets the growth zoning is truncated along subhedral and anhedral sides. However, there is no evidence for retrograde exchange reactions.

Joshimath Formation

Garnet porphyroblasts are euhedral to subhedral and contain quartz, plagioclase, calcite, titanite, and ilmenite inclusions. Most of the garnet porphyroblasts in the Joshimath Formation are petrographically similar to those found in the Munsíari Formation. However, calc-silicate layers within the Joshimath Formation commonly have “atoll” garnets (Figure 2e). These garnets have commonly been interpreted as having two stages of growth wherein the core is compositionally distinct from the rim. Fractures in the garnet later allowed retrograde reactions to preferentially resorb the
inner portion of the garnet leaving the unreacted rim preserved (Smellie, 1974; Homam, 2006). These garnets are commonly cored with calcite and secondary chlorite.

Garnets in a representative sample from the Joshimath Formation (GH15-2) display similar zonation as garnets from the Munsiari Formation. Fe concentration decreases slightly from core (Xalm = 0.56) to rim (Xalm = 0.77), Ca content is constant from core to near the rim (Xgrs = 0.16) with a slight decrease at the rim (Xgrs = 0.11), Mg content is relatively homogeneous in the core (Xpyr = 0.02 average) with a slight enrichment at the rim (Xpyr = 0.1), and Mn content decreases from core (Xsps = 0.24) to near the rim (Xsps = 0.01) with a thin outer rim of enriched Mn. As in the Munsiari Formation, garnets in the Joshimath Formation preserve growth zoning and does not show any evidence of modification by diffusion (Figure 3 and 5). Garnets are nearly all euhedral with exception to minor rim resorption due to retrograde exchange reactions. However, not all samples within the Joshimath Formation exhibit retrograde exchange reactions. Samples that do not show evidence of retrograde exchange reactions do not have a pronounced bell shaped curved in the Mn profile.

Pandukeshwar Formation

Garnet porphyroblasts have sigmoidal inclusion trails oriented at nearly a perpendicular angle to the dominant foliation, however this angle seems to vary by 30-40° from sample to sample and even within a single sample.

Garnets within the Pandukeshwar Formation are primarily sieve poikioloblastic in nature and exhibit bell-shaped growth zoning at the base of the formation grading to an increasingly homogenous composition at the top of the formation. Sample GH22-3 has
decrease in Mn content from the core ($X_{sp} = 0.07$) to rim ($X_{sp} = 0.02$), Fe, Mg, and Ca content remains constant from rim to core ($X_{alm} = 0.87$, $X_{pyr} = 0.08$, $X_{grs} = 0.01$).

**Badrinath Formation**

Garnet porphyroblasts are euhedral to subhedral and contain quartz, plagioclase, calcite, and ilmenite inclusions. Most of the garnet porphyroblasts in the Badrinath Formation are petrographically similar to those found in the Joshimath Formation. Muscovite in the middle portion of the formation has a wormy texture as signs of breakdown due to increasing migmatization upsection. Sillimanite is also present in the upper portion of the formation expressed as fibrolite.

Garnets from the Badrinath Formation are found entirely within migmatitic gneiss. Compositional maps of representative garnets show that they are nearly homogeneous but the rims have an abrupt increase in Mn content (Figure 3 and 5). There is also a slightly more gradual increase in Fe content from the core ($X_{alm} = 0.65$) to rim ($X_{alm} = 0.74$) and decrease in Mg from the core ($X_{pyr} = 0.26$) to rim ($X_{pyr} = 0.18$). Due to lack of Mn-bearing phases in the matrix the increase in Mn is attributed to resorption of the garnet.

**GEOTHERMOBAROMETRY**

Pressure-temperature conditions (Table 1) were calculated from standard mineral equilibria and the program GeoThermoBarometry (GTB; Spear and Kohn, 2001; Spear and others, 1991) using garnet-biotite Fe-Mg exchange and biotite-tourmaline Fe-Mg exchange thermometers (Ferry and Spear, 1978, with the Berman, 1990, garnet activity model; Colopietro and Friberg, 1987) and the garnet-plagioclase-muscovite-biotite, and
garnet-plagioclase-aluminosilicate-quartz (Hoisch, 1990, Koziol and Newton, 1988, with Berman, 1990 garnet activity model) barometer. The Ti content in biotite has been shown to increase as a function of temperature (Henry and others, 2005) and has been shown to provide reliable temperatures from 480 to 800 °C. Use of THERMOCALC (Powell and Holland, 1988, 1994; Holland and Powell, 1998) has been shown to yield results within error of the calculations presented in Kohn (2008).

Wu and Cheng (2006) systematically tested various garnet-biotite thermometers and garnet-plagioclase-aluminosilicate-quartz barometers in metapelites and conclude that the thermometers of Holdaway (2000) and Kleemann and Reinhardt (1994) and barometers of Holdaway (2001) and Newton and Haselton (1981) were the best calibrations due to their small errors in reproducing the experimental temperatures and good accuracy in successfully discerning the systematic temperature changes. They noted that both Ferry and Spear (1978) and Koziol and Newton (1988) produced higher respective temperatures and pressures than the other calibrations. However, in order to directly compare the results from this study with the results from the Langtang region of Nepal (Kohn, 2008) and eastern Bhutan (Daniel and others, 2003) we chose to use the same calibrations used in those studies. Furthermore, because we are comparing our results to various numerical models, and because the parameters of those models are potentially highly variable, the relative changes in pressure and temperature through the metamorphic core of the range is more important than the exact values; that is, if the conditions are realistic and internally consistent with other methods (RSCM, Tm-Bt, Ti-in-Bt).

For garnets with no evidence of retrograde net-transfer or exchange reactions rim compositions were used for thermobarometry. Garnet compositions with the lowest
Fe/(Fe + Mg) and Mn (that is near rim) were used as a close approximation of the garnet composition prior to resorption and diffusion effects during a high-grade metamorphic overprint, because these probably correspond most closely to the composition present at the peak of metamorphism (Spear, 1993; Kohn, 2003). For samples showing retrograde-exchange reactions, corrections are made to adjust for the Fe/Mg ratio in matrix biotite following the method of Kohn and Spear (2000). Matrix biotite compositions were analyzed as line transects across biotite clusters and were found to be chemically homogeneous in each sample. An average of the matrix biotite composition was used for geothermometric calculations. Muscovite analyses were conducted as line transects across several sheaths in the matrix of the samples. Both biotite and muscovite grains were analyzed at variable distances from garnet and show minimal zoning of variability with distance from garnet and therefore an average of the muscovite analyses was used. Plagioclase analyses were made as either point or transect analyses. To estimate metamorphic pressures, at the peak temperatures, the rim composition of plagioclase was used for PT calculations. Compositional transects across tourmaline revealed strong zoning so rim compositions were used to estimate compositions that were in equilibrium with matrix biotite. Despite the tourmaline-biotite thermometer having only been calibrated for temperatures <600 ºC (Abu El-Enen and Okrusch, 2007), the obtained higher temperatures (~830 ºC) are consistent with garnet-biotite thermometry for samples of close proximity to samples where tourmaline-biotite thermometry was used.

Analytical uncertainties for typically yield ±5 ºC and 0.25-0.5 kbar (Kohn and Spear, 1991). However, the geological uncertainty with choosing the most appropriate mineral compositions far outweigh any analytical imprecision (Daniel and others, 2003).
Phase equilibrium constraints were also considered in estimating temperatures and corresponding pressures after Kohn (2008) (see Figure 8). Muscovite dehydration melting reaction occurs at a minimum temperature of ~700 °C (Spear and others, 1999) and the presence of kyanite-bearing migmatites in the Badrinath Formation implies minimum pressures of 8 kbar (Kohn, 2008). For pressures >8 kbar, the staurolite-in and kyanite-in reactions occur at minimum temperatures of ~575° and ~600 °C, respectively (Spear and Cheney, 1989). For temperatures <500 °C, the presence of kyanite in the Joshimath Formation implies minimum pressures of ~3.8 kbar (Spear and others, 1999). Cordierite-bearing migmatites in the Badrinath Formation with calculated pressures between 7-10 kbar imply minimum temperatures of ~825-850 °C (Spear and others, 1999).

Within the Munsiari Formation, P-T estimates displays a steep inverted pressure gradient of a 2 kbar/km with pressures of ~5 kbar near the Munsiari Thrust and ~11.5 kbar towards the Main Central Thrust (Figure 8). Temperatures remain more or less constant between 550° and 575°C. Continuing up section, P-T estimates remain roughly constant through the Joshimath and Pandukeshwar Formations with pressures ranging between ~13-15 kbar and average temperatures of 785 °C. Within the Badrinath Formation, temperatures remain between ~810 and 860 °C to within 5-6 km of the South Tibetan Detachment. Pressures drop to ~8.5 kbar at -0.6 kbar/km to the South Tibetan Detachment.

TEMPERATURES OF RECRYSTALLIZATION

Stipp and others (2002), identified three main stages of quartz recrystallization from ~280 to ~700 °C. At the frictional - viscous transition (cataclasites to mylonites), the
three main stages of dynamic recrystallization of quartz are bulging recrystallization (~280 - 400 °C), subgrain recrystallization (~400 - 500 °C), and grain boundary migration recrystallization (~500 °C and above). Distinct textures associated with grain boundary migration recrystallization (chessboard extinction and amoeboid grain boundaries) form at even higher temperatures. Chessboard extinction has been interpreted to represent basal and prismatic subgrain rotation (Mainprice and others, 1986; Blumenfeld and others, 1986), and is estimated to occur at temperatures of ~630 °C (Stipp and others, 2002; Mancktelow and Pennacchioni, 2004). These temperatures for the formation of chessboard extinction are considered a minimum temperature because of the pressure dependence of this texture. As pressure increases, the temperature at which this texture is present increases to above ~800 °C at ~10 kbar (Passchier and Trouw, 2005).

Recrystallization of K-feldspar into multiple subgrains is also observed through the entire Greater Himalayan Sequence. This K-feldspar recrystallization texture indicates minimum deformation temperatures of ~450 °C (White, 1975; Voll, 1976; Simpson and Wintsch, 1989).

Using these microstructural classifications to estimate for temperature, the recrystallization criteria range of metamorphism for each sample along the Alaknanda and Dhauliganga transects is plotted according to distance from the Main Central Thrust (Figure 6 and 9). The degree of recrystallization, and therefore temperature remains more or less constant through the Munsari Formation with a clear temperature discontinuity within 0.5 km of the Main Central Thrust, at which the texture changes to the higher temperature chessboard and amoeboid patterns. Through the entire Greater Himalayan Sequence, the quartz textures are the higher temperature variety up to the
South Tibetan Detachment where the recrystallization temperatures of the Martoli Formation of the Tethyan Sedimentary Sequence decrease to minor bulging and include samples without any quartz recrystallization. This pattern is consistent with thermobarometry results and metamorphic index minerals.

PHASES OF DEFORMATION

Within the Munsiari Formation and the Greater Himalayan Sequence two deformational phases are recognizable. The earliest phase is a layer-parallel extension associated with the formation of the regional penetrative foliation (S1), and is parallel to Munsiari and Main Central Thrusts (Figure 7a). Also parallel to S1 is a ductile shear fabric that accommodated internal ductile shear strain related to the southwest ductile flow of the crystalline rocks, which is indicated by S-C fabrics found throughout the Greater Himalayan Sequence with higher degrees of shear strain in more pelitic units. The angle between the S and C planes is significantly reduced nearest to the Munsiari thrust indicating increasing degrees of non-coaxial deformation. Mica fish also show a top-to-the-southwest shear sense in the Joshimath Formation.

A second foliation is poorly developed; it is found mostly parallel to axial surfaces of small scale isoclinal folds of S1 throughout the Greater Himalayan Sequence (Figure 7a). These two fabrics most likely developed under the same progressive ductile flow regime.

Tight isoclinal to recumbent folds are found localized at the Main Central Thrust and in weak pelite-rich zones throughout the Greater Himalayan Sequence. All of the folds show top to the SW fold-asymmetry with the exception of those found near the South Tibetan Detachment which are top to the NE. The opposite vergence direction of folds
at the base and top of the Greater Himalayan Sequence may indicate ductile extrusion of the Greater Himalayan Sequence along the Main Central Thrust was either coeval with ductile movement along the South Tibetan Detachment or was partitioned near these boundaries with opposite sense of shear at different stages of deformation. Within the lower portion of the Greater Himalayan Sequence, S-C fabrics exhibit top up to the SW while these fabrics found within the Badrinath Formation nearest to the South Tibetan Detachment exhibits top down the NE flow. These opposite flow directions are commonly interpreted as top down to the northeast extension following top up to the southwest extrusion.

Ductile flow was accommodated in many places throughout the Munsiari Formation and the Greater Himalayan Sequence by sheaths folds. Sheath folds are defined as folds with curvilinear hinges that are progressively rotated into the direction of flow or transport by general shear (Alsop and Holdsworth, 2004a, 2004b, Searle and Alsop, 2007). Sheath folds are described at widely varying scales from sub-millimeter (Alsop and others, 2007) to recumbent sheath “nappes” (Orozco and others, 2004; Searle and Alsop, 2007).

Fold hinge lines within the Greater Himalayan Sequence from the Eastern Garhwal region of India display nearly 150° of variability in the transport direction indicated by lineations and S-C fabrics. In previous studies of this region, fold axes are reported to lie within two distinct populations separated by 90° with an overall spread of 150° (Gairola and Srivastava, 1987; Vannay and Grasemann, 2001). These limited data were collected from transects mostly along drainages and interpreted to be evidence for two deformational events whose principal stresses oriented ~90° apart (Gairola and Srivastava, 1987; Vannay and Grasemann, 2001). This interpretation predicts that the
Himalaya range underwent a deformational event with a maximum stress oriented parallel to the current strike of the range which should produce a series of fold interference patterns that are not observed. Our study did not find a bimodal distribution, but a nearly continuous range of fold hinge directions varying by ~140° with axes trending from NW to SSE (Figure 7b), which is consistent with a single “flow” event accommodated by sheath folds. Mineral stretching lineation plunge to the northeast, which is consistent with sheath fold flow direction. This relationship is also documented in Himachal Pradesh (Vannay and Grasemann, 2001) and the Pakistani Himalaya (Treloar and others, 2007). Recognizable sheath folds in outcrop within the Greater Himalayan Sequence of the Garhwal region range in scale from several centimeters to several meters. However, the range of fold hinge line directions predict that even larger scale folds may also occur.

In addition to the ductile shortening features described above, late stage orogen parallel and perpendicular extension features in the Eastern Garhwal region of India are found throughout the Greater Himalayan Sequence. These normal faults and associated conjugate fractures cross cut the major tectonic boundaries of the Greater Himalayan Sequence and are found throughout the Lesser Himalayan Duplex and the lower portion of the Tethyan Sedimentary Sequence.

The South Tibetan Detachment in the Garhwal region exhibits minor amounts of dextral slip evidenced by the rotation of mineral stretching lineations (Pecher, 1991; Gururajan and Choudhuri, 1999). It was previously reported that this brittle detachment was crosscut by the Malari Leucogranite (Gururajan and Choudhuri, 1999), however detailed observations show that the brittle normal fault cuts around the main body of the intrusion.
OROGEN PARALLEL EXTENSION

At the top of the Greater Himalayan Sequence, the South Tibetan Detachment juxtaposes the Greater Himalayan Sequence with the Martoli Formation of the Tethyan Sedimentary Sequence. The South Tibetan Detachment consists of a 1-2 km wide ductile shear zone with top-down-to-the-NE flow and is overprinted by a discrete brittle shear zone 10-30 meters thick which dips to the north ~35-45°.

Orogen parallel normal faults and conjugate fractures from the Greater Himalayan Sequence have an average strike of NNW (337°) (Figure 7c). Which is similar to the average trend of the range in this area of NW (310°). These brittle features increase in frequency upsection towards the Southern Tibetan Detachment and indicate a vertical maximum stress. Most orogen parallel normal faults we measured have minor displacements (<10 meters) with mostly top down to the ENE. These faults are subparallel to the Southern Tibetan Detachment. Similar extensional features, such as the Karcham Normal Fault Zone reported along the Sutlej transect (Janda and others, 2002; Vannay and others, 2004; Thede and others, 2004). However, the Karcham Normal Fault Zone includes a distinct detachment near the base of the Greater Himalayan Sequence cross cutting the Main Central Thrust.

OROGEN PERPENDICULAR EXTENSION

Orogen perpendicular conjugate fractures and normal faults with an average trend of 037° (Figure 7d) are less prevalent and exhibit similar amounts of displacement. They are also found throughout the Greater Himalayan Sequence as well as above and below its major tectonic boundaries. How the orogen perpendicular extension relates temporally with the orogen parallel extension is unclear, but both could be associated
with the same late-stage extension, if the intermediate and minimum stresses were nearly the same.

Applying a similar relationship described in the Marsvandi area of central Nepal, Coleman (1996) describes a change from extension perpendicular in the orogenic core early in deformation which is superimposed by orogen parallel extension later in the deformation. However, this relationship is described within discrete fault zones associated with the South Tibetan Detachment (as opposed to a wide zone with an indeterminable amount of extension) and is not a regional phenomena. Furthermore, extensive orogen perpendicular extension has not been documented south of the South Tibetan Detachment (Zhang and others 2000; Hurtado and others, 2001; Garizone and others, 2003; Kapp and Guynn, 2004; Kapp and others, 2008).

The north-south trending rift basins of southern Tibet are thought to accommodate the strain gradient between extension in Tibet and the shortening in the Himalaya (that is extension that is coeval with orogen-perpendicular compression) (Zhang and others, 2000; Hurtado and others, 2001; Kapp and Guynn, 2004; Kapp and others, 2008; Searle, 2010).

DISCUSSION

Combining the thermobarometry of the crystalline rocks of the Munsiari Formation and the Greater Himalayan Sequence with the thermometry of the Lesser Himalayan Crystalline Sequence of Célérier and others (2009b) along the Alaknanda and Dhauliganga rivers allows further characterization of the peak metamorphic temperatures from the Main Boundary Thrust to the South Tibetan Detachment.
Célérié and others (2009b) used Raman spectroscopy of carbonaceous material to obtain peak metamorphic temperatures in the Lesser Himalayan Crystalline Sequence from >330 °C to ~580 °C, with temperatures increasing towards the Munsíari thrust (Célérié and others, 2009b). Structurally above klippen of the Greater Himalayan Sequence, peak metamorphic temperatures of the Lesser Himalayan Crystalline Sequence are nearly isothermal at ~550 °C. Garnet - biotite thermometry from our study show a slight increase in temperatures up to ~600 °C nearest to the Main Central Thrust. To explain this slight increase in temperature towards the Main Central Thrust, we invoke a syn-thrusting, transient inversion of the isotherms at the level of the Main Central Thrust, as a result of downward heat conduction between the hot exhuming hanging wall (the Greater Himalayan Sequence) and the colder footwall of the thrust (the Munsíari Formation). Because of this, retrograde exchange reactions and the resorption of garnets are present in the lowermost Greater Himalayan Sequence. This is similar to the model proposed by Le Fort (1975) which predicts that, as a consequence of a retrograde metamorphic evolution in the hanging wall of the Main Central Thrust, the temperature should increase upwards across the thrust zone. This is consistent with the near isothermal structure of the Greater Himalayan Sequence with a slight decrease in temperature within two kilometers of the Main Central Thrust and similar to the PT profile found in Central Nepal (Kohn, 2008) and Eastern Nepal (Imayama and others, 2010). This is also consistent with numerical models which predict that melt migration from the lower to middle crust (Depine and others, 2008).

In its simplest form, this model should predict a decrease in temperature and pressure up section from the Main Central Thrust (for example Vannay and Grasemann, 2001; Dasgupta and others, 2009). The thermobarometric data from the Eastern Garhwal
region does show a decrease in pressure, but as stated before temperatures are nearly isothermal in the upper ~28 km of the Greater Himalayan Sequence.

The upper portion of the Greater Himalayan Sequence, where temperatures are predicted to decrease, contains increasing concentrations of migmatite and leucogranite. Isotope geochemistry of these leucogranites is indicative of a metasedimentary source most akin to the Greater Himalayan Sequence (Gariépy and others, 1985; Deniel and others, 1987; Guillot and Le Fort, 1995; Searle, 1999; Ahmad and others, 2000). Decompression during active low-angle detachment faulting along the South Tibetan Detachment may have triggered partial melting of the crust creating leucogranite bodies that rose into the uppermost levels of the Greater Himalayan Sequence (Searle, 1999; Harrison and others, 1999). Whether these partial melts represent in situ melting or melt migration from a structurally lower portion of the crust is unresolved (Harris, 2007). The relatively evolved bulk chemical composition, high Rb/Sr ratio, and normative corundum of the Malari leucogranite indicate melting of a (meta)sedimentary source, likely the underlying Greater Himalayan sequence (Sachan and others, 2010). The emplacement of partial melt in the uppermost portion of the Greater Himalayan Sequence is potentially responsible for the elevated metamorphic temperatures.

Compositional transects across representative garnets from from each of the garnet-bearing formations show increasingly flat profiles (Ca, Mn, Mg, Fe) upsection in the Badrinath Formation (Figure 4). Although, this is expected within an inverted metamorphic sequence, the temperature estimates within the Greater Himalayan Sequence are ~800-850 °C. The pattern of increasingly diffuse compositional profiles is
attributed to the increased duration of time at which various parts of the Greater Himalayan Sequence were at peak metamorphic conditions.

In the upper portion of the Greater Himalayan maximum calculated pressures (14.2 kbar) decrease to 8.5 kbar near the South Tibetan Detachment at an estimated pressure gradient of 710 bar/km (assuming average density of ~2750 km/m3). This pressure gradient is significantly higher than that assumed from lithostatic pressure (270 bar/km) with an average density of gneissic rocks (~2750 kg/m3) (Hodges and others, 1988; Larson and others, 2010). Fraser and others (2000) reported a pressure gradient of 540 bar/km in the Langtang region of Central Nepal and Larson and others (2010) reported a pressure gradient of ~620 bar/km in the Manaslu–Himal Chuli region of Central Nepal. As mentioned by Larson and others (2010), this high pressure gradient is interpreted as resulting from post-metamorphic tectonic thinning of the crust. This interpretation is consistent with the layer parallel extensional features we found within the Greater Himalayan Sequence (for example vertical conjugate fractures and normal faults). To achieve a pressure gradient more than double that of average lithostatic pressure the Greater Himalayan Sequence would need to have been vertically thinned by over 50%. It is unclear however, whether this thinning took place entirely by top down to the north extension via the South Tibetan Detachment, flattening during top up to the south thrusting via the Main Central Thrust, or a combination of the two via coeval motion along these bounding faults. North-verging fold-asymmetry in the upper Greater Himalayan Sequence attests to some degree of top down to the SE ductile shear and layer parallel extension via the South Tibetan Detachment. This is similar to what is seen in the Annapurna range (Kellet and Godin, 2009; Searle, 2010) and the tectonic
thinning is also predicted by numerical models of channel flow (Beaumont and others, 2001; Jamieson and others, 2001).

The variations in thermobarometric patterns along orogenic strike of the Greater Himalayan Sequence are used to better understand the relations between the thermal history and spatial variations in erosion and exhumation rates of the Greater and Lesser Himalayan Crystalline Sequences (Spear and others, 1984; Inger and Harris, 1992; Spear, 1993; Macfarlane, 1995; Jamieson and others, 1996; Vannay and others, 1996; Vannay and others, 1999; Fraser and others, 2000; Catlos and others, 2001; Vannay and others, 2001; Goscombe and others, 2005; Kohn, 2008; Imayama and others, 2010). This is plausible because the thermal evolution of orogenic belts is governed to a large extent by the competition between heat conduction and advection as material is transported through the crust at varying rates (Goscombe and others, 2005). Variation in the metamorphic gradient throughout the range is possibly due to variation in domain-specific parameters within the orogen, such as lithology, stages of magmatism, arrangement of shear zones, and erosion rates; all of which influence heat and material advection through the crust (Beaumont and others, 2001; Jamieson and others, 2004).

In the calculation of geothermal gradients the uncertainties of rock densities, the non-linear nature of geotherms, and the uncertainties of pressure-temperature conditions described above must be taken into account. Despite the non-linear nature of geotherms and thermobarometric uncertainties are assumed to effect all samples with a similar order of magnitude. Also, 2.8 gm/cm3 is used for the average metapelite density. Taking these assumptions into account, the absolute values of the geothermal gradients may be questionable. However, because the assumptions are consistent in all samples,
the relative difference between them is indisputable and can be used to infer the exhumation ratios of the studied transects (cf. Groppo and others, 2009).

In Eastern Nepal, Goscombe and others (2006) report high T (500-700 °C) and T/depth ratios (27-42 °C/km) from the Greater Himalayan Sequence. The T/depth ratio increases dramatically across the Main Central Thrust and tapers off gradually in the upper portion of the Greater Himalayan Sequence. On the Nepal/Bhutan border, Imayama and others (2010) reported a similar upsection pattern and a larger range of T/depth ratios (15-43 °C/km). In Central Nepal, temperatures range from 480-825 °C and T/depth ratios range from 12-41 °C/km (Catlos and others, 2001; Kohn and others, 2008 and references therein; Larson and others, 2010). T/depth ratios show a decrease upsection to the Main Central Thrust and increases dramatically at the top of the sequence (Catlos and others, 2001; Larson and others, 2010). In Western Garhwal, temperatures range from 570-880 °C and T/depth ratios range from 14-25 °C/km (Vannay and others, 2001 and references therein). As with the data from Central Nepal, the T/depth ratios do not show a distinct pattern. In Zanskar, Stephenson and others (2001) report T/depth ratios of 15-40 °C/km from the Greater Himalayan Sequence. The T/depth ratios increase gradually through the Greater Himalayan Sequence and decrease steeply across the South Tibetan Detachment.

In comparison to the rocks in the Eastern Garhwal region (this study), the Greater Himalayan Sequence displays higher temperatures (700-850 °C), higher pressures (12-15 kbar) and generally lower T/depth ratios (14-30 °C/km). The T/depth ratio pattern shows an decrease across the Main Central Thrust, which is consistent with conductive heating of foot-wall rocks (the Lesser Himalayan Crystalline Sequence) and cooling of the hanging-wall rocks (the Greater Himalayan Sequence) and advective heat transport
by thrusting. At the top of the Greater Himalayan Sequence, the T/depth ratio increases, which is consistent with conductive cooling of the Greater Himalayan Sequence due to exhumation along the Southern Tibetan Detachment. This is also consistent with the pattern documented in Central and Eastern Nepal by Larson and others (2010) and Imayama and others (2010) respectively. However, this is opposite to the trend found along the same Eastern Nepal transect of Imayama and others (2010), where Goscombe and others (2006) found that the T/depth ratios increase gradually towards the Main Central Thrust and remain constant throughout the Greater Himalayan Sequence.

We assume that the exhumation of the Greater Himalayan Sequence occurred rapidly enough to preserve the peak metamorphic assemblages because the T/depth ratios in the Eastern Garhwal region increase to similar degrees at both the top and base of the crystalline rocks. High-grade assemblages in Greater Himalaya Sequence persist during syntectonic cooling because fluids were unavailable for retrograde hydration reactions (Ketcham and Karabinos, 1989). Retrograde assemblages are restricted to the area nearest to the Main Central Thrust (the Lesser Himalayan Crystalline Sequence) and the hanging wall of the South Tibetan Detachment (the Tethyan Sedimentary Sequence) where fluids generated by prograde reactions migrate along fault planes and fracture networks.

The predicted T/depth ratios of the Greater Himalayan Sequence from the channel-flow numerical models (18-27.5 °C/km from models HT1 and HT111) (Jamieson and others, 2004; 2006) span a similar range as those found in the Eastern Garhwal region (14-30 °C/km). However, the upsection pattern of the T/depth ratios predicted by the model HT1 of Jamieson and others (2004) matches very closely to the pattern of Eastern
Garhwal region, wherein the \( T/\text{depth} \) ratios drop dramatically across the Main Central Thrust and increase across the South Tibetan Detachment. Despite this similarity, the pressures and temperatures predicted by the numerical models vary widely from the observed data.

Importantly, the decreasing temperature with increasing structural level in the model HT1 of Jamieson and others (2004) contradicts the observed nearly constant temperature in the Greater Himalayan Sequence. The discrepancy between the model and nature might be ascribed to the advective heat transfer by melt and/or fluid migration associated with migmatization and emplacement of the leucogranite bodies of the High Himalaya, which is not considered in the HT1 model. This can potentially transfer large amounts of heat towards the structurally higher level of the Greater Himalayan Sequence (for example Miyazaki, 2007; Depinein and others, 2008; Imayama and others, 2010). In central Nepal, Hodges and others (1988) posits that the widespread migmatization and melt escape acted as a buffer to produce nearly uniform temperatures within the high-grade gneiss of the Greater Himalayan Sequence. Such modification of the channel flow models (that is addition of heat advection by melt and/or fluid migration) would lead to a lower field temperature gradient in the model coinciding with the low field gradient found in the field (Imayama and others, 2010).

The broad high temperature region at high structural level shown in the peak temperature profile is compatible with the dome extrusion style models (HT111) Jamieson and others (2006) (Figure 9). These models predict higher peak pressure over a broader region than HT1. The scale of the change in pressure in the model predicted is much larger than observed in the Eastern Garhwal region. Model HT111 is similar to HT1 except that the upper crust contains an embedded weak layer between 4.5 and 7
km made to represent weak sedimentary rock with high pore fluid pressure. This weak layer facilitates the detachment and outward flow of the upper crust overlying the channel. Consequently, the model channel propagates much farther to the south in HT111 than it does in HT1, forcing the foreland fold and thrust belt farther into the foreland basin.

Model HT1 predicts that the highest peak T and P conditions should be recorded in the lowermost Greater Himalayan Sequence, just above the MCT (Fig. 10a; Jamieson and others, 2004). In contrast, model HT111 predicts a high broad peak P-T profile between the MCT and the inner STDS resulting from duplication of the Greater Himalayan Sequence section by dome extrusion (Fig. 10b, Jamieson and others, 2006) (Figure 9). The broad peak in the P-T profile of the model is very similar to the P-T profile of the Garhwal Region presented in this study.

Models HT1 and HT111 require displacement along the Main Central Thrust of ≥600 and ≥400 km respectively (Jamieson and others, 2004; Jamieson and others, 2006). However, estimates of displacement along the Main Central Thrust are on the order of 100 to 250 km based on panisplastic reconstructions (Brunel and Kienast, 1986; Molnar, 1984; Schelling, 1992; Stephenson and others, 2001; Hodges and others, 2002). Dominant fabrics in both the hanging wall and footwall of the Main Central Thrust are parallel. This geometry may indicate that Greater and Lesser Himalayan rocks were once stacked vertically in a flat-on-flat geometry (DeCelles and others, 2001; Robinson and others, 2003). The farthest extent of the thrust front of the Main Central Thrust is expressed in klippen composed of medium grade metasediments of the same affinity as the Greater Himalayan Sequence (Ahmad and others, 2000; Robinson and others, 2001; Célérier and others, 2009). The thermal gradient is also inverted in the Greater
Himalayan klippen as it is at the top of the Lesser Himalayan Crystalline Sequence and as with the top of the Lesser Himalayan Crystalline Sequence, the inverted thermal gradient is localized nearest the thrust. This inverted thermal gradient is due to heat advection from the thrusting of the Greater Himalayan Sequence on top of the Lesser Himalayan Crystalline Sequence. Despite this late stage inverted thermal gradient, Johnson and others (2005) documented Eohimalayan, regional scale right-way-up metamorphic zonation in the klippen of the Eastern Garhwal region. This relationship is consistent with the tectonic models of Ahmad and others (2000), DeCelles (1998, 2001), Robinson and others (2003, 2006a, 2006b, 2008), which are most similar to the foreland propagating fold and thrust belt and the critical taper theory. However, the channel flow and wedge extrusion models of Grujic and others (1996), Beaumont and others (2001), Jamieson and others (2004, 2006), and Beaumont and others (2006) cannot account for the right-way-up metamorphic zonation of these klippen.

The Greater Himalayan Sequence was subsequently tilted due to underplating of the down-going slab and the formation of the Lesser Himalayan Duplex (Johnson and others, 2001; DeCelles and others, 2001; Robinson and others, 2001; Robinson and others, 2003; Célérier and others, 2009a; 2009b). Since rotation of the Main Central Thrust from development of the Lesser Himalayan Duplex, possible reactivation of the Main Central Thrust with as much as 40 km of slip during late Miocene-Pliocene time has been reported (Harrison and others, 1997; Harrison and others, 1998; Catlos and others, 2001; Catlos and others, 2002) and is potentially currently active (Hodges and others, 2001). However, Robinson and others (2003) and Robert and others (2009) have shown that kinematics, metamorphic ages, and cooling ages do not require major late stage reactivation of the Main Central Thrust.
SYN-CONVERGENCE EXTENSION AND CRITICAL TAPER

While extension along the South Tibetan Detachment is thought to have accommodated thrusting along the Main Central Thrust and the extrusion of the Greater Himalayan Sequence (that is coeval extension and shortening) (Hubbard and Harrison, 1989; Searle and Rex, 1989; Burchfiel and others, 1992; Hodges and others, 1992, 1996; Searle, 2010), there is no consensus for synchronous displacement (Murphy and Harrison, 1999; Vannay and Grasemann, 2001).

Extension along orogen parallel normal faults is generally attributed to one of two mechanisms: 1) taper angle adjustments to a supercritical wedge (Robinson and others, 2006, 2008) or 2) syn-convergence extension due to extrusion of midcrustal material along opposite-sense shear zones (Zhang and others, 2000; Vannay and others, 2004) (that is channel flow).

Critical taper theory states that a critical taper angle is maintained by deformation between the basal detachment and the topographic surface of the orogen. If increased erosion decreases the taper angle to a subcritical state, the wedge cannot move until it reestablishes the taper through an interval of shortening by out-of-sequence thrusting in the hinterland increases this angle to reach its critical state. Likewise, if the taper angle increases to a supercritical state, hinterland normal faulting decreases the taper angle (Dahlen, 1990).

Alternatively, channel-flow models propose that an overthickened hinterland and foreland results in an outward lateral flow of weakened midcrustal material in a channel bounded by more rigid layers (Jamieson and others, 2006; Beaumont and others, 2006, 2008). Focused erosion at the deformation front of the orogen allows for
the extrusion of midcrustal rocks to the surface along coeval, opposite-sense shear zones.

Although extension along orogen parallel normal faults in the Greater Himalayan Sequence as seen in the Eastern Garhwal region is inferred by the channel-flow model (that is as material flowing in the channel crosses the ductile-brittle transition), the suite of extensional features of this study that crosscut the tectonic boundaries of the Greater Himalayan Sequence precludes the strict application of the channel-flow model. Moreover, the widespread late stage orogen-parallel extensional features in the Eastern Garhwal region can be attributed to orogenic collapse as minor adjustments to the critical taper of the orogenic wedge (Dahlen, 1990; Robinson and others, 2006, 2008; Thede and others, 2008).

APPLICATION OF FOLD STRUCTURES TO CHANNEL-FLOW MODEL

The channel-flow model predicts the SW extrusion of the Indian middle crust (the Greater Himalayan Sequence) along the Himalayan topographic front through a narrow channel with a thrust sense below and an apparent extensional sense above (Harris, 2007). The boundary conditions of this channel exhibit melt weakening along the upper surface (South Tibetan Detachment), and strain softening along the base (Beaumont and others, 2004). The mechanism of the syn-convergence extension has been described as a combination of pure shear and simple shear (Vannay and Grasemann, 2001; Jessup and others, 2006). The lateral boundaries of the extruding channel are virtually unconstrained with the exception of the east and west syntaxes. For channel-flow to operate, the viscosity of the Greater Himalayan Sequence must be lowered substantially. One way of lowering the viscosity is by dehydration melting of muscovite...
at >700ºC and thus creating in situ melt (Jamieson and others, 2004). However, unless the overall viscosity of the Greater Himalayan Sequence remained constant along the entire strike of the range, the divergent flow of the predicted channel would potentially create salients and recessionals along the Main Central Thrust. However, large scale salients are not found within the crystalline rocks along the Himalayan Range as evidenced by the lack of breaks in the lateral metamorphic gradient (for example Long and McQuarrie, 2010).

**SHEATH FOLDS AND CHANNEL FLOW**

The presence of sheath fold structures within the Greater Himalayan Sequence does not necessarily require channel-flow as an emplacement mechanism. Sheath folds have been identified within zones of intense non-coaxial deformation well below the temperatures required by channel-flow (Alsop and Carreas, 2007). It should, therefore be noted that the presence of sheath folds does not preclude the emplacement of the Greater Himalayan Sequence via critical taper (Dahlen, 1990; Kohn, 2008) or tectonic wedging (Webb 2007). However in theory, the critical taper taper model does not require coeval motion along the Main Central Thrust and the South Tibetan Detachment. Furthermore, the tectonic wedging model, which asserts that the South Tibetan Detachment is a roof thrust with limited displacement cannot explain significant amounts of displacement required to juxtapose the unmetamorphosed Martoli Formation with the high grade Greater Himalayan Sequence, or the association of partial melting with decompression along the South Tibetan Detachment (Harris and Massey, 1994).

**NORTH-VERGING FOLDS AND CHANNEL FLOW**
In the Tethyan Sedimentary Sequence overlying the Greater Himalayan Sequence, Kanungo and Murthy (1981) report a northeastward vergence direction in the folds of the Tethyan Sedimentary Sequence in the Garhwal Region. The structures reported by Kanungo and Murthy (1981) also include minor southwestward verging folds that are overprinted by the more dominant northeastward verging folds. The fold axes within the unmetamorphosed Tethyan Sedimentary Sequence and Mandhali Formation of the Lesser Himalayan Crystalline Sequence vary drastically from those found in the crystalline rocks of the Greater Himalayan Sequence and the Munsiaari Formation. The fold axes measured within the unmetamorphosed sedimentary rocks are, with few exceptions parallel to the average orientation of the range, whereas the crystalline rocks exhibit fold axes that have values ranging from parallel to the average orientation of the range to perpendicular to the range. This is consistent with sheath folds only forming within the ductily deformed rocks whereas cylindrical folds associated with thrust faults dominate the unmetamorphosed rocks.

The north-verging folds in the Tethyan Sedimentary Sequence of the eastern Garhwal region reported by Kanungo and Murthy (1981) are similar to those reported by Kellet and Godin (2009) and Searle (2010) in central Nepal. This is contrary to the southwestward verging folds in the Tethyan Sedimentary Sequence in the western Garhwal region (Wiesmayr and Grasemann, 2002; Vannay and others, 2004). These convergent structures in the Tethyan Sedimentary Sequence have been used to help identify the potential exhumation mechanisms by comparing the predictions of the channel flow numerical models (for example Kellet and Godin, 2009). The southwestward vergence direction of folds in the western Garhwal region indicate a model similar to a tectonic wedging model, in which both the Tethyan Sedimentary
Sequence and the Greater Himalayan Sequence are transported to the south. However, differing transport rates results in an initial top-to-the-south slip along the South Tibetan Detachment wherein the South Tibetan Detachment acted as a passive roof thrust, followed by top-to-the-north slip (Webb and others, 2007), or a duplexing model, in which the South Tibetan Detachment cuts through a southward-propagating thick-skinned fold and thrust belt (Robinson and others, 2006; Célérier and others, 2009). However, Searle (2010) concludes that the South Tibetan Detachment was initiated as a passive roof fault during the extrusion of the middle crustal material that currently makes up the Greater Himalayan Sequence. This passive roof fault subsequently caused the north-verging folds seen in the Tethyan Sedimentary Sequence and enhanced these folds by backsliding during the extrusion of the Greater Himalayan Sequence.

TIMELINE

Development of the Main Central Thrust and South Tibetan Detachment with emplacement of the Greater Himalayan rock over Lesser Himalayan rock (see Figure 10a). The Main Central Thrust was active in the Garwhal Region from 21-14 Ma (Metcalfe, 1993), whereas the South Tibetan Detachment was also active between 23-21 Ma in the Garwhal Region (Searle and others, 1999). This phase of Early Miocene channel exhumation coincided with focused intense erosion along the south flank of the range (Beaumont and Jamieson, 2010). The Gangortri, Badrinath, and Malari granites in the Garhwal Region were emplaced at this time (22-19 Ma, Harrison and others, 1997; Sachan and others, 2010).

As erosion rates progressively decreased from Mid-Miocene to Pliocene time (Clift and others, 2008), channel exhumation ceased and the Greater Himalayan Sequence thrust
sheet behaved as a thrust-sense critical wedge (see Figure 10b) with propagation of the thrust front into the foreland (Beaumont and Jamieson, 2010). This phase of deformation coincides with subsequent tectonic wedging of the Greater Himalaya Sequence and Tethyan Sedimentary Sequence creating both top-to-the-south and top-to-the-north shear along the South Tibetan Detachment (Webb and others, 2007). As the thrust front propagates into the foreland the frontal portion of the Greater Himalayan Sequence exhibits a normal metamorphic gradient (Vannay and Grasemann, 2002; Johnson, 2005; Robinson and Pearson, 2006), whereas the distal portion has an inverted metamorphic gradient due to channel flow modification (Figure 10b).

Increased erosion between 10-3 Ma created a subcritical taper which led to the formation of the Lesser Himalayan Duplex (see Figure 10c) as evidenced by the onset of Lesser Himalayan Sequence derived sediments in the Bengal and Indus Fans (Amano and Taira, 1992; Clift and others, 2008; Kohn, 2008). This subsequently uplifts and tilts the Greater Himalayan Sequence and Tethyan Sedimentary Sequence.

As the erosive front continued to push further into the hinterland, channel flow is initiated again as the Main Central Thrust is reactivated as an out-of-sequence thrust (~5.9-4 Ma) (Catlos and others, 2001; 2002) along with reactivation of the South Tibetan Detachment ca. 2.5 Ma in the Garhwal Region (Bojar and others, 2005) (see Figure 10d). A low velocity zone found in the High Himalaya suggests that a low viscosity, partial melt in the crust may potentially sourcing the melt necessary for modern channel flow (Ashish and others, 2009). If the present aggressive erosion persists for approximately 10 Ma, the modern channel will be exhumed in a similar manner to that of the first Miocene phase (Beaumont and Jamieson, 2010). Modern earthquakes in the Garhwal Region along the Munsiaari Thrust and within the Lesser Himalayan Duplex (for
example 1991, m = 6.6, Uttarkashi (Kayal, 1996); 1999, m = 6.3, Chamoli (Kayal and others, 2003)) may indicate the wedge has not yet achieved a critical taper.

CONCLUSION

The metamorphic rocks of the High Himalayas in the Eastern Garhwal region of northwest India are divided into the two tectonometamorphic units: the Munsiari Formation and the Greater Himalayan Sequence. These two zones separated by the Main Central Thrust have two distinct peak metamorphic conditions. At the top of the Greater Himalayan Sequence, the Southern Tibetan Detachment places the unmetamorphosed Martoli Formation against the migmatite-grade Greater Himalayan Sequence.

The peak metamorphic conditions of the Munsiari Formation range from 550-600 °C and 5-9 kbar. Peak metamorphic conditions near the base of the overlying Greater Himalayan Sequence range from 700-800 °C and 10-12 kbar revealing a stark discontinuity between these two metamorphic zones. Peak metamorphic temperature, calculated from mineral equilibria remain nearly constant (~800-850 °C) through the rest of the Greater Himalayan Sequence to the South Tibetan Detachment. Peak temperature metamorphic pressure increases from ~14 kbar 3 km above the the Main Central Thrust and decreases to ~9 kbar at the South Tibetan Detachment. Quartz recrystallization temperatures also reveal the metamorphic discontinuity between the Munsiari Formation and the Greater Himalayan Sequence. A slight upturn in metamorphic temperatures in the footwall (Munsiari Formation) and downturn in the hanging wall (Greater Himalayan Sequence) across the Main Central Thrust is evidence for
modification of the temperature profiles due to a “hot iron effect” of thrusting the hotter Greater Himalayan Sequence on top of the Munsíari Formation.

The thermobarometric profiles found in the Garhwal Himalaya are consistent with the patterns predicted by the numerical models of channel flow (Beaumont and others, 2004; Jamieson and others, 2006) and critical taper (Kohn, 2008). Despite the supposed dichotomy between the channel flow model and critical taper model, Beaumont and Jamieson (2010) claim that the critical taper model applies to the foreland portion of the orogen external to the channel. Channel exhumation is claimed to have coincided with intense erosion focused along the front of the range. As erosion decreases, the wedge forms a thrust-sense supercritical wedge. If this is the case, then the interpretation of thermobarometric data from the Greater Himalayan Sequence across the range should only be applied to the ductile deformation of the extruding metamorphic core or “channel”.
Table 1: Thermobarometric results from rocks of the Eastern Garhwal Region of India.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stratigraphic distance above MCT (km)</th>
<th>T (°C)</th>
<th>P (kbar)</th>
<th>T/d</th>
<th>Depth</th>
<th>Formation</th>
</tr>
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<tbody>
<tr>
<td>GH54</td>
<td>22.1</td>
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<td>8.5±0.1</td>
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<td>28.3</td>
<td>South Tibetan Detachment</td>
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<tr>
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<td>9.7±0.6</td>
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<td>Badrinath</td>
</tr>
<tr>
<td>10A</td>
<td>19.6</td>
<td>810±25</td>
<td>10.6</td>
<td>*</td>
<td>21.4</td>
<td>Badrinath</td>
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<tr>
<td>GH32b</td>
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<td></td>
<td>†</td>
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<td>†</td>
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<tr>
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<td>14.2±0.2</td>
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<tr>
<td>GH21</td>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
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<td>2.6</td>
<td>835±25</td>
<td>14.9</td>
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<tr>
<td>GH17</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>735±20</td>
<td></td>
<td>†</td>
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<td>14.1</td>
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<td>Joshimath</td>
</tr>
</tbody>
</table>

Assuming 45° Dip  Rounded to nearest 5°C

§ Ti in Bt    Henry et al., 2005
† Bt-Tm    Colapietro and Friberg, 1987
* Gt-Pl-Ms-Bt    Hoisch, 1990
# Gt-Pl-Al-Qtz    Koziol, 1989 w/Berman, 1990 Gt model
Figure 1: a) Generalized tectonic map of the Himalayan orogen after Ahmad and others (2000). Major fault systems include the South Tibetan Detachment system (STD), Main Central Thrust system (MCT), Main Boundary Thrust system, and the Main Frontal Thrust system (MFT). Study area shown in box. b) Simplified geologic map and c) tectonostratigraphic column of the Eastern Garhwal Region (after Virdi, 1986, Valdiya and others, 1999 and references therein). Locations of samples used for thermobarometry and quartz thermometry shown in white circles whereas sample used only for quartz thermometry are shown in gray circles.

Figure 2: Simplified geological cross-section of the Alaknanda/Dhauli ganga transect with approximate sample locations and elevations. Insets a-g are photomicrographs of representative microstructures and mineral assemblages for various samples throughout the transects. All photomicrographs are crossed polars. (a) Garnet-bearing schist from the Munsiari Formation. Inclusions within garnet define contorted S1. (b) Garnet-bearing schist from the Munsiari Formation. Sense of shear is top-to-left with well developed sigma-tails surrounding garnets. (c) Garnet-bearing quartzite from the Pandukeshwar Formation. Inclusion rich portions of garnets seem to delineate former quartz-rich zones whereas inclusion poor areas, former clay-rich zones where the plane between these zones define S1. (d) Garnetite vien from the Pandukeshwar Formation. Garnet makes up nearly 80 modal percent confined within 3 cm layer parallel to dominant foliation. (e) Atoll garnet in the Badrinath Formation. The thin garnet rim is cored primarily by calcite and plagioclase with smaller garnet, titanite and apatite inclusions. (f) Kyanite-garnet gneiss in the Joshimath Formation. Mineral assemblage includes kyanite, garnet, plagioclase, muscovite, and biotite. (g) Sillimanite bearing gneiss the Badrinath Formation. Sillimanite forms fibrous clots. Muscovite is secondary and grew during retrograde metamorphism.

Figure 3: Compositional maps of representative garnet porphyroclasts showing relative concentrations of Fe, Ca, Mg and Mn for the crystalline rocks in the Eastern Garhwal region.

Figure 4: Representative garnet compositional transects for representative garnet porphyroblasts. Mn profiles in garnet porphyroblasts shows a general increasingly diffuse profile up section. Black line through garnets represent location of transect. See text for explanation.

Figure 5: Inferred average pressure-temperature condition for samples from the Munsiari Formation and Greater Himalayan Sequence.

Figure 6: Photomicrographs illustrating quartz recrystallization microstructures from the Mandhali Formation of the Lesser Himalayan Crystalline Sequence upsection through the crystalline rocks of the Munsiari Formation and the Greater Himalayan Sequence and the lowest portion of the Tethyan Sedimentary Sequence (Martoli Formation); cross-polarized light. All thin sections cut perpendicular to S1, and parallel to mineral stretching lineation. Quartz microstructure classification and temperature estimates defined by Stipp and others (2002). Shown in tectonostratigraphic order from lowest to highest. (a, b, c) GH3, GH4b, GH12: Mandhali Formation quartzite and quartz-rich schist from the Munsiari Formation exhibiting bulging recrystallization (>300 ºC). (d, e) GH20, GH62: kyanite gneiss of the Joshimath
Formation and and quartzofelspathic gneiss from the Pandukeshwar Formation exhibiting chessboard extinction ($\geq 630 \, ^\circ C$). (f) GH31: migmatitic gneiss from the Badrinath Formation with classic amoeboid grain boundary migration with chessboard extinction ($\geq 630 \, ^\circ C$). (g) GH55b: slate with quartz viens from the Martoli Formation of the Tethyan Sedimentary Series with minor bulging recrystallization ($>300 \, ^\circ C$).

Figure 7: Ductile and brittle structures plotted on equal-area lower-hemisphere stereographs and associated photographs in the Greater Himalayan Sequences in the Alaknanda and Dhauliganga valleys. Poles to planes of the (a) dominant penetrative foliation (S1), axial planar foliation (S2), mineral lineation, (b) fold axes, and great-circle plane orientation of (c) orogen parallel conjugate fractures, (d) orogen perpendicular conjugate fractures, and (e) normal faults, South Tibetan Detachment (STD).

Figure 8: Tectonostratigraphic column with pressure and temperature estimates, quartz recrystalization fabrics (after Stipp and others, 2002), index minerals, and representative garnet zoning. Due to the homoclinal nature of the Greater Himalayan Sequence, P-T conditions are plotted versus structural distance with respect to the Main Central Thrust, assuming a constant dip angle of 45° (Macfarlane and others, 1992; Kohn, 2008). In the pressure field diamonds represent Gt-Pl-Ms-Bt barometry (Hoisch, 1990) and circles represent Gt-Pl-AlSiO5-Qtz barometry (Koziol and Newton, 1989 with the Berman, 1990 garnet activity model). Phase equilibria constraints are from Kohn (2008). In the temperature field circles represent the Ti in Bt thermometry (Henry and others, 2005), diamonds represent the Gt-Bt thermometry (Ferry and Spear, 1978, with the Berman, 1990 garnet activity model), and squares represent the Bt-Tm thermometry (Colopietro and Friberg, 1987). The $T \,(^\circ C)/depth \,(km)$ ratio was calculated assuming an average rock density of 2.8 g/cm$^3$. Minimum estimates for $T/depth$ ratios were calculated using minimum temperature and maximum pressure estimates and maximum estimates were calculated using maximum temperature and minimum pressure. Quartz recrystallization fabrics abbreviations are NRC: no recrystallization; BLG: bulging grain boundaries; SGR: sub-grain rotation; GBM: grain boundary migration; CSB: chessboard extinction. Garnet zoning patterns primarily defined by Mn zoning pattern. Concept of data presentation modified from Goscombe and others, 2006 and Jessup and others, 2008.

Figure 9: Schematic diagrams of PT profiles channel flow models HT1 (Jamieson and others, 2004) and HT111 (Jamieson and others, 2006) predictions and the PT profile from the Eastern Garhwal region. RSCM from the Alaknanda transect in the Eastern Garhwal region from Célérier and others (2009). Note: stratigraphic distance from the Main Central Thrust only applies to the PT profile from the Eastern Garhwal region. MCT: Main Central Thrust, MT: Munsiari Thrust, STD: South Tibetan Detachment. Gt-Bt (garnet-biotite), Tr-Bt (tourmaline-biotite), Ti Bt (titanium in biotite) thermometry methods described in text.

Figure 10: Schematic tectonic cross-section showing evolution of the fold and thrust belt in eastern Garhwal since Early Miocene time (modified after Robinson and Pearson, 2005). a) Development of the Main Central Thrust and South Tibetan Detachment with emplacement of the Greater Himalayan rock over Lesser Himalayan rock. b) Channel exhumation ceased due to
decreased erosion rates from Mid-Miocene to Pliocene time, wherein the Greater Himalayan Sequence thrust sheet behaved as a thrust-sense critical wedge with propagation of the thrust front into the foreland (Beaumont and Jamieson, 2010). c) Increased erosion between 10-3 Ma created a subcritical taper which led to the formation of the Lesser Himalayan Duplex. This subsequently uplifts and tilts the Greater Himalayan Sequence and Tethyan Sedimentary Sequence. d) Channel flow is initiated again as the Main Central Thrust is reactivated as an out-of-sequence thrust (~5.9-4 Ma) (Catlos and others, 2001; 2002) along with reactivation of the South Tibetan Detachment ca. 2.5 Ma in the Garhwal Region (Bojar and others, 2005) Modern earthquakes (shown as stars) in the Garhwal Region along the Munsiai Thrust and within the Lesser Himalayan Duplex (e.g. 1991, m = 6.6, Uttarkashi (Kayal, 1996); 1999, m = 6.3, Chamoli (Kayal and others, 2003)) may indicate the wedge has not yet achieved a critical taper. See text for further explanations and references.
Figure 1:
Figure 2:
Figure 4:
Figure 5:

[Diagram showing the relationship between pressure and temperature with markers for different formations such as Munsiari Fm, Joshimath Fm, Badrinath Fm, Pandukeshwar Fm, and South Tibetan Detachment.]
Figure 6:
Figure 7:

a. Fold axes
b. Field area

48
Figure 9:
Figure 10:

- **a. Early Miocene** (23-16 Ma)
  - MCT
  - STD
  - Normal metamorphic gradient
  - Tip of channel (inverted metamorphic gradient)

- **b. Middle Miocene** (16-11 Ma)
  - MCT
  - STD
  - TSS
  - LHS
  - GHS
  - Inverted metamorphic gradient

- **c. Late Miocene** (11-5.2 Ma)
  - MCT
  - STD
  - TSS
  - LHS
  - GHS
  - Normal metamorphic gradient

- **d. Pliocene to Present** (5.2-present)
  - MCT
  - STD
  - TSS
  - LHS
  - GHS
  - Inverted metamorphic gradient
  - Normal metamorphic gradient
  - Location of major earthquake (m<6)
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