Piezometry and Strain Rate Estimates Along Mid-Crustal Shear Zones

Matthew Keegan Francis

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Richard D. Law
James A. Spotila
Mark J. Caddick

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Abstract

Dynamically recrystallized quartz microstructure and grainsize evolution along mid-crustal shear zones allows for the estimation of tectonic driving stresses and strain rates acting in the mid-crust. Quartz-rich tectonites from three exhumed mid-crustal shear zones, the Main Central Thrust (MCT; Sutlej valley, NW India), South Tibetan Detachment System (STDS; Rongbuk valley, S Tibet), and Moine thrust (NW Scotland), were analyzed. Deformation temperatures estimated from quartz microstructural and petrofabric thermometers indicate steep apparent thermal gradients (80—420 °C/km) across 0.5—2.3 km thick sample transects across each shear zone. Quartz recrystallization microstructures evolve from transitional bulging/sub-grain rotation to dominant grain boundary migration at ~200 m structural distance as traced away from each shear zone. Optically measured quartz grainsizes increase from ~30 μm nearest the shear zones to 120+ μm at the largest structural distances. First-order Zener space analysis across the Moine nappe suggests strong phyllosilicate control on recrystallized quartz grainsize. Recrystallized quartz grainsize piezometry indicates that differential stress levels sharply decrease away from the shear zones from ~35 MPa to 10 MPa at ~200 m structural distance. Strain rates estimated with quartz dislocation creep flow laws are tectonically reasonable, between $10^{-12} - 10^{-14}$ s$^{-1}$. Traced towards each shear zone strain rate estimates first decrease one order of magnitude before rapidly increasing one to two orders of magnitude at structural distances of ~200 m. This kinked strain rate profile is likely due to the steep apparent thermal gradients and relatively constant differential stress levels at large structural distances.
Acknowledgements

I’ve been a geologist for five years now and a curious little boy for at least three times as long. Driving from Stevens Point, Wisconsin to Estes Park, Colorado during summer vacations multiple times over my childhood piqued my interest in the powerful Earth forces that shape mountains. I remember straining my neck in the drudgery that is Nebraska, just so I could catch the first glimpse of the Rocky Mountain foothills. Stopping at Dick’s Rock Shop in Estes Park was mandatory in order to cut open geodes and buy fish fossils. Hiking past The Loch and climbing around the waterfall towards Sky Pond in Rocky Mountain National Park was also mandatory. I was always astonished by the views, both up and down, as well as the 20 or 30 degree temperature change from the trailhead parking lot to the tarn. Snow, a year-round occurrence in Rocky Mountain National Park, awed me so much that I had to collect some in a water bottle – my mom kept that “glacial snow” in the freezer for over a decade. I thought rocks and mountains were cool.

My parents, Ted and Rose Francis, deserve the credit for turning me on to geology. For as little as they comprehend my geologic interests now, they allowed me to pursue whatever I wished an equal amount as a child, even if it meant that I was the strange kid who liked rocks. I will always remember and be thankful for their appreciation of the learning and curiosity process.

I didn’t become hooked on geology until taking Geology 100 my sophomore year at the University of Wisconsin—Madison. I knew before the first exam that I wanted to become a geology major. I was even disappointed when that class ended because I would have to endure a whole summer without learning more about the Earth. Over the next year I was introduced to a plethora of Earth processes and fields of geology, including structural geology – mountains and mountain building processes, sign me up!

Basil Tikoff and Laurel Goodwin each took me under their wing at one point or another during my undergraduate career and provided me the best possible environments to succeed. Their roles in my development as a geologist cannot be understated. Laurel allowed me to become an undergraduate tutor for her structural geology course, offering me a chance to improve and expand my structural geology knowledge and ability. Basil advised over my senior research project, provided brutally honest manuscript revisions, and suggested future Master’s advisors; all of which has well prepared me as a scientist for future endeavors.

Rick Law, my Master’s advisor, has been bloody excellent in providing the perfect level of research support and insight. Starting with very detailed project plans and outlines and gradually setting me free on independently conceived projects, Rick allowed me to grow as a scientist and structural geologist. Even as I was actively pursuing a career outside of academia, Rick allowed me to follow my interests and always let me choose what was best for myself. The weekly pints at the Underground with he and his wife, Claire, were crucial in keeping me sane and will be fondly remembered.

The office would not have been the same without Don Stahr, Ben Roth, and Sarah Mazza to discuss the necessity of data dumps, desktop monitor appropriation,
and who was most annoying, respectively. My friends Mike Cangialosi, Kathy Davenport, Kyle Ashley, and Kristie Dorfler were always up for sharing beers, laughs, and horror stories.

Lastly, but most importantly, my loving girlfriend, Erin Schofield, has been especially supportive of me and my goals over the past two years. While this process has been difficult at times, she was always there to keep me going. I am better person due to her perseverance.
Attributions

Chapter one will be submitted for publication to the Journal of Structural Geology as “Francsis, M.K., Law, R.D. Piezometry and strain rate estimates on the upper and lower margins of the Greater Himalayan Series.” M.K. Francsis was responsible for grainsize, stress, and strain rate estimates. R.D. Law wrote the NSF proposal that funded this research, collected samples in the field, and provided all the temperature data. M.K. Francsis wrote the manuscript and drafted all the figures.

Chapter two may be submitted for publication to the Journal of the Geological Society as “Francsis, M.K., Law, R.D. The effect of 2nd phase minerals on piezometry and strain rate estimates from the Moine thrust nappe, NW Scotland.” M.K. Francsis was responsible for grainsize, stress, and strain rate estimates. R.D. Law wrote the NSF proposal that funded this research, collected samples in the field, and provided all the quartz c-axis fabric opening angle temperature data. M.K. Francsis wrote the manuscript and drafted all the figures.
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CHAPTER 1

Piezometry and strain rate estimates on the upper and lower margins of the Greater Himalayan Series

M.K. FRANCSIS¹, R.D. LAW¹
¹Department of Geosciences, Virginia Tech, Blacksburg, Virginia 24061, USA

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Abstract

Quartz microstructural and fabric analyses across shear zones marking the lower (Main Central Thrust – MCT) and upper (South Tibetan Detachment System – STDS) margins of the Greater Himalayan Series (GHS) indicate significant changes in high temperature ductile deformation traced towards each fault. Three structural transects across both the STDS in Rongbuk Valley, S Tibet and the MCT in Sutlej Valley, NW India document a change of quartz dynamic recrystallization mechanism from grain boundary migration in the GHS interior to transitional bulging/sub-grain rotation traced towards the STDS/MCT. Accompanying the change in recrystallization mechanism, optically measured average quartz grainsizes decrease from 120+ μm to ~ 30 μm. Quartz grainsize piezometry indicates differential stresses increase from ~ 10 MPa in the GHS interior to ~ 35 MPa closest to the GHS margins. Recently published deformation temperatures, combined with differential stress estimates, provide strain rate estimates ranging from 4.2 x 10^{-12} to 2.3 x 10^{-14} s^{-1} using quartz flow laws. Traced towards both faults into progressively lower deformation temperature tectonites, strain rate estimates first decrease by one to two orders of magnitude and then abruptly increase one to two orders of magnitude at structural distances of less than ~ 200 m from the faults.

1. Introduction

Ductile extrusion and pervasive deformation of the Greater Himalayan Series (GHS; also known as the Higher Himalayan Crystalline Series) controlled the Miocene evolution of the Himalayan orogen in Bhutan, Nepal, and India (Fig. 1.1; Herren, 1987; Grujic et al., 1996; Dezes et al., 1999; Beaumont et al., 2001; Vannay and Grasemann, 2001; Searle et al., 2003; Godin et al., 2006; Searle et al., 2011). Bounding the upper and lower margins of the GHS are the South Tibetan Detachment System (STDS), a package of north-vergent normal
Fig. 1.1. Schematic geologic sketch map of the Himalayan orogen modified from Law et al. (2004). The Greater Himalayan Series (High Himalaya) is bounded above by the South Tibetan Detachment System and below by the Main Central Thrust. Rongbuk and Sutlej study areas (Fig. 3 and Fig. 4, respectively) are indicated. P, Peshawar basin; K, Kashmir Neogene basin; ZSZ, Zanskar shear zone; S, Sutlej basin.
faults, and the south-vergent Main Central Thrust (MCT), respectively. These mid-crustal ductile shear zones have accommodated 50—200 km of dip-slip displacement (Hodges, 2000; Searle et al., 2003; Yin, 2006; Law et al., 2011).

The extrusion processes and flow properties of the GHS are well studied and relatively well constrained (Fig. 1.2; Hodges et al., 1992; Jain and Manickavasagam, 1993; Hubbard, 1996; Grasemann et al., 1999; Grasemann and Vannay, 1999; Beaumont et al., 2001; Vannay and Grasemann, 2001; Law et al., 2004; Jessup et al., 2006; Law et al., 2011). The channel flow model (e.g. Beaumont et al., 2001) has arguably become the preferred tectonic model to explain the observed inverted metamorphic sequence structurally above the MCT and the right-way-up metamorphic sequence structurally below the STDS (Law et al., 2006). Deformation at the margin of the GHS has been fairly well characterized in terms of strained material lines (metamorphic isograds, isotherms), vorticity of flow, and minimum finite strain estimates (Herren, 1987; Dezes et al., 1999; Grasemann et al., 1999; Law et al., 2004; Jessup et al., 2006; Larson and Godin, 2009; Larson et al., 2010). However, local flow stress and associated strain rate estimates have never been reported from the GHS margins; these parameters are essential for documenting and modeling the deformatonal history of the Himalayan orogen.

Here we report recrystallized quartz grainsizes and microstructures in three structural transects across both the STDS and MCT. Inputting our grainsizes into the Stipp and Tullis (2003) quartz piezometer yields stress estimates that, as intuitively expected, increase towards the GHS margins. Combining stress estimates with recently published deformation temperatures from the quartz c-axis thermometer (Kruhl, 1998) in quartz dislocation creep flow laws allows strain rate estimates to be made. The flow properties along each shear zone are startlingly similar and provide new insight into the deformational processes and kinematics associated with extrusion of the GHS between the STDS and MCT.
Fig. 1.2. Schematic geologic cross section parallel to Himalayan transport showing channel flow extrusion of the mid-crust. Metamorphic isograds and deformation isotherms (material lines) of the GHS are apparently recumbently folded and telescoped along the GHS margins. Based on Zanskar-Kishtwar Himalaya of NW India; Searle and Rex, 1989; Searle et al., 1999.
2. Background to GHS Geology

The GHS contains the highest-grade metamorphic rocks in the Himalayan orogen. Consisting of a suite of amphibolite to rare granulite facies ortho- and paragneisses, the GHS inevitably varies in composition across the orogen but always maintains a high metamorphic grade (Searle et al., 2003; Yin, 2006; Cottle et al., 2011). Abutted to the north by the north-dipping, normal-sense STDS and to the south by the north-dipping, thrust-sense MCT, the GHS represents a 5-30 km thick tectonic slab extruded southward from beneath the Tibetan Plateau during Miocene times (Fig. 1.1). The STDS separates generally unmetamorphosed—low grade Tethyan passive margin sedimentary sequences in the hanging-wall from the high-grade metamorphic and leucogranite intrusive suites of the GHS in the footwall. As defined by Searle et al. (2008), the MCT places a hangingwall of Tertiary GHS metamorphic rocks over unmetamorphosed or low-grade Lesser Himalayan rocks. Initiation, displacement, metamorphism, and anatexis were broadly synchronous along both the STDS and MCT as indicated by structural and geochronologic studies (Burchfiel et al., 1992; Hodges et al., 1992; Godin et al., 2006; Searle et al., 2011). Both margins are observed to be thick (2+ km) ductile shear zones culminating in discrete faults at the structurally highest (STDS) and lowest (MCT) positions.

Our two field regions are Rongbuk valley located immediately north of Mount Everest in east-central Tibet and Sutlej valley in northwest India (Fig. 1.1). Oriented north-south, Rongbuk valley exposes the south-dipping STDS for ~ 30 km along transport. Three fluvial subsidiary side valleys transect the STDS and comprise our sample areas (Fig. 1.3). The Sutlej river valley, oriented NE-SW, essentially parallels the GHS transport direction in NW India and transects the whole GHS tectonic slab. Where out-of-sequence deforma-

Fig. 1.3. Next page. Simplified geologic map of Rongbuk Valley, southern Tibet showing the three sample traverses across the STDS: a) Northern transect, b) Rongbuk Monastery, c) Hermit’s Gorge. See Jessup et al. (2006) and Law et al. (2011) for enlargements of detailed sample transects and sample locations.
Rongbuk Valley

- limestone
- Everest Series (undivided)
- marble/calc-silicate
- mylonitic leucogranite
- psammitic schist
- Qomolangma detachment
- summit

N

2 km

Everest

Changtse

Rapu La
High Himalayan Crystalline Sequence (HHCS)
Sangla Detachment (SD)
Main Central Thrust (MCT)
Munsiari Thrust (MT)
Main Boundary Thrust (MBT)
Lesser Himalayan Crystalline Sequence (LHCS)
Lesser Himalayan sedimentary series (LH)
Sub-Himalaya
tion and differential erosion have exposed multiple basal sections of the GHS and the MCT, sample traverses perpendicular to the MCT were collected (Fig. 1.4).

2.1 Rongbuk geology

North of Mount Everest, in Rongbuk valley, the STDS is composed of two major north-dipping detachment structures, the upper brittle Qomolangma detachment (QD) and the lower ductile Lhotse detachment (LD, Fig. 1.3). These structures merge, are closely parallel, or dissect each other traced to the north, coalescing within 30 km NNW of Mount Everest (Searle et al., 2003; Cottle et al., 2007; Cottle et al., 2011; Searle et al., 2011).

Traced structurally down section from the summit of Mount Everest, metamorphic grade increases. Fine-grained, recrystallized Ordovician limestones of the Everest summit pyramid have a maximum burial temperature of 338 °C as indicated by Raman spectroscopy on carbonaceous material (Cottle, 2007; Cottle et al., 2011). The Yellow Band, a prominent 200-250 m thick section of coarse-grained, dynamically recrystallized marbles lies structurally below the summit limestones. Below the Yellow Band is the pelitic green-schist-amphibolite facies Everest Series. Recent thermobarometric analysis of the Everest Series indicates maximum temperatures of ~ 650 °C (Waters et al., 2006; Law et al., 2011). Structurally lowest are the amphibolite-facies metasedimentary rocks and leucogranites of the GHS.

Structural relations between the different rock packages in the Rongbuk area also vary down section. The QD, as mentioned above, is a brittle detachment separating the summit limestones from the Yellow Band. Juxtaposing the Everest Series and GHS leucogranites is the ductile LD. Both structures dip gently to the NE with the QD assuming a

Fig. 1.4. Previous page. Simplified geologic map of Sutlej Valley, NW India modified from Wiesmayr & Grasemann (2002). Sample transect locations across the MCT are indicated with red circles; a) Shimla Klippe, b) NW Sutlej, c) SW Sutlej. Geologic cross section from X-X' across the Himalayan orogen sub-parallel to the tectonic transport direction. Adapted from Vannay et al. (2002).
slightly steeper orientation creating a northward-tapering tectonic wedge encompassing the Everest Series and Yellow Band. Brittle deformation of the QD has overprinted the higher-temperature ductile deformation of the LD where the two intersect and merge NNW of Everest (Fig. 1.3).

Micro- and macrostructures at the top of the GHS slab indicate top down to the NNE normal shear sense along the STDS. Several generations of leucogranite intrusions are variably mylonitized or sheared with a top to the NNE shear sense (Carosi et al., 1998; Hodges et al., 1998; Murphy and Harrison, 1999; Searle et al., 2003). Shear bands, rotated porphyro-blasts, -clasts, S-C fabrics, mica fish, and quartz c-axis fabrics consistently indicate normal shear sense at the microscale (Carosi et al., 1998; Law et al., 2004; Waters et al., 2006; Law et al., 2011). Vorticity analysis of these tectonites indicates a significant pure shear component (Law et al., 2004; Jessup et al., 2006). Metamorphic isograds at the top of the GHS slab are known to be telescope/condensed (e.g. Herren, 1987 for Zanskar). Recently published data on the thermal profile of the GHS upper margin in Rongbuk and western Bhutan suggests deformation isotherms are also telescoped (Burchfiel et al., 1992; Law et al., 2011; Kellett and Grujic, 2012).

Three structural transects were sampled through the STDS within Rongbuk valley, two through the LD and one through the QD (Fig. 1.3, Table 1). From north to south (Fig. 3a-3c, respectively) are the Northern, Rongbuk Monastery, and Hermit’s Gorge transects, as previously described by Jessup et al. (2006) and Law et al. (2011). The Northern transect (Fig. 1.3a) contains a suite of samples within 100 m structural distance of the brittle, QD, portion of the STDS. The Rongbuk Monastery and Hermit’s Gorge sample transects extend to a depth of ~ 500 m in structural distance beneath the LD. Law et al. (2004) reported preliminary microstructural, strain, quartz c-axis fabric, deformation temperature and flow vorticity data from Hermit’s Gorge and Rongbuk Monastery transects. Jessup et al. (2006) and Law et al. (2011) subsequently published more detailed analyses of flow vorticities, deformation temperature, and kinematic models for the Rongbuk valley transects. Sample
Table 1: Rongbuk sample transect data

### Hermit’s Gorge

<table>
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<th>Sample #</th>
<th>Detachment distance (m)</th>
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### Northern Traverse

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<th>Grainsize (μm)</th>
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<td></td>
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<td>/a</td>
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<tr>
<td>R-03-15 (R2)</td>
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<td>R-03-26A</td>
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<td>565</td>
<td>54.6</td>
<td>48.7</td>
<td>51.2</td>
</tr>
</tbody>
</table>

---

* From talus pile, structural distance estimated from deformation temperature
1. See Law et. al (2011) for complete details on data collection and interpretation
2. Arithmatic mean of grains measured parallel to the macroscoic foliation
3. Arithmatic mean of grains measured perpendicular to the macroscoic foliation
4. Avg grain size equals the diameter of a circle with identical area to an ellipse with major and minor axes equal to /a and ±a

Example Calculation for R-03-41:

Area of Ellipse = \( \pi \times (39.0/2) \times (22.1/2) = 676.9 \, \mu m^2 \)

Area of Circle = Area of Ellipse

Diameter of Circle = \( 2 \times (676.9/\pi)^{1/2} = 29.4 \, \mu m \)
locations and structural positions referred to in this paper are from Law et al. (2011, their Fig. 3) and are summarized in Table 1.

2.2 Sutlej geology

Mylonitic orthogneisses mark the position of the MCT as a major SW-vergent thrust zone in the western Sutlej valley (Fig. 1.4; Grasemann et al., 1999). Low grade, Precambrian, metasedimentary rocks of the Lesser Himalaya are exposed below the brittle, basal thrust. Above the MCT, amphibolite facies orthogneiss mylonites, schists, and paragneisses of the GHS form a ~ 10 km thick tectonic slab (e.g. Wiesmayr and Grasemann, 2002). Insequence thrusting along the underlying Main Boundary Thrust has openly folded and deformed the foreland-most portion of the MCT, leaving the Shimla Klippe, while out of sequence thrusting along the Munsiari Thrust has formed the antiformal Larji Kulu Rampur Window (Fig. 1.4; Wiesmayr and Grasemann, 2002).

Deformation along the MCT is distributed and varies according to structural position. Grasemann et al. (1999) present quartz crystallographic fabric and tension gash data along the Sutlej section suggesting that deformation associated with the MCT followed a decelerating strain path (i.e. simple shear-dominated deformation progressively evolving to pure shear-dominated deformation). Pervasive and intense general shear along the MCT has inverted and telescoped metamorphic isograds, paleoisotherms, and deformation isotherms (Everest, Hubbard, 1996; Sutlej, Grasemann et al., 1999). Dynamic recrystallization of quartz near the MCT has been documented to vary between bulging and subgrain rotation close to the thrust, and grain boundary migration at greater distances above the thrust, qualitatively indicating higher temperatures and lower differential stresses with increasing structural distance above the thrust (Bhutan, Grujic et al., 1996; Sutlej, Grasemann et al., 1999; Garhwal, Spencer et al., 2012).

Three sample transects were collected perpendicular to the MCT in the Shimla area
Table 2: Sutlej sample transect data

<table>
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<tr>
<th>NW Sutlej</th>
<th>Detachment distance (m)</th>
<th>Deformation Temp °C</th>
<th>Grainsize (μm)</th>
<th>Differential Stress (MPa)</th>
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<tr>
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<td>//a₂</td>
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<td>542</td>
<td>64.3</td>
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</table>

1: See Law et. al (2011) for complete details on data collection and interpretation
2: Arithmetic mean of grains measured parallel to the macroscopic foliation
3: Arithmatic mean of grains measured perpendicular to the macroscopic foliation
4: Avg grain size equals the diameter of a circle with identical area to an ellipse with major and minor axes equal to //a and ⊥a (See Table 1 for details)
and Sutlej valley (Fig. 1.4, Table 2). We take advantage of the multiple MCT exposures along the base of the GHS by sampling in the Shimla Klippe (a in Fig. 1.4) and two structural transects along the SW part of Sutlej valley (b and c in Fig. 1.4). This sampling approach allows for collection of a suite of rocks with low to high deformation temperatures traced from foreland to hinterland (see Section 3.3). The Shimla Klippe transect contains a suite of samples within 100 m structural distance above the MCT. Containing samples from ~ 70 to 1150 m above the MCT, the NW Sutlej transect documents a more complete structural section than the Shimla Klippe transect. The SW Sutlej sample transect also contains a suite of samples from a large range of structural positions (~ 70 – 700 m) above the thrust. Specific sample locations, quartz c-axis fabrics, and deformation temperatures are reported by Law et al. (in prep).

3. Microstructures

Previous microstructural work on the STDS has focused on vorticity of flow, strain estimates, and quartz crystallographic fabrics (Law et al., 2004; Jessup et al., 2006; Kellett, 2009; Law et al., 2011). Quartz-based work along the MCT has documented quartz recrystallization mechanisms and crystallographic fabrics (Bouchez and Pecher, 1981; Grujic et al., 1996; Stephenson et al., 2000; Larson and Godin, 2009; Larson et al., 2010; Spencer et al., 2012). We briefly summarize the recrystallized quartz microstructures from these previous studies and highlight the dominant recrystallization mechanisms present at each structural level. For clarity, we use the terminology originally suggested by Stipp et al. (2002b) for naturally deformed quartz tectonites: bulge recrystallization (BLG), subgrain rotation (SGR), and grain boundary migration (GBM). Many studies, both experimental and natural, document the simultaneous operation of these mechanisms, although usually one mechanism is dominant over the others (Hirth and Tullis, 1992; Stipp et al., 2002a). BLG tends to dominate at high stress/low temperature, SGR at intermediate stress and tempera-
ture, and GBM at low stress/high temperature.

Across the Annapurna and Manaslu regions of the lower GHS and MCT, Bouchez and Pecher (1981) document ‘elongate mosaic’ (SGR) microstructures near the MCT transitioning to ‘grain growth’ (? SGR/GBM) and ‘exaggerated grain growth’ (GBM) within 2 km structural distance from the MCT. Photomicrographs of quartzites from the GHS in Bhutan exhibit pervasive GBM with average grainsize ~ 100 μm at low structural levels increasing to 1-2 mm in the GHS interior (Grujic et al., 1996). X-ray texture goniometry of the Bhutanese quartzites yields dominant single girdle c-axis fabrics and relatively few asymmetric cross-girdle fabrics (Grujic et al., 1996). A full sequence of recrystallized quartz microstructures, from BLG to SGR to GBM, is observed in the Garhwal region of the Himalaya (Spencer et al., 2012; their Fig. 7). Larson et al. (2010) noted regime 1-3 quartz microstructures (Hirth et al., 2001), which roughly correlate to BLG, SGR, and GBM, and a change in quartz petrofabric strengths across the GHS in the Manaslu Himalaya. Quartz from the Kishtwar window is large (> 200 μm) and presumably recrystallizing via GBM (Stephenson et al., 2000).

Previous studies of the Rongbuk Valley strand of the STDS observed transitional BLG/SGR to GBM quartz microstructures with increasing distance below the fault (Law et al., 2004; Jessup et al., 2006; Law et al., 2011). Dynamically recrystallized tectonites from the Bhutanese strand of the STDS dominantly preserve GBM and locally SGR (Kellett, 2009). In general, these previous studies have indicated relatively high stress quartz microstructures near the upper and lower GHS margins with a progressive evolution towards lower stress microstructures towards the GHS interior.

3.1 Rongbuk quartz microstructures

Traced structurally down section from the STDS in all three Rongbuk transects quartz recrystallization tends to evolve from higher stress to lower stress microstructures,
that is, from BLG/SGR to GBM. Close to the LD (within ~ 80 m) SGR is the dominant recrystallization mechanism as indicated by fairly equant 15-20 μm grains in association with larger (30-50 μm) more tabular grains (Fig. 1.5a-b). BLG microstructures are sporadic and equivocal (Fig. 1.5a-b); we suggest that peak deformational conditions produced microstructures no higher stress than transitional SGR/BLG. Traced down structural section, SGR, as indicated by subgrain development, becomes slightly more prevalent (Fig. 1.5c). GBM is present in the structurally lowest samples; indicated by lobate grain boundaries, lack of subgrain development, local mica inclusions within quartz grains, and grainsizes of 50-200+ μm. Static, temperature-driven grain growth tends to straighten grain boundaries at the lowest structural levels. However local lobate grain boundaries are always locally observed (Fig. 1.5d). The operation of both BLG and SGR near the STDS produces a bimodal grainsize distribution, which will be discussed in Section 3.2. Undulose extinction and deformation bands are rare in the deeper structural positions; leading Law et al. (2011) to interpret these as rapidly “quenched” microstructures.

3.2 Sutlej quartz microstructures

Microstructures in samples from the Sutlej transects also correlate with structural position in relation to underlying the MCT, with SGR microstructures at the lowest structural positions (nearest the MCT) evolving to GBM microstructures towards the GHS interior. Within ~ 100 m, SGR produces slightly tabular grains and subgrains while local grain boundary bulges produce local and sporadic, small (< 20 μm) equant grains (Fig. 1.5h). Recrystallized grains contain little undulose extinction and grain boundaries are relatively straight suggesting that GBM is controlling grain growth following nucleation via SGR (Fig. 1.5g). Newly recrystallized grains become more polygonal and equant with increasing structural distance (> 120 m). Undulose extinction is weakly present and subgrain development is limited. A few samples at ~ 200 m above the MCT exhibit slight oblique grain
STDS - Rongbuk

A. 

B. 

C. 

D. 

E. 

F. 

G. 

H. 

MCT - Sutlej

STDS

MCT

Structural Distance (m)

Sample Number

GHS Interior

STDS - Rongbuk

R03-23

ET-07

R03-32

R03-72

S09-31a

S09-29

S09-33

S09-26a

006º - 24º

02º - 23º

028º - 01º

212º - 14º

212º - 24º

05º - 023º

035º - 035º

212º - 02º

006º - 24º
shapes consistent with a top to the south shear sense and possibly suggest SGR recrystallization. However, local mica inclusion trails within recrystallized quartz grains indicate that GBM is the dominant recrystallization mechanism. At the highest structural positions (> 250 m) recrystallized grains are polygonal and grain boundaries become straight (Fig. 1.5e-f). Some grain boundary junctions are close to 90° possibly indicating that prism <c> slip has been activated. Interestingly, local deformation lamellae are present in the structurally highest Sutlej sample and may be caused by localized late-stage deformation.

Recrystallization mechanisms occurring in tandem create a composite whole rock microstructure that can make the deformational history difficult to interpret. Behr and Platt (2011) recently analyzed the mylonitic footwall of the Whipple Mountains metamorphic core complex, a low-angle crustal scale detachment fault in southern California, where anastomosing macro-scale shear zones have been interpreted as strain localization features recording continued deformation during exhumation. The anastomosing nature of deforma-

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**Fig. 1.5.** Previous page. Photomicrographs from representative samples across the STDS and MCT. The left column (A-D) are STDS samples and the right column (E-H) are MCT samples; photomicrographs arranged in order of structural distance, identical to schematic cross section. Scale bars are all 100 μm, except E which is 1000 μm. **Central column:** Schematic cross section of GHS with sample locations plotted as structural distance relative to the STDS (top) and MCT (bottom); note the break in scale across area labeled "GHS Interior". **Rongbuk samples:** A) Sample R03-23 from the Northern Traverse at 30 m structural distance beneath the STDS. Grain boundary bulges (BLG) indicated with red arrows. Undulose extinction fairly prominent. Sparse subgrain development, generally obscured by extinction. B) Sample ET-07 from Hermit’s Gorge at 144 m structural distance. BLG indicated with arrows. Some subgrain development and wavy undulose extinction observed. C) Sample R03-32 from Hermit’s Gorge at 420 m structural distance. Large grains with generally straight grain boundaries; very limited interlobate grain boundaries (see text for interpretation). D) Sample R03-72 from Rongbuk Monastery at 514 m structural distance. Very large quartz grainsize and limited grain boundary curvature. **NW Sutlej samples:** E) Sample S09-31a from 1150 m structural distance. Red arrow pointing to 120° triple junctions and white arrow pointing to a grain with lobate boundaries. F) Sample S09-29 from 560 m structural distance. Subgrains developing in nearly extinct quartz lithion indicated with a red star. Black star highlighting a large lobate grain. G) Sample S09-33 from 275 m structural distance. All quartz grain boundaries are lobate with some subgrain development. H) Sample S09-26a, from same sample as S09-26b, at 71 m structural distance. Subgrain development occurring at the red star. BLG indicated by red arrows. Grain boundaries not pervasively lobate.
formation produced composite whole rock microstructures wherein samples near the anastomosing shear zones recorded higher stress, and presumably later, microstructures, while samples collected away from these localized shear zones recorded earlier, lower stress microstructures. Behr and Platt (2011) suggested that composite microstructures reflect continued deformation and strain localization as the core complex was exhumed through cooler temperatures and increasing differential stresses. In Rongbuk, contemporaneous microstructures exist but macro-scale anastomosing structures facilitating strain localization have not been observed. Without relative timing controls, microstructural relations are difficult to constrain. The lack of relatively homogeneous overprinting microstructures led Law et al. (2011) to suggest that the locus of deformation in Rongbuk progressively migrated up structural section, essentially leaving “quenched” microstructures in its wake at lower structural positions. We address the possible tectonic implications of these microstructures, and the data extrapolated from these microstructures, in Section 6.

### 3.3 Deformation temperatures

Deformation temperatures (i.e. the ambient temperature as deformation ceased) as recorded by quartz c-axis fabric opening angles and the Kruhl (1998) thermometer were reported by Law et al. (2011; their Fig. 7-10 and Supplementary Table 2) for the three structural transects of the STDS in Rongbuk (Figs. 1.3 & 1.6). The Kruhl (1998) thermometer relies on an increasing component of prism [c] slip becoming progressively more important with increasing temperatures, leading to larger quartz c-axis fabric opening angles. Qualitative uncertainties for the Kruhl (1998) deformation thermometer are reported at ± 50 °C. Complex interactions between intrinsic and extrinsic conditions affect the topology of crystal fabrics (e.g. Lister and Hobbs, 1980; Lister and Dornsiepen, 1982), hence, utilizing the quartz c-axis fabric opening angles as a deformation thermometer assumes that deformation temperature is the prime control on fabric opening angle. Caveats for the
Kruhl (1998) deformation thermometer, with specific reference to the Rongbuk transects, are discussed by Law et al. (2011; their section 3.8).

Each Rongbuk transect displays a linear relationship between deformation temperature and structural distance below the STDS (Fig. 1.6, Table 1). The Hermit’s Gorge, Rongbuk Monastery, and the Northern transects have deformation temperature estimates that range from 488-625 °C, 460-650 °C, 543-565 °C, respectively. Apparent thermal gradients for the Hermit’s Gorge, Rongbuk Monastery, and Northern transects are 420, 385, and 369 °C per km, respectively. Law et al. (2011; their Fig. 18) also compiled the thermal profiles of several other, more hinterland, traverses of the STDS, all of which exhibit extreme telescoping of isotherms and condensed thermal gradients.

Deformation temperatures from the MCT in Sutlej have also been estimated using the quartz c-axis fabric thermometer (Law et al., in prep). Deformation temperature estimates from these fabric analyses are summarized in Fig. 5. Estimates of deformation temperature in the NW Sutlej, SW Sutlej, and Shimla Klippe transects range from 535-615 °C, 545-608 °C, 512-548 °C, respectively (Fig. 1.6, Table 2). Unlike the Rongbuk transects, deformation temperatures exhibit a power-law relationship with structural distance above the MCT. Taken as a whole, the data show a continually decreasing apparent thermal gradients with increasing structural distance above the MCT, ranging from ~ 300 °C per km at 60-215 m above the MCT to ~ 35 °C per km at 750-1150 m above the MCT.

We emphasize that these steep apparent thermal gradients record the final geometry of isotherms (i.e. material lines) and that actual geothermal gradients in the Rongbuk and Sutlej areas never approached such extreme values. Additionally, the thermal gradients

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**Fig. 1.6.** Next page. Profile of deformation temperature (°C) plotted against structural distance measured down from the STDS and up from the MCT towards the GHS interior. Temperatures are estimated from quartz c-axis fabric opening angle thermometry (see details in text and Law et al. 2011). Qualitative errors for temperature estimates are ± 50 °C, error bars are not shown for clarity. Apparent thermal gradients below the STDS are 360—420 °C/km and linear. Apparent thermal gradients above the MCT exhibit a power law distribution; steep near the base of the section (~ 175 °C/km) and shallow at ~ 1 km above the MCT (~ 35 °C/km).
cannot continue their steep profiles to any great distance into the GHS interior. As summarized by Jessup et al. (2008; their Fig. 4), peak metamorphic temperatures in the core of the GHS are ~ 700-800 °C, which effectively limits the spatial extent of condensed isotherms to ~ 1 km below the STDS and ~ 2 km above the MCT, as suggested by the shallowing thermal profile observed in Sutlej.

Deformation temperatures can also be qualitatively assessed by quartz recrystallization microstructures. The quartz microstructural thermometer of Stipp et al. (2002a) indicates deformation temperatures of ~ 420-510 °C where subgrain rotation is the dominant microstructure, and temperatures > 510 °C where grain boundary migration dominates. A transition zone between the two microstructural regimes is found at temperatures of 490-530 °C. As noted above, subgrain rotation recrystallization is present in the structurally highest and lowest samples along the STDS and MCT, respectively, rapidly transitioning to grain boundary migration with increasing distance away from the bounding faults towards the GHS interior. This suggests deformation temperatures increase towards the GHS interior from ~ 450 °C to > 500 °C (from average SGR conditions to predominant GBM conditions) in our traverses. Furthermore, local plastic deformation of small orthoclase and plagioclase feldspar grains suggests temperatures > 450-500 °C near the STDS and MCT (Fitz Gerald and Stünitz, 1993; Law et al., 2004). With increasing distance from both faults, feldspar grains become increasingly plastic, indicating increasing deformation temperatures. These qualitative temperature assessments agree well with our estimates from Rongbuk and Sutlej utilizing the Kruhl (1998) thermometer (Fig. 1.6).

3.4 Quartz grainsize measurements

Recrystallized quartz grainsizes were measured optically on a standard petrographic microscope (Fig. 1.7). Each grain was measured parallel and perpendicular to the macroscopic foliation (Tables 1 & 2). Oblique recrystallized grain shapes (sensu Means,
1981) were not observed, although many grain long axes were parallel to the macroscopic foliation trace. Very few large porphyroclasts (plagioclase, hornblende) disrupt the foliation. Where present, mica-bounded quartz grains were generally avoided to obviate potential pinning issues. Quartz grain boundary mobility during recrystallization is inhibited by grain boundary mica (e.g. Song and Ree, 2007). Samples from Rongbuk valley are qualitatively more micaceous than those from Sutlej valley and measurements were not always taken on unbounded quartz grains from the Rongbuk samples. Hence, grainsizes from the STDS at Rongbuk are considered to be minimum grainsizes.

A minimum of 50 grains were measured in each sample. Average grainsize was calculated by assuming that an ellipse approximated the area of each grain with axes equal to the foliation-parallel and perpendicular measurements of the grain. The diameter of a circle with the same area of the average ellipse was taken to be the average grainsize; see Table 1 for an example calculation. No correction for stereological effects was applied, in keeping with the Stipp and Tullis (2003) methodology. Grainsizes measurements of the largest grains (> 120 μm), interpreted to be GBM microstructures, are minima due to the presence of possible island grains and dissection microstructures (Stipp et al., 2002a). The standard deviation of each average grain size measurement is listed in Table 1 and Table 2 and is illustrated by the shading in Fig. 1.7.

3.4.1 Rongbuk quartz grainsizes

Average quartz grainsizes at Rongbuk in the footwall to the STDS range from 158.1 μm at 564 m structural distance beneath the STDS to 26.7 μm at 10 m structural distance (Fig. 1.7, Table 1). Both the Hermit’s Gorge and Rongbuk Monastery transects incorporate most of this grainsize range. The shorter Northern transect only contains grains between 51.2 – 26.7 μm. The decrease in grainsize traced towards the STDS is non-linear. A shallow grainsize gradient is observed at distance of 600 m (158 μm) to 100 m (100 μm) beneath
Fig. 1.7. Average quartz grainsize plotted against structural distance below and above the STDS and MCT, respectively. Grainsize generally decreases along a shallow gradient from the GHS interior towards the boundary faults until ~ 200 m structural distance. Traced towards the faults from 200 m structural distance, average grainsizes abruptly decrease along steep gradients to grainsizes of ~ 30 μm. Symbols same as Fig. 6. Shading represents one standard deviation of grainsize measurements. See Tables 1 and 2 for grainsize and error data, respectively.
the detachment (Fig. 1.7). The grainsize gradient at a structural distance of < 100 m beneath the STDS is much steeper, with grainsizes decreasing from ~ 100 μm to ~ 25 μm. A distinct kink in the grainsize trend is present at the intersection of the two gradients (Fig. 1.7).

A change in recrystallization mechanism in samples collected at < 200 m beneath the STDS, as noted above, creates a slightly bimodal grainsize distribution. The recrystallized grainsize frequency is plotted in Fig. 1.8b. A 5-step moving average highlights two grainsize frequency maxima at 28 μm and 38 μm, with an intermediate frequency minimum at 33 μm. Also exhibited is the log-normal grainsize distribution of the accrued measurements, a common feature of grainsize distributions (e.g. Higgins, 2000). Figure 1.8a shows all grainsize measurements from Rongbuk; unsurprisingly, the bimodal trend seen in Fig. 1.8b is still present. More curiously, a much more pronounced grainsize frequency minimum is noted at 61 μm with an associated frequency maximum at 77 μm. While not extremely pronounced, we suggest that this bimodal distribution is real and that our measurement technique has decreased the comparative amplitude of the frequency peaks.

Measuring whole-rock average quartz grainsizes depends on collecting the full spectrum of grainsizes present in a particular sample, and hence decreases the potential bias of selecting only certain size quartz grains. However, this also decreases the effect of a large population of a specific grainsize on the grainsize frequency distribution.

3.4.2 Sutlej quartz grainsizes

Average grainsizes at Sutlej in the hanging wall to the MCT range from 217.3 μm at 1150 m structural distance above the MCT to 32.3 μm at 60 m structural distance (Fig. 1.7, Table 2). This structural range, as mentioned above, is wholly covered by both the NW Sutlej and SW Sutlej transects, while the Shimla Klippe transect only includes the structurally closest 100 m. At greater than 100 m above the MCT, average grainsizes exhibit a large
Fig. 1.8. Plots of grainsize frequency for both Rongbuk (A-B) and Sutlej (C-D) with two populations of measured grains; all grains from a given region (A, C) and all grains from samples at < 200 m from each fault (B, D). Red squares indicate each 1 μm grainsize bin and the black line is the 5-step moving arithmetic mean. Data are noisy due to the sampling methodology and the minimum grainsize measurement. A log-normal grainsize distribution is noted in all populations. A) Total grainsize distribution from Rongbuk samples. 5-step moving average exhibits three local maxima (see text for details). B) Grainsize distribution for all Rongbuk samples within 200 m structural distance of the STDS. A slightly bimodal distribution is noted with the two black arrows. C) A roughly unimodal grainsize distribution from all Sutlej samples. D) Grainsize distribution for all Sutlej samples within 200 m structural distance from the MCT. Distribution is unimodal.
distribution centered around relatively large grainsizes, generally $\sim 50 - 100 \, \mu m$ (Fig. 1.7). Average grainsizes decrease sharply to the smallest grainsizes at structural distances of less than 100 m above the MCT following a steep grainsize gradient of $\sim 65 \, \mu m/100 \, m$ (Fig. 1.7). Similar to the average grainsize trend at Rongbuk, the grainsize trend versus structural distance at Sutlej exhibits a distinct kink at $\sim 100 \, m$ structural distance (Fig. 1.7).

The grainsize distribution of the Sutlej samples from within 200 m structural distance of the MCT is shown in Figure 1.8d. Unlike the Rongbuk samples, no obvious bimodal grainsize frequency distribution is noted with a 5-step moving average, though the general distribution is log-normal like the Rongbuk samples. The complete grainsize frequency distribution for all Sutlej samples is illustrated in Figure 1.8c. A 5-step moving average of the frequency distribution is noisy, but still broadly log-normal, and exhibits no observable bimodal trend.

4. Piezometry estimates

Paleo-piezometry relies on the empirically derived inverse logarithmic relation between dynamically recrystallized grain size and differential stress in order to estimate flow stress in rapidly quenched shear zones. The theory behind the piezometric relation has been vigorously debated (Twiss, 1977; Austin and Evans, 2007; Shimizu, 2008; Platt and Behr, 2011). However, empirical piezometers indicate that this relation holds for many minerals and metals, including quartz, feldspar, and olivine (van der Wal et al., 1993; Post and Tullis, 1999; Stipp and Tullis, 2003). The similarity between experimental quartz microstructures and natural microstructures suggests that the recrystallized grainsize piezometer can be used to estimate natural flow stresses in rocks deformed by dislocation creep (Stipp et al., 2002a; Stipp and Tullis, 2003). As noted above, natural dislocation creep microstructures in quartz include high stress/low temperature BLG, medium stress and temperature SGR, and low stress/high temperature GBM. Hirth and Tullis (1992) have
documented the experimentally produced dislocation creep microstructures in quartz. Regime 1, regime 2, and regime 3 of Hirth and Tullis (1992) correlate broadly to BLG, SGR, and GBM, respectively (Twiss and Moores, 2007; but c.f. Stipp et al., 2010), and this correlation implicitly allows for the use of empirical piezometers on naturally deformed tectonites.

Stipp & Tullis (2003) empirically documented the piezometric relationship in quartz with a molten salt assembly in a Griggs apparatus. Holyoke and Kronenberg (2010) recently published a systematic correction for stress measurements in the Griggs rig and have also updated the quartz piezometer to reflect this experimental correction. This piezometer has been directly calibrated for grainsizes up to 45 μm and regime 1, 2, and 3 microstructures (Hirth and Tullis, 1992; Stipp and Tullis, 2003), although it may also be applicable to recrystallized grainsizes up to ~120 (Stipp et al., 2010). Note that stress estimates from grainsizes > 45 μm may be minima (Stipp et al., 2010). Stipp and Tullis (2003) did not correct for stereologic effects of grainsize measurements. Temperature, water content of quartz, and the α-β transition in quartz apparently show no effect on the piezometer (Stipp et al., 2006).

4.1 Rongbuk differential stress estimates

As noted in Section 3.4.1, recrystallized grainsize in the Rongbuk transects is roughly inversely proportional to distance beneath the STDS with grainsizes ranging from 26.7-158.1 μm (Fig. 1.7). These grain sizes reflect flow stress estimates based on the Stipp and Tullis (2003) piezometer of 36.1-8.8 MPa, respectively (Fig. 1.9). We note that five samples exhibited average grainsizes > 120 μm, the inferred maximum grainsize applicable to the quartz piezometer (Stipp et al., 2010). Justification regarding our continued use of these samples, and the > 120 μm grainsizes from the Sutlej transects, will be addressed in Section 6.2.

A hook shape topology of the flow stress versus structural distance plot (Fig. 1.9) re-
**Fig. 1.9.** Differential stress estimates from average quartz grainsizes (Fig. 7) employing the Holyoke & Kronenberg (2011) correction to the Stipp & Tullis (2003) recrystallized quartz piezometer; plotted against structural distance. Near constant stress estimates as traced from the GHS interior to 200 m structural distance from both the STDS and MCT are caused by the piezometer being relatively insensitive to changes in average grainsize > 100 μm. Symbols same as Fig. 6. Shading reflects grainsize measurement errors only.
Reflects the similar, but mirror image, topology of the grainsize versus structural distance plot (Fig. 1.7). Samples taken < 100 m beneath the STDS have flow stress estimates 2-3.5 times greater than those taken from > 100 m structural distance. No specific trend in flow stress is noted at < 100 m beneath the STDS. Starting at ~ 100 m structural distance beneath the STDS, and traced towards the GHS interior, there is a small decreasing trend in flow stress from ~ 12 MPa to 8.8 MPa, respectively. The hook topology in Fig. 1.9 is documented by two of the three sample transects in the Rongbuk area, with the Northern transect being wholly within 100 m structural distance.

Given the multi-modal distribution of grainsizes across the STDS (Fig. 1.8a-b), differential stress estimates would be expected to vary multi-modally as well. From Fig. 1.8b, the 5-step moving average of grainsize frequency exhibits local maxima at 28, 38, and 77 μm. These grainsizes produce differential stress estimates of 35, 27, and 15 MPa, respectively, using the Stipp and Tullis (2003) quartz piezometer.

4.2 Sutlej differential stress estimates

Mimicking the average quartz grainsizes (Fig. 1.7), flow stress estimates also have a hook shape topology – decreasing flow stress with increasing distance above the MCT (Fig. 1.9). Average flow stress from the Sutlej transects ranges from 6.8-31.1 MPa (Table 2). The abrupt kink in Fig. 1.9 occurs at ~100 m structural distance above the MCT. Structurally below this kink, flow stress estimates show no observable trend but are ostensibly higher by a factor of two. At greater than ~100 m structural distance above the MCT, our estimates vary between 6.8-19.9 MPa but are centered around ~15 MPa – the flow stress estimate from the hook vertex. Quartz recrystallization microstructures show a progression from medium flow stress/temperature SGR to low flow stress/high temperature GBM with increasing structural distance above the MCT (Fig. 1.6). This pattern is reflected in the decreasing grainsizes and increasing flow stresses.
5. Strain rate estimates

Quartz deforming via dislocation creep follows a power law relation between strain rate, differential stress and deformation temperatures (e.g. Gleason and Tullis, 1995). Using our flow stress and deformation temperature estimates we calculate strain rates using the naturally constrained quartz flow low from Hirth et al. (2001). This flow law takes the form:

\[ \dot{\varepsilon} = A f_{H_2O}^m \sigma^n e^{\frac{-Q}{RT}} \]

where \( \dot{\varepsilon} \) is strain rate, A is a material parameter, \( f_{H_2O} \) is water fugacity, m is the water fugacity exponent, \( \sigma \) is differential stress, n is the stress exponent, Q is the activation energy, R is the ideal gas constant, and T is absolute deformation temperature (Hirth et al., 2001). From Hirth et al. (2001): A=10^{-11.2} MPa^-n/s, m=1, n=4, and Q=135 kJ/mol. Water fugacity has been estimated in our two localities by assuming lithostatic pore fluid pressure in the manner of Behr and Platt (2011). Rongbuk lithostatic pressure estimates were based on sample R74 from Hodges et al. (1992) at the base of the Hermit’s Gorge transect using simultaneous solutions of the garnet-biotite and garnet-plagioclase-sillimanite-quartz thermobarometers to calculate ‘final equilibrium’ conditions of 630 °C and 4.6 kbar. Initial depths were calculated using a geothermal gradient of 40 °C/km and pressures were calculated using a geobaric gradient of 0.285 kbar/km and sample R74 as a benchmark (Hodges et al., 1992; Law et al., 2011). In Sutlej, where pressure estimates are poorly constrained (e.g. Vannay and Grasemann, 2001) we projected an initial geothermal gradient of 40 °C/km onto our deformation temperatures to estimate initial depths and used a geobaric gradient of 285 bar/km to calculate lithostatic pressures. These are crude estimations of pressure and temperature; however, we note that water fugacities roughly double when assuming a geothermal gradient of 25 °C/km, which acts to increase depth/pressure estimates. A 2-fold increase or decrease in the resultant water fugacity produces a variation in strain rate that is less than the propagation of our average grainsize measurement error (Fig. 1.10) and we therefore
deem the uncertainty of our water fugacity values as being, in practice, unimportant.

Another, more recent, empirically derived quartz flow law from Rutter and Brodie (2004) was also used to estimate strain rates in the GHS. Estimates from the Rutter and Brodie (2004) flow law consistently produced strain rate estimates 1-2 orders of magnitude slower than corresponding estimates from the Hirth et al. (2001) flow law (Table 1 & 2). While the estimates from the Rutter and Brodie (2004) flow law remain within generally accepted tectonic strain rate values, we choose to favor use of the Hirth et al. (2001) flow law for the slightly faster, and perhaps more realistic, strain rate estimates given the active tectonic environment. A more complete discussion on strain rate expectations for the STDS and MCT, based on ductile dip-slip displacement estimates and timing information, is addressed in Section 6.3.

5.1 Rongbuk strain rate estimates

Strain rate estimates from the STDS in Rongbuk range from $4.2 \times 10^{-12} - 2.33 \times 10^{-14}$ s$^{-1}$ (Fig. 1.10, Table 1). Increases in flow stress predictably increase strain rate at a given temperature. Likewise, decreases in deformation temperature decrease strain rates at a constant flow stress. The Northern transect samples (dark red squares, Fig. 1.10) are roughly an order of magnitude faster strain rate than samples from the other two transects at $\sim 550$ °C. At a flow stress of $\sim 25$ MPa a deformation temperature difference of $\sim 60$ °C leads to an order of magnitude difference in strain rate between the Northern and Hermit’s Gorge transect samples.

When plotted against structural distance, strain rate has very distinct hook topology (Fig. 1.11). Structurally near (< 100 m) the STDS strain rates are at a maximum (Fig. 1.10, Table 1). The slowest strain rate estimate ($2.33 \times 10^{-14}$ s$^{-1}$) is present at 107 m below the STDS. Strain rate estimates from progressively deeper structural positions increase by $\sim 1.5$ orders of magnitude. Note that the hook topology of Fig. 1.11 reflects the topology seen in
**Fig. 1.10.** Differential stress estimates plotted against deformation temperature (Fig. 6). Iso-strain-rate curves from the Hirth et al. (2001) quartz flow law are indicated. Note that data are not expected to fit any one strain rate contour; see text for details. Error swath, represented by the shaded region, indicates the error from grainsize measurements and deformation temperature estimates. Also note that iso-strain-rate curves are not expected to follow any specific path through the locally migmatitic GHS interior. Symbols same as Fig. 6.
both Fig. 1.7 and Fig. 1.9. This topology is fully present in two of the three sample transects of the STDS (Hermit’s Gorge and Rongbuk Monastery) while the third transect (Northern Traverse) is located wholly with 100m structural distance beneath the STDS. In other words, the Northern Traverse is not long enough to exhibit this trend.

5.2 Sutlej strain rate estimates

Near the MCT in Sutlej, strain rate estimates vary from $2.4 \times 10^{-12} – 4.1 \times 10^{-14}$ s$^{-1}$ (Fig. 1.10, Table 2). Strain rate estimates from the MCT, while utilizing different water fugacity values than the STDS samples, are similarly sensitive to variations in deformation temperature and flow stress (see above discussion on water fugacity sensitivity). Unlike the STDS samples, no one MCT transect has a distinct trend in deformation temperature – flow stress space (Fig. 1.10).

A hook shape topology is observed when strain rate estimates are plotted against structural distance above the MCT, similar to the STDS samples (Fig. 1.11). Strain rate estimates within ~100 m structural distance range from $1.9 \times 10^{-12} – 3.5 \times 10^{-13}$ s$^{-1}$, with no observable trend within this structural section. Structurally higher (> 100 m) samples have increasing strain rate estimates to a maximum of $2.4 \times 10^{-12}$ s$^{-1}$ (Fig. 1.11). The structurally highest sample (1150 m) above the MCT yields the slowest strain rate estimate in the MCT transects (Fig. 1.11).

6. Discussion and Tectonic Implications

6.1 Quartz grain pinning

Quartz grain growth in both dynamic and static conditions can be significantly inhibited, or pinned, by 2nd phase mineral assemblages (e.g. mica, epidote; Tullis and Yund, 1982;
Fig. 1.11. Strain rate estimates from the Hirth et al. (2001) quartz flow law plotted against structural distance away from both the STDS and MCT. Strain rate estimates decrease 1.5-2 orders of magnitude as traced from the GHS interior to ~ 200 m structural distance from the MCT/STDS. Within 200 m structural distance, strain rate estimates abruptly increase of 1-2 orders of magnitude. Shading represents grain size measurement errors only. Symbols same as Fig. 6.
Grain boundary pinning may be more pronounced at lower/higher structural levels (STDS/MCT, respectively) as traced towards the GHS interior to higher deformation temperatures (Fig. 1.6). As noted in Fig. 1.8, a bimodal grainsize distribution is observed within 200 m structural distance from the STDS. Such a distribution can be attributed to either: A) a grainsize measuring bias, B) differing contributions of 2nd phase pinning in various samples, or C) a change in recrystallization mechanism. In regards to A), all samples were analyzed similarly and any methodological bias would be expected to permeate the whole data set and affect the Sutlej grainsize distribution (Fig. 1.8c-d) identically. Differing contributions of 2nd phase mineral pinning on quartz would act to randomize the data, not generate a bimodal distribution, because the 2nd phase content varies within and across all samples. A change in (the dominant) recrystallization mechanism from BLG/SGR to GBM would be expected to produce a marked change in grainsize (Stipp et al., 2010). Because the change in recrystallization mechanism occurs at very low structural levels (< 200 m from either fault) and all recrystallization at greater structural distances (> 200 m) occurs solely by GBM, any variation in grainsize towards the GHS interior can be attributed to 2nd phase interactions.
6.2 Piezometry estimates and methodology

Our flow stress estimates have included average grainsizes > 120 μm, which, in the past, have been considered to be outside the extrapolated range of the Stipp and Tul- lis (2003) recrystallized quartz piezometer (Stipp et al., 2010). While most of our average grainsizes are < 120 μm, the structurally highest Sutlej sample, and three samples from the Rongbuk transects, are larger than 120 μm (Fig. 1.7, Table 1 & 2). Stipp et al. (2010) sug- gested that the Stipp and Tullis (2003) recrystallized quartz grainsize piezometer provides reliable flow stress estimates for grainsizes < 46 μm (corresponding to the original experi- mental grainsizes), yields reasonable results for grainsizes between 46-120 μm, and sig- nificantly under-estimates paleostress for grainsizes > 120 μm. Our interpretation of the quartz grainsize piezometer relies primarily on a correlation of microstructures, not solely on grainsizes. While somewhat tangential to our study of transitional BLG/SGR to GBM mi-crostructures, the following discussion on piezometer applications raises important points that have not be explicitly addressed in the literature, and will be followed by justification regarding our use of grainsizes larger than 120 μm.

The experimental deformation conditions used to calibrate the quartz piezometer produced regime 2 and 3 microstructures, i.e. medium stress/temperature and low stress/high temperature experimental dislocation creep microstructures (Hirth and Tullis, 1992; Stipp and Tullis, 2003). Additionally, Stipp and Tullis (2003) published results and es- tablished a piezometric relation from experiments producing regime 1 (high stress/low temperature) microstructures. While not directly comparable, regimes 1, 2, and 3 of Hirth and Tullis (1992) are fairly analogous to the natural microstructures BLG, SGR, and GBM, respectively (c.f. Stipp et al., 2002a). The steady-state recrystallized grainsizes from this set of experiments ranged from < 2 μm to 46 μm; regime transitions occurred at ~ 3 μm (regime 1 and 2) and at ~ 8 μm (regime 2 and 3; Stipp and Tullis, 2003). Stipp et al. (2010) compiled grain size and microstructure data from a number of natural sources and docu-
mented grainsize bins for each recrystallization microstructure; BLG yields grainsizes < 35 μm, SGR produces grains 35-120 μm, and GBM > 120 μm. Accordingly, most of the experimentally produced grainsizes are in the natural BLG field and vice versa nearly all naturally produced BLG grainsizes reside in the experimental regime 2 or 3 field. Previous studies utilizing the grainsize piezometer have relied solely on recrystallized grainsize and disregarded microstructural observations during the piezometric analyses (e.g. Faleiros et al., 2010). No study known to us has applied the regime 1 grainsize piezometer of (Stipp and Tullis, 2003). Certainly, flow stress estimates from BLG microstructures need to be quantified through the empirical piezometric relationship which characterized similar microstructures.

The previous discussion leads us to believe that grainsizes > 120 μm, while not achieved experimentally, are a natural extension of empirically produced regime 3 microstructures. Hence, the Stipp and Tullis (2003) piezometric relation that describes regime 3 microstructures should satisfactorily predict flow stresses of GBM microstructures > 120 μm, provided that those grains can be accurately measured. We note that an inherent feature of the inverse logarithmic quartz piezometer is that increasingly larger grainsizes produce differential stress estimates which decrease exponentially. As an example, grainsizes of 50, 100, 150, and 500 μm produce differential stress estimates of ~ 22, 13, 9, and 4 MPa, respectively. It is not known, in natural rocks, whether the piezometric relation breaks down at a specific stress state or if, contradictory to experimental data (e.g. Stipp et al., 2006), temperature becomes a controlling factor of dynamically recrystallized grain size. Temperature has been shown to affect quartz grain size in static annealing experiments (e.g. Heilbronner and Tullis, 2002) and could conceivably affect grain size at low differential stresses. In such a situation, where temperature increases grain size, the piezometer would indeed underestimate the ambient differential stress. However, the total underestimation would be no greater than a few 10’s of MPa. The high temperature (> 600 °C) samples from Rongbuk and Sutlej have very low differential stress estimates (< 12 MPa) but fast strain
rate estimates (> $10^{-13}$ s$^{-1}$, Fig. 1.11). In these samples, an increase in differential stress of only 20 MPa would increase strain rates to ~ $10^{-11}$ s$^{-1}$, which are geologically unreasonable. Therefore, the underestimation of stress levels estimated from large grainsizes is, in practice, rather insignificant. Given the significant debate regarding dynamic recrystallization theory (see Section 4), we favor the empirically proven (Stipp and Tullis, 2003) piezometer and assume that it provides reasonable estimations of differential stress for all dynamically recrystallized quartz grains.

6.3 Strain rate estimates

Average geologic strain rates are usually estimated to be between $10^{-12} - 10^{-16}$ s$^{-1}$ (e.g. Pfiffner and Ramsay, 1982). Our strain rate estimates agree well with the expected tectonic strain rates and can be further bounded by natural dip-slip displacement estimates and deformation time intervals. Dip-slip estimates of transport magnitude along the STDS in the Everest region range from 25-216 km (Searle et al., 2003; Law et al., 2011). Importantly, these dip-slip estimates are constrained by the ductile deformation of the GHS in the footwall to the STDS; this allows us to broadly constrain the strain rates occurring along the STDS during ductile deformation. Searle et al. (2003) estimated the ductile shearing in the STDS footwall in the Everest region deformation lasted ~ 5 Myr. The width of the STDS is commonly referenced as ~ 2 km, though our microstructural data suggests that the width during the last stages of ductile deformation may have been ~ 0.5 km. For simplicity we assume that deformation was simple shear (Wm=1; cf. Law et al., 2004; Jessup et al., 2006). A 500 m wide shear zone needs shear strains ($\gamma$) of 50-432 for displacements of 25-216 km. Over 5 Myr, these shear strains produce strain rates ranging from $3.17 \times 10^{-13}$ s$^{-1}$ to $2.74 \times 10^{-12}$ s$^{-1}$, respectively. Shear strains for a 2000 m wide shear zone range from 12.5-108 and over 5 Myr would produce time averaged strain rates between $7.93 \times 10^{-14}$ s$^{-1}$ and $6.85 \times 10^{-13}$ s$^{-1}$, respectively. Given the grossly oversimplified model shear zone, we are encouraged
by the broad correlation between these expected strain rates and the strain rates estimated from the Hirth et al. (2001) quartz flow law for samples nearest to both the STDS and MCT.

6.3.1 Temperature input in quartz flow laws

A majority of natural strain rate estimates that utilize quartz dislocation creep flow laws employ petrologic thermometry (Dunlap et al., 1997; Stipp et al., 2002a, b; Jerabek et al., 2007; Faleiros et al., 2010) and, more recently, Ti-in-quartz thermobarometry (Kohn and Northrup, 2009; Behr and Platt, 2011; Grujic et al., 2011). These methods, while acceptable in general for order of magnitude estimations, fail to fully capture the deformation history. Petrologic controls can occasionally be linked to syn-deformational events but are not necessarily temporally identical to the deformation history recorded in the quartz microstructures. Dynamically recrystallized quartz microstructures are assumed to be rapidly "quenched", which preserves grain size, SPO, and CPO and records the final increments of plastic strain. Metamorphic assemblages may or may not be preserved at the same time as the quartz microstructures. Ti-in-quartz analyses are heavily dependent on Ti activity, which is a difficult parameter to estimate and can change within the system at either short or long timescales. Using a technique, such as the quartz c-axis fabric opening angle thermometer, which is directly linked to the end of crystal-plastic deformation in quartz, to determine deformation temperature provides stronger constraints on the deformation conditions and history. It should be noted that in several instances petrologic temperature estimates have been statistically identical to estimates of deformation temperature from quartz c-axis fabrics, in which case, each thermometer presumably records the same deformational event (e.g. Law et al., 2011, p. 1576).
6.3.2 Strain rate profile

The apparent hook in strain rate estimates near both the MCT and STDS is probably a reflection of the parameter sensitivity of the Hirth et al. (2001) quartz flow law. Fast strain rates documented at > 200 m structural distance (Fig. 1.11) suggest a strong temperature control, given that flow stress estimates (Fig. 1.9) are relatively constant as traced towards the GHS interior and deformation temperatures (Fig. 1.6) increase towards the GHS interior. As structural distance decreases and deformation temperatures cool to ~ 550 °C, strain rate estimates also decrease approximately linearly on the log-linear plot in Figure 1.11. Each 50 °C decrease in deformation temperature leads to an approximate 0.5 order of magnitude decrease in strain rate for a given flow stress. Inferred deformation temperatures decrease ~ 50 °C in the 200 m closest to the GHS margins, suggesting a 0.5 order of magnitude decrease in strain rate due to temperature control. However, the addition of 10-20 MPa of flow stress within ~ 200 m structural distance drastically increases strain rate estimates by 1-2 orders of magnitude, even with the negative temperature input. This suggests that, under the prevailing deformation conditions near the GHS boundary faults, flow stress, rather than temperature, is the major controlling parameter of strain rate. Strain rate estimates from our transects evidently exhibit changing sensitivities to the ambient deformation conditions as traced from the margins of the GHS, where differential stress dominates, towards the GHS interior, where temperature controls the strain rate.

6.4 Tectonic interpretations

Differential stress estimates from both the Sutlej and Rongbuk transects compare well to previously determined crustal stress profiles from other orogens. The stress profile constrained in the Whipple Mountains, California, documenting changing stress environments during exhumation of a core complex, has a range of estimated differential stress
from 10—136 MPa at ~ 22—9 km depth and 544—308 °C (Fig. 1.12; Behr and Platt, 2011). This profile is interpreted to document exhumation-related deformation from the relatively homogeneously deforming mid-crust to the highly strain-localized brittle-ductile transition in the upper crust. In the case of the STDS at Rongbuk, being a mid-crustal normal fault, our stress profile fits well with the high-temperature, low-differential stress end member of the Whipple Mountain stress profile (Fig. 1.12). Surprisingly, however, stress estimates from the MCT in Sutlej are nearly identical to those from Rongbuk along the STDS and are reasonably similar to the Whipple Mountain stress profile of Behr and Platt (2011).

The STDS and MCT hanging wall and footwall rocks were obviously deforming well beneath the brittle-ductile transition, and thus cannot be analogously compared with stress estimates for normal and reverse faults above the brittle-ductile transition (Sibson, 1974). However, it is still surprising that stress estimates along the normal STDS and the thrust MCT yield identical stress profiles, as intuitively higher stresses might be expected on a thrust than a normal fault at a given crustal depth. One possible interpretation involves lessening the resolved shear stress on the MCT via basal slip on foliation-parallel mica. Macroscopically, multiphase rocks commonly exhibit interconnected weak layers (e.g. mica-rich layers anastomosing around quartz lenses); hence their flow properties are expected to be vastly different from monophase rocks (Handy, 1994; Handy et al., 1999). Slip on the biotite (001) basal glide plane is known to be a factor of 2-5 times weaker than dislocation creep in quartz (Kronenberg et al., 1990). Such a contribution by through-going mica folia and, on a larger scale, micaceous schists, could certainly decrease the resolved shear stress on quartz aggregates and quartzites. Additionally, if stress were localized on mica lathes and away from quartz lenses, recrystallization in the quartz lenses would reflect the lower resolved shear stress and cause any differential stress estimates to be minima. However, inherently weak rock rheology cannot by itself explain the nearly identical strength profiles of the faults because the Rongbuk transects are generally more micaceous than the Sutlej transects. It follows that stress estimates from the Rongbuk transects would be more un-
Fig. 1.12. Comparison of differential stress and temperature data from the Rongbuk and Sutlej transects with comparable data from the Whipple Mountain detachment, southern California (Behr & Platt, 2011). Rongbuk and Sutlej symbols same as previous figures. Whipple Mountain detachment symbols are pink circles. Error bars are not shown for clarity, but all data is bracketed by the $10^{-11}$ and $10^{-15}$ s$^{-1}$ strain rate contours. All stress estimates are from quartz grainsize piezometry. Temperature estimates for Rongbuk and Sutlej transects are from quartz c-axis opening angle thermometry, while the Whipple Mountain temperature estimates are from Ti-in-quartz thermometry. Strain rate contours of $10^{-11}$ and $10^{-15}$ s$^{-1}$ from Hirth et al. (2001) quartz flow law (see text for details) are plotted as dark gray curves. Note how data from all three locations overlap and how Rongbuk and Sutlej data follow the Whipple Mountain stress profile.
derestimated than the stress estimates from Sutlej.

Another possibility is a reduction of strength due to pore fluid pressure increases along the MCT. Hydrothermal springs are common features near the MCT and are expected to tap from the whole of the MCT (Derry et al., 2009). Additionally, the hydrolytic weakening effects on plastic quartz deformation are well known (e.g. Koch et al., 1989) and a concentrated fluid flux along an orogen-scale fault (MCT) would be expected to promote focused water weakening. However, unpublished IR spectra data from A. Kronenberg (2011) suggests that recrystallized quartz grains from the NW Sutlej transect contain unusually low water contents (sample S09-31B; 25-80 ppm H/10^6Si). Additionally, quartz fabric opening angles clearly decrease traced towards both the MCT and STDS, which is the opposite trend to what would be predicted if fluid flow was focused towards the fault surfaces (see discussion in Law et al., 2011). Water content/activity appears to play very little role in the plastic strength of the MCT hanging wall rocks and we now look at possible structural explanations for the similar strength profiles of the GHS bounding faults.

The MCT and STDS may remove slices of the GHS slab and thus juxtapose higher temperature tectonites of the GHS interior on the Lesser Himalayan Series and under the Tibetan Sedimentary Sequence (TSS), respectively. If this were the case, the shear zone rocks would not necessarily provide appropriate estimates of the original ductile deformation conditions along the GHS margins. In order to investigate possible tectonic excision, we now briefly review thermal gradients across the hanging and footwall of both the MCT and STDS. If tectonic excision has occurred a break in thermal gradient is expected and where no tectonic excision has occurred a continuous thermal gradient is expected. Temperature estimates for the TSS in Rongbuk and the Lesser Himalayan Series in Sutlej are not well constrained and we therefore cannot investigate tectonic excision in our field areas. Well constrained and documented temperature profiles across the STDS in western Bhutan (Kellett and Grujic, 2012) and across the MCT in the Annapurna region (Beyssac et al., 2004; Bollinger et al., 2004; Celerier et al., 2009) exhibit smooth and continuous trends
of decreasing temperatures from the GHS interior towards the TSS and Lesser Himalayan Series, respectively. These trends suggest that no tectonic excision has occurred, and thusly, deformation conditions recorded along both faults are expected to be true estimates. Structural excision of thermal and piezometric data cannot produce the similar stress profiles of the MCT and STDS.

The above discussion has assumed a form of Anderson fault mechanics in which orientations of principal stress axes differ for normal and reverse faults. However, if the wedge extrusion model (e.g. Grujic et al., 1996) or channel flow model (e.g. Beaumont et al., 2001) is appropriate, then both the STDS and MCT may have been formed in similar stress fields. Given the broadly similar dip magnitudes towards the hinterland and coincident principle stress orientations, similar stress profiles along the STDS and MCT would be expected.

7. Conclusions

1. Optically measured recrystallized quartz grainsizes decrease from > 150 μm to ~ 100 μm at 200 m structural distance as traced towards the upper and lower margins of the GHS; the STDS in Rongbuk valley, S Tibet and the MCT in Sutlej valley, NW India, respectively. A pronounced reduction in grainsize, associated with a change in dominant recrystallization mechanism from GBM to BLG/SGR, occurs at a structural distance of < 200 m from the boundary fault along each margin.

2. Differential stress estimates (from the Holyoke and Kronenberg (2010) correction to the Stipp and Tullis (2003) recrystallized quartz grainsize piezometer) are relatively constant (8-15 MPa) traced from the GHS interior to ~ 200 m from the margins. At < 200 m structural distance from the MCT and STDS, estimated differential stresses increase to 31 MPa and 36 MPa, respectively. The striking similarity in stress profiles across the STDS and MCT may be produced from coincident principle stress axes
and similar structural orientations of each fault.

3. Employing the Hirth et al. (2001) quartz dislocation creep flow law with inferred deformation temperatures from quartz c-axis fabric opening angles and our flow stress estimates, we estimate strain rates between $2.4 \times 10^{-12} - 4.1 \times 10^{-14}$ s$^{-1}$ near the MCT and $4.2 \times 10^{-12} - 2.3 \times 10^{-14}$ s$^{-1}$ near the STDS.

4. When plotted against structural distance, we document an abrupt hook in strain rate estimates along both margins. Traced towards the STDS strain rate estimates decrease from $7.5 \times 10^{-13}$ s$^{-1}$ to $2.3 \times 10^{-14}$ s$^{-1}$ at $\sim 200$ m before rapidly increasing to $4.2 \times 10^{-12}$ s$^{-1}$. The MCT displays a similar strain rate profile, decreasing from $2.4 \times 10^{-12}$ s$^{-1}$ to $1.3 \times 10^{-13}$ s$^{-1}$ at $\sim 200$ m structural distance and then increasing to $1.9 \times 10^{-12}$ s$^{-1}$ near the MCT. This type of strain rate profile may be typical of ductilely deformed tectonites that preserve telescoped deformation isotherms.
References


Stipp, M., Stünitz, H., Heilbronner, R., and Schmid, S. M., 2002b, The eastern Tonale fault zone; a “natural laboratory” for crystal plastic deformation of quartz over a temperature range from 250 to 700 degrees C: Journal of Structural Geology, v. 24, p. 1861-1884.


CHAPTER 2

The effect of 2nd phase minerals on piezometry and strain rate estimates from the Moine nappe, NW Scotland

M.K. FRANCSIS¹, R.D. LAW¹
¹Department of Geosciences, Virginia Tech, Blacksburg, Virginia 24061, USA

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Abstract

Dynamically recrystallized quartz grains are commonly pinned by phyllosilicates. First order Zener space analysis of samples across the northern part of the Moine nappe in NW Scotland suggests that quartz grainsizes are primarily controlled by mica size and content, and secondarily by differential stress. Two populations of dynamically recrystallized quartz grains, referred to as mica-bound and mica-free, exhibit grainsizes from 19—203 \( \mu \) m and microstructures from transitional bulging/subgrain rotation to grain boundary migration with increasing structural distance above the Moine thrust. Grainsize piezometry suggests differential stress levels of 47—7 MPa. Quartz-based microstructural and petrofabric analyses indicate an inverted thermal gradient above the Moine thrust, with deformation temperatures of 375-610 °C traced across the overlying Moine nappe. Strain rate estimates from the Hirth et al. (2001) quartz flow law range from \( 1.52 \times 10^{-14} \) s\(^{-1} \) to \( 1.78 \times 10^{-13} \) s\(^{-1} \). Traced from the highest structural distance above the Moine thrust, strain rates decrease roughly one order of magnitude to 300 m above the thrust before rapidly increasing one order of magnitude near the thrust surface. The kink-shape strain rate profile may be caused by the inverted thermal gradient. Interestingly, the overlying Ben Hope thrust does not appear to influence differential stress or strain rate estimates.

1. Introduction

Recrystallized quartz microstructures form in response to a competition between extrinsic and intrinsic variables; temperature, water content, bulk mineral composition, differential stress, and strain rate. Increases in temperature drive grain growth through grain boundary surface energy reduction (Tullis and Yund, 1982). Increases in water content and hydrolytic weakening can promote grain boundary diffusion and diffusive mass transport (Wheeler, 1992; Wintsch and Yi, 2002). Secondary mineral phases can pin quartz grain
boundaries, inhibiting grain growth. Differential stress and strain rate variations are interdependent; increases in one variable leads to an increase in the other.

Differential stress drives so-called dynamic recrystallization wherein grainsize is reduced in response to an increase in differential stress. Much work has been done in many different tectonic settings in ascribing the associated quartz microstructures to stress levels (Etheridge and Wilkie, 1979; Ord and Christie, 1984; Hacker et al., 1990; Hacker et al., 1992; Dunlap et al., 1997; Behr and Platt, 2011). However, the majority of this work has been pursued under the premises that quartz is: 1) the load-bearing mineral phase (Twiss, 1977; Hirth and Tullis, 1992; Stipp and Tullis, 2003; but see also Handy, 1994; Handy et al., 1999) and, 2) dynamically recrystallized quartz grainsize is completely controlled by differential stress (Stipp and Tullis, 2003; Stipp et al., 2006; compare Shimizu, 2008; Platt and Behr, 2011). Most rocks do not comply with these premises.

Many recent studies, in an effort to assess the influence of other grainsize controls, focus on statically recrystallized tectonites and note a recrystallized grainsize dependence on 2nd phase mineral size and distribution (Herwegh et al., 2011). For example, recent work on calcite recrystallization in both experimental and natural settings has described and quantified the relationship between recrystallized grainsize and 2nd phase mineral size and distribution (Herwegh and Berger, 2004; Ebert et al., 2008; Herwegh et al., 2008; Brodhag and Herwegh, 2010). In comparison, the effect of 2nd phase minerals on quartz recrystallization is not well understood.

While quartz grainsize demonstrably decreases with increasing 2nd phase mineral content and grainsize (Krabbendam et al., 2003; Song and Ree, 2007; see also Herwegh et al., 2011), the relative controlling effect on quartz grainsize between differential stress and 2nd phase size/content has not been quantified as previous studies have analyzed rocks exhibiting only one dislocation creep microstructure (grain boundary migration/regime 3 recrystallization of Hirth and Tullis (1992)). Grainsize evolution in mid-crustal shear zones is highly dependent on ambient differential stress conditions, hence sample transects
Fig. 2.1. Geological map of the NW Scottish Highlands; adapted from Thigpen et al. (2010b). Glen Golly transect marked in green. Major geologic structures and locations referred to in text are indicated.
across mid-crustal shear zones provide good opportunities to constrain the relative influence of differential stress on recrystallized grainsizes.

In this study, we measure two populations of quartz grainsizes, mica-bound and mica-free, along a 2.5 km deep transect across the Moine nappe in NW Scotland (Fig. 2.1). Mica size and content were also measured. By quantifying each type of grainsize population from all samples, we control for dynamic recrystallization and ensure that only 2\textsuperscript{nd} phase mineral interactions contribute to the quartz grainsize difference noted between each population. First order Zener space analysis of the two quartz populations suggests that while mica size/content appears to control both the mica-bound and mica-free quartz grainsize, the mica-free grainsizes represent the final equilibrium grainsize. Quartz-based microstructural and petrofabric analyses provide deformation temperature estimates of 375—610 °C. A differential stress profile is created by converting our measured grainsizes into differential stress estimates using the Holyoke and Kronenberg (2010) correction to the Stipp and Tullis (2003) recrystallized quartz grainsize piezometer. Strain rates were estimated using our differential stress and temperature estimates and the Hirth et al. (2001) quartz dislocation creep flow law. Plotted against structural distance above the Moine thrust, strain rate estimates display a curious hook-shape profile, first decreasing as traced down from the top of the nappe and then increasing at a structural distance of ~ 300 m above the Moine thrust.

2. Geologic Background

The Grampian (475—460 Ma) and Scandian (435—425 Ma) orogenies have deformed and metamorphosed the Moine Supergroup (~ 1000-870 Ma) metasedimentary rocks of the NW Scottish Highlands (Strachan et al., 2002, 2010). Formation of several mid-crustal thrust sheets and the preservation of an inverted metamorphic gradient within individual sheets (Read, 1931; Soper and Brown, 1971; Winchester, 1974; Barr et al., 1986)
are the results of the Scandian event (Strachan et al., 2010; Thigpen et al., in review). At the base of the Caledonian orogenic wedge, and in the foreland of the Scandian deformation, lies the Lewisian gneiss (3000—2700 Ma metagranitoids, metabasites, and lesser metasediments), Scourian basic dikes (~ 2400 Ma and ~ 2000 Ma), and Laxfordian granite (1900-1600 Ma; Park et al., 2002). Overlying the foreland basement package are the Torridonian (1200—1000 Ma) continental red bed sediments and a ~ Cambro-Ordovician platform sedimentary sequence.

In NW Scotland, Scandian deformation extends south from the north coast at Tongue and Loch Eriboll to Skye (Fig. 2.1) and comprises the Moine thrust zone (MTZ), an imbricated belt of mylonites and cataclasites first described in detail by Peach et al. (1907) at the foreland edge of the orogenic wedge. The Moine thrust, the dominant structure in the foreland-hinterland Scandian transition zone, has been variably defined by many workers (see review by Law and Johnson, 2010, p. 480-482). We choose to define the Moine thrust as the mylonite belt which places polydeformed Moine schists on top of mylonitic Lewisian/Cambrian quartzite, in agreement with British Geological Survey (2009) mapping of the area (see Ben Hee sheet). Although only a relatively minor issue of semantics, note that north of our transect, at Eriboll, British Geological Survey mapping places the Moine thrust in between an over-riding sliver of mylonitic Lewisian and underlying mylonitic Cambrian quartzites (compare British Geological Survey Loch Eriboll and Ben Hee sheets (2002, 2009)). The overlying polydeformed thrust sheet containing the Moine metasedimentary rocks is termed the Moine nappe and preserves an inverted metamorphic gradient, as traced up structural section from west to east progressing from greenschist facies at the lowest structural levels to amphibolite facies at the highest structural levels (Holdsworth et al., 2001). Unpublished garnet-biotite thermometry indicates peak metamorphic temperatures of 480—520 °C along the base of the Moine nappe (R. Tracy, 2012). The Ben Hope thrust bounds the top of the Moine nappe. Scandian ductile thrusting was dominantly directed towards the WNW as indicated by tight to isoclinal folding accompanied by wide-
spread formation of an ESE-dipping foliation and ESE- to SE-trending mineral lineation (Barr et al., 1986).

We have sampled a transport-parallel structural section across the Moine nappe along the Glen Golly river roughly 20 km south of Loch Eriboll (Figs. 2.1 & 2.2). Two samples, MT-09-112 and MT-09-115, are from the immediate footwall (west) to the Moine thrust and the remaining samples are from progressively higher structural positions (Fig. 2.2, Tables 1-3). All samples, except MT-09-115, are psammitic. Structural distance was measured along a transect oriented 310° – 130°, roughly parallel to the average mineral stretching lineation and therefore the general tectonic transport direction. Note that the average lineation trends turn from NW-SE to WNW-ESE traced towards the Moine thrust. An average sheet dip of 15° was assumed for the Moine thrust based on mapping by Cheer (2006) and British Geological Survey (2009) as well as unpublished structure contours on the thrust surface as shown on the British Geological Survey (2009) Ben Hee sheet. Structural distance was simply taken to be the perpendicular distance above the Moine thrust as defined above. Total structural distance between the Moine thrust and Ben Hope thrust was ~2.3 km. Note that this thickness may vary for different section trends, fault dips, and fault outcrop traces. Cheer (2006) inferred a minor strike-slip fault through the Moine and overlying Ben Hope nappes roughly parallel and coincident to the Glen Golly section line (see also Ben Hee sheet, British Geological Survey, 2009)). Any increase or decrease in structural height of individual samples above the Moine thrust caused by this structure is assumed to be negligible and our structural distances do not account for this fault.

Fig. 2.2. Previous page. Simplified geologic cross section viewed towards NNE across the Moine nappe 6.5 km south of Glen Golly transect; modified from Cheer (2009) and similar to Section 1 of Ben Hee geological map (British Geological Society, 2009). Note that cross section shows ~ 3.5 km thick Moine nappe, whereas along the Glen Golly transect the Moine nappe is ~2.3 km thick. Blue circle indicates the structural level of SGR-dominated sample projected from north of the Glen Golly transect; used for correlation of Thigpen et al. (2010a, 2010b) data to the Glen Golly transect (see text for details). Structural relationships are interpreted at depth. No vertical exaggeration. MT, Moine thrust; BHT, Ben Hope thrust.
### Table 1: Mica-bound quartz grain population parameters

<table>
<thead>
<tr>
<th>Sample</th>
<th>Structural Distance (m)</th>
<th>Deformation Temperature (°C)</th>
<th>Grain Shape Ratio</th>
<th>Grainsize (μm)</th>
<th>Differential Stress (MPa)</th>
<th>Lithostatic Pressure (MPa)</th>
<th>Water Fugacity (MPa)</th>
<th>Strain Rate (Hirth, s⁻¹)</th>
<th>Strain Rate (Rutter, s⁻¹)</th>
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<td>MT-06-112</td>
<td>-92</td>
<td>430</td>
<td>1.6 ± 0.5</td>
<td>31.2 ± 13.4</td>
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<td>491.1</td>
<td>80.6</td>
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<td>9.51E-17</td>
</tr>
<tr>
<td>MT-09-18</td>
<td>316</td>
<td>461</td>
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<td>55.3 ± 20.3</td>
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<td>695.4</td>
<td>314.0</td>
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### Table 2: Mica-free quartz grain population parameters

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<th>Grain Shape Ratio</th>
<th>Grainsize (μm)</th>
<th>Differential Stress (MPa)</th>
<th>Lithostatic Pressure (MPa)</th>
<th>Water Fugacity (MPa)</th>
<th>Strain Rate (Hirth, s⁻¹)</th>
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### Table 3: Whole-rock quartz grain parameters

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<td>106.0</td>
<td>2.77E-14</td>
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3. Microstructures

Moine rocks in the hanging wall of the Moine thrust primarily consist of feldspathic-micaceous psammite and quartzite with lesser pelite and semipelite, and rare amphibolite (Thigpen et al., 2010a). The Moine thrust footwall contains mylonitized Archean Lewisian basement gneiss, composed of varying amounts of quartz, plagioclase, K-feldspar, muscovite, chlorite, and accessory mineral phases (Thigpen et al., 2010a). The Moine psammites rocks are dominantly composed of quartz and phyllosilicates with variable presence of porphyroclastic feldspar (primarily plagioclase), epidote, and opaque minerals. Foliation is defined by the phyllosilicate-rich domains. Oblique dynamically recrystallized quartz shape preferred orientation (SPO; sensu Means, 1981) and S-C fabrics occasionally produce secondary foliations. Where present, garnets are sub- to euhedral and occasionally preserve winged σ-type mantles indicating top to the WNW shearing. Opposing sets of shear bands in several samples indicate a component of pure shear deformation, though the top-to-the-WNW set is always dominant. Muscovite is abundant through the whole Glen Golly transect, while biotite is present in lesser amounts at low structural distances and chlorite occurs as an accessory phase near the top of the Moine nappe.

Quartz grains exhibit pervasive dynamic recrystallization and a range of associate microstructures (Fig. 2.3). Natural and experimental studies on the recrystallization mechanisms of quartz have identified three dominant microstructures; grain boundary bulging (BLG), subgrain rotation (SGR), and grain boundary migration (GBM; Hirth and Tullis, 1992; Stipp et al., 2002b). These recrystallization mechanisms have been shown in experiments to operate contemporaneously; however, a single mechanism usually, though not always, dominates the bulk microstructure (Hirth and Tullis, 1992; Stipp et al., 2002b). Specifically, each mechanism has a broadly unique set of temperature and driving stress conditions in which it dominates. BLG dominates at high stress and low temperatures, SGR is dominant at medium stress/temperature, and GBM dominates at low stress and high temperature.
Structural distance from the Moine thrust (m)

-500
0
500
1000
1500
2000
2500

Moine thrust
Ben Hope thrust

A
BH-07-08
20° → 150°
200 μm

B
MT-09-22
12° → 128°
200 μm

C
MT-09-20
23° → 124°
200 μm

D
MT-06-112
15° → 104°
200 μm
BLG is indicated by serrated and sutured grain boundaries and typically a dearth of subgrains. Grainsizes characteristic of BLG microstructures range up to ~ 30 μm. SGR microstructures generally contain pervasive subgrain development, slightly tabular recrystallized grains which are sometimes aligned in an oblique grain shape orientation, undulose extinction, and sutured grain boundaries. GBM is characterized by interlobate grain boundaries, few subgrains, and minimal undulose extinction.

Mechanisms for recrystallization are correlated in our samples to structural distance above the Moine thrust. At the lowest structural levels of the Glen Golly transect, and specifically present in the footwall mylonitic Lewisian rocks within 100 m of the overlying thrust surface, are transitional BLG/SGR microstructures (Fig. 2.3d). The dominant microstructure in the lower hanging wall rocks is SGR (Fig. 2.3c). At greater structural distances above the thrust GBM becomes the dominant microstructure (Fig. 2.3b). The transition between SGR and GBM does not occur at a distinct structural level, rather there is a relatively lengthy transition zone extending to structural distances of at least ~ 400 m above the thrust which contains ambiguous microstructures or distinct microstructural indicators for both SGR and GBM recrystallization mechanisms. At the highest structural levels (> 1500 m), grain boundaries tend to be straighter; however, there are always interlobate

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Fig. 2.3. Previous page. Photomicrographs from Glen Golly transect samples cut perpendicular to foliation and parallel to lineation. All micrographs are viewed towards NNE and macroscopic foliation is always horizontal. Arranged in order of structural height above/below the Moine thrust; see cross section in Fig. 2. All photomicrographs taken at 10x magnification and in XPL. A) Sample BH-07-08 from a structural distance of 2294 m above the thrust. Note generally straight quartz grain boundaries except at red star indicating strong temperature control and minimal stress-driven dynamic recrystallization. Red arrow illustrates mica-pinned quartz grain boundary. B) Sample MT-09-22 from a structural distance of 756 m. Undulose extinction is relatively common and subgrain development is minor. Some interlobate grain boundaries are present with few 120° triple junctions suggesting GBM is dominant over SGR. C) Sample MT-09-20 from a structural distance of 342 m. Prevalent subgrain development (red star) and minor undulose extinction. Possible grain boundary bulge indicated by red arrow. D) Sample MT-06-112 from a minor quartz vein at a structural distance of -92 m below the thrust. Note the highly sutured grain boundaries, pervasive subgrain development, and oblique recrystallized grain shape preferred orientation (Sb). Microstructures are indicative of transitional BLG/SGR.
grains which may indicate a competition between static annealing grain growth and GBM (Fig. 2.3a).

It must be emphasized that while the overlying Ben Hope thrust is a major structure of the Scottish Caledonides, quartz microstructures immediately adjacent to it, both in the Moine nappe footwall and Ben Hope nappe hanging wall, are dominated by recovery, not dynamic, features. Grain boundary triple junctions are commonly 120° and virtually no undulose extinction is observed. Quartz grainsizes increase significantly (200+ μm) towards the east into hotter and structurally higher rocks of the Ben Hope nappe. Due to the lack of dynamically recrystallized quartz microstructures, we will not further consider the tectonic influence of the Ben Hope thrust on microstructural development.

3.1 Grain size Measurements

Each sample contained two populations of targeted quartz grains, mica-free and mica-bound. In order to characterize the unpinned (at least in two dimensions) steady state quartz grain size, we measured quartz grains that were not bound by a phyllosilicate phase (i.e. mica-free). Characterization of pinned quartz grains required measurement of grains bound by phyllosilicates (mica-bound). Samples MT-09-20, MT-09-22, MT-09-25, and BH-07-08 are characterized by a large volume percent mica, a homogeneous and pervasive distribution of mica, or both. In order to achieve a relatively robust mica-free sample size in these specific samples, we relaxed our “mica-free” constraint to include quartz grains with no more than one side in contact with a mica lathe and no obvious pinning microstructures (Fig. 2.3; cf. Passchier and Trouw, 2005, p. 49).

Quartz grains were measured optically parallel and perpendicular to the macroscopic foliation on sections cut perpendicular to foliation and parallel to the mesoscopic stretching lineation. Where oblique quartz SPO foliation was present – generally in cm-scale quartz veins – grains were measured with regard to the SPO foliation. Grain size was
Fig. 2.4. Plot of three populations of average quartz grainsize for each sample against structural distance above/below the Moine thrust. BH thrust, Ben Hope thrust; green triangles, mica-bound quartz population; blue diamonds, whole rock quartz population; red squares, mica-free quartz population (see text for details). Error bars illustrate one standard deviation of whole rock quartz grain population; note that errors from mica-bound and mica-free quartz populations are less than and constrained by the whole rock errors.
assumed to be the diameter of a circle with area equal to that of the best-fit ellipse of the
long and short measurements; an arithmetic mean of the measured grains produced the
sample average grainsize. Care was taken during the measurement process to either avoid
or target mica-bounded quartz grains in accordance with the above definitions for the
different quartz domains. At least 50 grains of each type were measured for each sample,
except for MT-09-18, which contained hardly any mica-free quartz grains and hence were
not recorded. Mica-free grainsize measurements are inherently biased towards smaller
grainsizes because smaller grains are less likely to be in contact with any single mica lathe.
Therefore, all mica-free estimates are likely to be minima. Whole-rock grainsize estimates
combine both the mica-free and mica-bound estimates. In the case of sample MT-09-18,
whole-rock estimates equal the mica-bound estimates.

In Figure 2.4, grainsize is plotted against structural distance from the Moine thrust
for mica-free and mica-bound quartz grains as well as a whole rock average, respectively
(Tables 1-3). Mica-free grains increase in size with greater distance into the Moine nappe,
however, the two immediate footwall samples (MT-06-115C and MT-06-112C) show the
opposite trend. Grainsize estimates for mica-bound grains generally, though, not consis-
tently, increase at higher structural levels. The two samples in the immediate footwall also
increase in grainsize with increasing distance away from the Moine thrust, though note that
the difference in structural distance below the Moine thrust is not resolvable in Figure 2.4
(Tables 1-3). Whole rock estimates also exhibit increasing grainsize with increasing struc-
tural distance.

Mica grainsize was also quantified optically. A minimum of 50 mica lathes were
measured along each long and short axis. Following Song and Ree (2007), and similar to
the quartz grainsize measurements, average mica grainsize was taken to be the diameter of
a circle with the same area as an ellipse with axes equal to the mica measurements. Mica
grainsize generally increases up structural section from < 25 µm in the immediate foot-
wall to > 100 µm at the top of the Moine nappe (Table 4). The spatial distribution of mica
Table 4: Zener parameter inputs

<table>
<thead>
<tr>
<th>Sample</th>
<th>Structural Distance (m)</th>
<th>Mica Percent</th>
<th>Mica size (um)</th>
<th>Zener Parameter (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT-06-112</td>
<td>-92</td>
<td>26.6</td>
<td>24.7</td>
<td>92.9</td>
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<tr>
<td>MT-06-115</td>
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<td>12.5</td>
<td>26.2</td>
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<td>MT-09-18</td>
<td>316</td>
<td>35.6</td>
<td>57.7</td>
<td>162.1</td>
</tr>
<tr>
<td>MT-09-20</td>
<td>342</td>
<td>33.5</td>
<td>71.1</td>
<td>212.2</td>
</tr>
<tr>
<td>MT-09-21</td>
<td>411</td>
<td>22.0</td>
<td>60.0</td>
<td>272.7</td>
</tr>
<tr>
<td>MT-09-22</td>
<td>756</td>
<td>25.8</td>
<td>43.2</td>
<td>167.4</td>
</tr>
<tr>
<td>MT-09-25</td>
<td>1538</td>
<td>18.0</td>
<td>51.5</td>
<td>286.1</td>
</tr>
<tr>
<td>BH-07-08</td>
<td>2294</td>
<td>29.7</td>
<td>106.4</td>
<td>358.2</td>
</tr>
</tbody>
</table>
within each sample changes slightly with increasing structural distance. In the lower half of the nappe, mica is distributed rather homogeneously throughout each sample with few dominant through-going foliation planes observed, and is almost entirely situated along grain boundaries. In the structurally highest portion of the Moine nappe, mica tends to be distributed along discrete foliation planes and shear bands. Mica is also found along grain boundaries and included within quartz grains, indicating high grain boundary mobility near the top of the nappe.

Mica content has been measured in all samples from the Glen Golly transect. Point counting of at least 1000 points in each sample was accomplished using micrographs in Adobe Illustrator© and overlain grids. Grid spacing was a maximum of ~ 62.5 μm² and a minimum of 12.3 μm² depending on the magnification of the micrograph. Measured mica contents, listed in Table 4, range from 18.0 – 47.7%. Mica content generally decreases with increasing structural distance above the Moine thrust. With the exception of MT-06-115, mica contents reflect the general whole rock modal percentage and do not specifically reflect mica content where the mica-bound or mica-free quartz populations were measured. This was due to the heterogeneous distribution of the mica-free quartz grain population. It was possible to separately analyze the two quartz population regions in sample MT-06-115; here, the mica-bound quartz grain population region contained 47.7% mica and the mica-free quartz grain population region contained 16.7% mica.

Mica pinning affects both quartz recrystallized grainsize and quartz grain shape. The mica-bound quartz grains exhibit a larger shape factor (long/short axis ratio) than the mica-free population as shown in Figure 2.5. The one exception is sample MT-06-112 where the mica-free quartz grain shape factor is larger than the mica-bound population. No trend of quartz grain shape factor is observed against structural distance. While each population of quartz grains exhibits a particular range of shape factors, each population is within one standard deviation of the other (Fig. 2.5).
Fig. 2.5. Plot of quartz grain shape ratio (long/short axis) against structural distance above/below the Moine thrust. One standard deviation error bars exhibit significant overlap for both populations.
Quartz c-axis fabrics of samples BH-07-08 and MT-09-25 have been analyzed using a Leitz universal stage on sections cut perpendicular to foliation and parallel to the mineral stretching lineation. Both samples exhibit crossed girdle fabrics that quantitatively indicate a top-to-the WNW sense of shear. Previous quartz petrofabric studies across the Moine nappe have primarily documented single-girdle fabrics consistent with top to the WNW shearing (Evans and White, 1984; Holdsworth and Grant, 1990). The fabric opening angle has been proposed as a potential thermometer for recording temperatures at the time ductile deformation ceases, with the opening angle increasing with increasing deformation temperatures (Kruhl, 1998). The fabrics from samples BH-07-08 and MT-09-25 indicate deformation temperatures of 610 °C and 575 °C, respectively. Errors in the Kruhl (1998) fabric opening angle thermometer are qualitatively assessed at ± 50 °C. Unpublished quartz fabric-based temperature data (R. Law, 2012) from the base of the Moine nappe north of Assynt and located along orogenic strike from the Glen Golly transect indicates deformation temperatures of ~ 430 °C. A linear interpolation of deformation temperatures estimated from the c-axis opening angles, projected along strike onto the Glen Golly transect, are plotted against structural distance in Figure 2.6. Potential caveats for the Kruhl (1998) fabric opening angle thermometer include strain-rate variation and hydrolytic weakening; for a more complete discussion on use of this geothermometer and its caveats see Law et al. (2011; their Section 3.8).

Deformation temperatures can also be approximated from quartz recrystallization microstructures. According to Stipp et al. (2002b), BLG, SGR, and GBM microstructures correspond to temperature ranges of ~ 275-400 °C, 400-525 °C, and > 525 °C, respectfully (cf. Dunlap et al., 1997). Implementing the Stipp et al. (2002b) microstructural thermometer for the Glen Golly section, inferred temperatures increase with increasing structural distance above the Moine thrust (Fig. 2.6). At the lowest structural levels, where BLG and
Fig. 2.6. Plot of temperature estimates against structural distance above/below the Moine thrust. White pentagons, quartz c-axis fabric opening angle thermometry; black pentagons, microstructural thermometer of Stipp et al. (2002a). Error bars for each technique are reported at ± 50 °C. Microstructural thermometry estimates are linearly interpolated between 375 °C in the immediate footwall to the Moine thrust and 525 °C at the top of the Moine nappe (see text for details). Quartz c-axis fabric thermometry estimates are reported for Glen Golly transect samples BH-07-08 and MT-09-25, and projected from along strike for samples MT-06-112 and MT-06-115 (see text for details). Temperature estimates using the quartz c-axis fabric thermometer in samples between 250-750 m above the Moine thrust are a result of a linear interpolation between BH-07-08 (610 °C) and MT-06-115 (430 °C).
the BLG/SGR transitional microstructures are present, we infer temperatures of ~ 375°C. Microstructures at the top of the Moine nappe are dominated by GBM, corresponding to temperatures of at least 525 °C, and possibly up to ~ 650 °C. These temperature inferences broadly agree with deformation temperature estimates from the Kruhl (1998) quartz c-axis opening angle thermometer across the Moine thrust front and overlying nappe (Law et al., 2010; Thigpen et al., 2010a, 2010b; Law, unpublished data).

4. Mica Pinning

Grainsize modification under constant external conditions, such as chemical environment, temperature, lithostatic pressure, differential stress, and secondary mineral phase concentration will result in a steady state microstructure and a specific equilibrium grainsize (e.g. Urai et al., 1986; Evans et al., 2001). Water content from experimentally deformed quartz-rich samples has shown no appreciable effect on recrystallized grainsize (Stipp et al., 2006). Temperature increases greatly increase grain boundary mobility and lead to larger statically recrystallized, or annealed, grainsizes. The large and measurable effect of differential stress on recrystallized grainsize will be discussed later. Grain boundary migration can be severely inhibited, or even stopped completely, in the presence of secondary mineral phases (Brodhag and Herwegh, 2010). As reviewed by Herwegh et al. (2011), steady state grainsize in a recrystallized polyphase rock depends primarily on the size ($d_p$) and volume fraction ($f_p$) of secondary phase minerals. This relationship, originally suggested by Zener (in Smith, 1948) and subsequently modified by Herwegh et al. (2011; their Eq. 4 and Fig. 4c), is a function of the Zener parameter:

$$D = c(d_p/f_p)^{m^*}$$  \hspace{1cm} (1)

where $D$ is the steady state recrystallized grainsize, $c$ is a material constant, is the Zener parameter (also referred to as $Z$; units are $\mu$m), and $m^*$ is the slope of the trend lines in Zener space. Zener space is a plot of $D$ against $Z$ (e.g. Herwegh et al., 2011). As seen in Fig. 2.7,
Fig. 2.7. Effect of the Zener parameter, defined by the ratio between size ($d_p$) and fraction ($f_p$; not shown) of second phase minerals. For constant $d_p$, small Zener values indicate larger $f_p$ and smaller matrix grainsizes ($D$; e.g. quartz) and large Zener values indicate smaller $f_p$ and larger $D$ (see text for details). Adapted from Herwegh et al. (2011).
given a constant \( d_p \), \( Z \) will be large when \( f_p \) is small and conversely \( Z \) will be small when \( f_p \) large; following, \( D \) is large when \( Z \) is large and vice versa (Herwegh et al., 2011). Grainsize at high Zener levels (i.e. low 2\(^{nd}\) phase content) tends to reach an equilibrium based on the ambient deformation conditions. In Zener space, a horizontal line of equal grainsize and increasing Zener values would represent this. Where matrix grains are pinned, at low Zener values, there is a positive correlation between matrix grainsize, \( D \), and \( Z \) in Zener space.

In dynamically recrystallized polyphase rocks, matrix grainsize can decrease due to the addition of secondary mineral phases, similar to statically recrystallized polyphase rocks. However, instead of reaching an equilibrium grainsize at regional metamorphic temperature and differential stress (static) conditions, equilibrium grainsize is reached during strain localization conditions with static temperatures and high differential stresses. As will be noted below, differential stress acts to reduce grainsize, thus for a common Zener value one would expect larger matrix grainsizes at regional metamorphic conditions relative to strain localization conditions.

The Zener parameter has been calculated for the Glen Golly transect using the previously discussed mica grainsize and content measurements (Fig. 2.8, Table 4). Plotted against mica-bound quartz grainsizes, the Zener values range from 26.2 to 358.2 µm and exhibits a much stronger correlation than found for modal mica percentage. A strong correlation between quartz grainsize and the Zener parameter may indicate that quartz grainsizes from the Glen Golly transect are controlled by 2\(^{nd}\) phase mineral interactions. The Zener parameter generally increases up structural section from the Moine thrust with the two samples from the immediate footwall exhibiting the smallest Zener levels while the sample at the top of the Moine nappe (BH-07-08) exhibits the largest Zener parameter.

5. Quartz grainsize piezometry

Dynamically recrystallized grainsize, at least in monophase rocks, can be correlated
Fig. 2.8. Plot of Zener space (average quartz grainsize against Zener parameter) for mica-bound quartz population of the Glen Golly transect. Note the logarithmic scale on both axes. Mica-bound quartz grainsize shows strong positive correlation to Zener parameter.
with the driving differential stress that produced the microstructure via the piezometric relationship. Documented empirically, the piezometric relationship predicts smaller steady-state recrystallized grainsizes for larger differential stresses (Post and Tullis, 1999; Stipp and Tullis, 2003). Additionally, different recrystallization mechanisms, such as bulging nucleation, subgrain rotation, and grain boundary migration, have been shown to activate and dominantly control the bulk microstructure at different differential stress and temperature conditions (Stipp et al., 2002b; Stipp and Tullis, 2003). The theoretical basis for the piezometric relationship has been the focus of energetic discussion (Twiss, 1977; Austin and Evans, 2007; Shimizu, 2008; Platt and Behr, 2011); however the relationship has been empirically documented for many minerals and metals (van der Wal et al., 1993; Post and Tullis, 1999; Stipp and Tullis, 2003). Provided that microstructures in naturally deformed rocks are similar to experimentally produced microstructures, use of the empirical grain-size piezometers seems reasonable (Stipp et al., 2002a; Behr and Platt, 2011).

We apply the experimentally derived recrystallized quartz grainsize piezometer of Stipp and Tullis (2003) with the recent Griggs apparatus correction (Holyoke and Kronenberg, 2010) to our measured quartz grainsizes. The piezometer is calibrated for grainsizes between 1-45 µm and experimental quartz deformation regimes 1-3 (Hirth and Tullis, 1992; Stipp and Tullis, 2003). This range of grainsizes predominantly corresponds to the natural BLG recrystallization field and grainsizes > 120 µm may provide minimum stress estimates (Stipp et al., 2010). Temperature, water content, and the α/β quartz transition apparently show no systematic control on the quartz piezometer (Stipp et al., 2006).

Piezometry estimates for mica-bound and mica-free quartz grains and the corresponding whole rock estimates are presented in Fig. 2.9 and in Tables 1-3. Stress estimates from mica-bound domains range from 46.9 MPa at the lowest structural levels to 9.6 MPa at the highest structural levels. Stress estimates from the mica-free quartz grains range from 36.7 MPa near the Moine thrust to 7.2 MPa at large structural distances. Whole rock stress estimates ranging from 41.5 MPa to 8.2 MPa are roughly equal to the mean of the mica-
Fig. 2.9. Plot of differential stress estimates for all three quartz grain populations of the Glen Golly transect against structural distance above/below the Moine thrust. Error bars reflect grain size measurement errors and are not piezometer related. Note the general increase in differential stress estimates traced towards the Moine thrust.
bound and mica-free estimates. As shown in Figure 2.9, the decrease in differential stress decrease traced upwards from the Moine thrust for any suite of measurements is non-linear; rather differential stress exhibits a general power law relation against structural distance.

Two previous studies have analyzed the stress conditions along the Moine thrust (Weathers et al., 1979; Ord and Christie, 1984). Weathers et al. (1979) documented relatively constant (15-20 μm) quartz grainsizes at structural distances of 0-115 m beneath the Moine thrust at the Stack of Glencoul and 0-35 m beneath the thrust at Loch Eriboll (Fig. 2.1). Reanalyzing these grainsizes in the Holyoke and Kronenberg (2010) quartz grain size piezometer indicates differential stress estimates ranging between 45—57 MPa. Ord and Christie (1984) measured quartz grainsizes from both the hanging wall and footwall to the Moine thrust from several locations in the Assynt area. Quartz grainsizes from the footwall range from 12.7—34.6 μm and hanging wall grainsizes range from 33.1—61.2 μm (Ord and Christie, 1984). Inputting these grainsizes into the quartz grain size piezometer yields differential stress estimates of 29—65 MPa and 18—30 MPa for the footwall and hanging wall samples, respectively. These previously studied quartz mylonites produce differential stress estimates ~ 10-20 MPa higher than those from the Glen Golly transect (Fig. 2.9).

6. Strain rate estimates

Quartz deforming via dislocation creep follows a power law relation between strain rate, differential stress, and deformation temperatures (Gleason and Tullis, 1995). Using our flow stress and deformation temperature estimates we estimate strain rates with the naturally constrained quartz flow low from Hirth et al. (2001). This flow law takes the form:

\[ \dot{\varepsilon} = A f_{H_2O}^m \sigma^n e^{\left(\frac{Q}{RT}\right)} \]  

where \( \dot{\varepsilon} \) is strain rate, \( A \) is a material parameter, \( f_{H_2O} \) is water fugacity, \( m \) is the water fugacity
exponent, σ is differential stress, n is the stress exponent, Q is the activation energy, R is the ideal gas constant, and T is absolute temperature (Hirth et al., 2001). From Hirth et al. (2001): A=10^{-11.2} \text{MPa}^n/\text{s}, m=1, n=4, and Q=135 \text{kJ/mol. Water fugacity has been estimated by assuming lithostatic pore fluid pressure in the manner of Behr and Platt (2011). Our temperature estimates (Fig. 2.6) were used as proxies for depth with an assumed geothermal gradient of 25 °C/km, and those depths were converted to pressure using a “normal” geobaric gradient of 28.5 MPa/km (Tables 1-3). These are crude estimations of pressure and may not be reasonable if more hinterland thrust sheets have stacked on top of the Moine nappe (Thigpen et al., in prep). In such a case, the geotherm would effectively become very shallow (?10 °C/km) and thus significantly increase the estimated depths and lithostatic pressures.

Strain rate estimates are shown in Figure 2.10 plotted against temperature and stress as well as in Figure 2.11 plotted against structural distance above the Moine thrust. Whole rock strain rate estimates range from $1.86 \times 10^{-13}$ s$^{-1}$ to $1.63 \times 10^{-14}$ s$^{-1}$ (Table 3). Mica-free strain rate estimates range from $1.78 \times 10^{-13}$ s$^{-1}$ to $1.52 \times 10^{-14}$ s$^{-1}$ (Table 2). Finally, mica-bound strain rate estimates range from $2.35 \times 10^{-13}$ s$^{-1}$ to $1.17 \times 10^{-14}$ s$^{-1}$ (Table 1). All estimates are within the expected range of tectonic strain rates (Pfiffner and Ramsay, 1982). Strain rate estimates from the Rutter and Brodie (2004) experimentally derived flow law are ~ 2-3 orders of magnitude slower and are not tectonically reasonable. Clearly, the total range of strain rates estimated for each population of grains varies insignificantly; at most the mica-bound and mica-free strain rate estimates from a single sample produce a range of less than one order of magnitude in strain rate. The three grainsize populations in sample MT-09-25 result in strain rate estimates less than 0.1 order of magnitude difference. Plotted as a function of structural distance (Fig. 2.11), strain rate decreases roughly one order of magnitude traced towards the Moine thrust for each grain population. For the samples collected, the slowest strain rates occur at ~ 300 m above the Moine thrust. Samples MT-06-112 and MT-06-115, from the immediate footwall to the Moine thrust, both
**Fig. 2.10.** Plot of differential stress estimates (Fig. 9) against deformation temperature estimates from quartz c-axis fabric thermometry (Fig. 6). Hatched box reflects grain size and temperature estimates from Thigpen et al. (2010a,b) taken at the base of the Moine nappe along strike of the Glen Golly transect (see text for details). Strain rate contours from the Hirth et al. (2001) quartz flow law (see text for details) are plotted as dark gray curves. Note that due to the inverted thermal gradient, strain rate increases towards the upper right. Differential stress error bars are identical to Fig. 9 and temperature errors (± 50 °C) are not shown for clarity.
Fig. 2.11. Strain rate estimates from the Hirth et al. (2001) quartz flow law plotted against structural distance above/below the Moine thrust. Error bars reflect grainsize measurement uncertainty (Fig. 4). Hatched box illustrates range of estimated deformation conditions projected along strike near the base of the Moine nappe (Thigpen et al. 2010a,b; see text for details). Note the decrease in estimated strain rate traced from the top of the Moine nappe towards the Moine thrust and the order of magnitude increase in estimated strain rate in the immediate footwall to the Moine thrust.
produce strain rates faster than those in the immediate hanging wall to the Moine thrust, and sample MT-06-115 produced the fastest strain rates of the Glen Golly section. Again, the Ben Hope thrust does not appear to have dynamically modified the immediately adjacent quartz microstructures, so any variation in strain rate near the top of the Moine nappe (close to the Ben Hope thrust), is arguably not a result of motion on the Ben Hope thrust.

7. Discussion

7.1 Sampling gap filled in from along strike

The Glen Golly transect has a conspicuous sample gap in the immediate hanging wall of the Moine thrust. Thigpen et al. (2010a, 2010b) documented quartz microstructures along strike of the leading edge of the Moine thrust and noted the presence of SGR-dominant recrystallization in the immediate hanging wall. Projected along strike to the base of the Glen Golly transect (Figs. 2.10 & 2.11), SGR-dominant microstructures fit extremely well into established recrystallization gradient from high stress/low temperature BLG/SGR at the base to low stress/high temperature GBM at the top of the Moine nappe. This along strike extrapolation is strengthened by a recrystallized quartz vein sample in the immediate hanging wall to the Moine thrust several km to the north of the Glen Golly transect (blue circle in Fig. 2.2) which displays strong SPO, indicative of dominant SGR recrystallization. SGR recrystallization produces grainsizes between 35-120 μm (Stipp et al., 2010). Given the continuous and apparently linear relation between average grain size and structural distance (Fig. 2.4), a recrystallized quartz grain size of 40-60 μm in the immediate hanging wall seems appropriate. Differential stress estimates of this grain size range indicate stresses of 26.2-19.0 MPa. Interpolation of temperature and water fugacity from the established thermal and water gradients for the Glen Golly transect (Fig. 2.6) predicts a temperature of ~ 445 °C and a water fugacity of ~ 85 MPa. Inputting these parameters into the Hirth et al.
(2001) quartz flow law produces strain rate estimates between $1.04 \times 10^{-14}$ s$^{-1}$ and $3.76 \times 10^{-14}$ s$^{-1}$. These inferred data are illustrated in Figure 2.10 and Figure 2.11 as hatched boxes. While we have generally interpolated these data, meaning the grainsize, differential stress, and deformation temperature are fit to the previously established data trends, the estimated strain rate is a product of these inferences. Hence, strain rate, when plotted against structural distance (Fig. 2.11), does not follow a previous data trend; instead, it illustrates an overall kink-shape strain rate profile for the Glen Golly transect. Strain rate estimates traced down structural section towards the Moine thrust first decrease from $\sim 1.1 \times 10^{-14}$ s$^{-1}$ to $\sim 1.1 \times 10^{-15}$ s$^{-1}$ at 316 m structural distance and then increase $\sim 1$ order of magnitude in both the immediate hanging wall and footwall (Fig. 2.11).

7.2 Comparison to other Zener-space studies

While many studies of calc-mylonites have documented a relationship between grainsize and 2nd phase mineral size and content (e.g. Herwegh et al. 2011), only two studies have analyzed the effect of 2nd phase minerals on quartz-rich mylonites. Quartz ‘ribbons’ in a primarily muscovite-rich matrix document a systematic decrease in quartz grainsize with decreasing mica content (Song and Ree, 2007). Quartz-graphite mylonites from Naxos exhibit a systematic decrease in quartz grainsize with increasing graphite content (Krabbenbendam et al., 2003).

Working on a quartz-mica mylonite across the Sunchang shear zone of South Korea, Song and Ree (2007) documented changes in quartz grainsize with increasing mica content. Quartz and mica grainsize and content were measured in quartz-rich ‘ribbons’ using various software packages. Grainsizes ranged from 25—106 μm for quartz and 5.5—9.9 μm for mica. Mica content varied from 0.47—24.28 % volume. A fairly well constrained logarithmic relation between quartz grainsize and mica volume percentage was observed (Song and Ree, 2007; their Fig. 5). The Zener parameter calculated for the Sunchang shear zone
mylonites ranges from 37.8—1925.5 μm. Deformation temperature estimates (400-450 °C) for the mylonites rely completely on feldspar recrystallization microstructures; however, quartz recrystallization in these mylonites is dominated by regime 3 microstructures (Hirth and Tullis, 1992), possibly indicating deformation temperatures > 525 °C (Stipp et al., 2002b; Song and Ree, 2007). First illustrated by Herwegh et al. (2011; their Fig. 13) and reproduced here (Fig 2.12), quartz grainsize from the Sunchang shear zone data is strongly correlated by the Zener parameter, suggesting that quartz grainsize is primarily dependent on the size and volume percentage of mica.

High temperature quartz-graphite tectonites from the Naxos dome exhibit changing quartz grainsizes with varying graphite contents (Krabbendam et al., 2003). Deformation temperatures of 500-650 °C were interpreted from the proximity to the sillimanite metamorphic isograd and migmatic core of the adjacent Naxos dome (Krabbendam et al., 2003). Quartz grainsizes ranged from 72.5—39 μm. Graphite particles displayed relatively constant sizes from 7.9-10.1 μm, while volume percentages of graphite ranged from 0.3—2.6 %. Combined in the Zener parameter, values range from 386.5—2257 μm (Fig. 2.12), exhibiting a kink-shaped quartz grainsize/Zener parameter profile, where low Zener values produce a steeper grainsize gradient, while higher Zener values produce essentially constant grainsizes. This trend suggests that the quartz grainsizes are strongly controlled in lower Zener value samples (high graphite contents) and quartz grainsizes have stabilized or achieved a steady-state fabric independent of graphite size/content at high Zener values (low graphite contents).

Qualitatively compared to the Glen Golly transect, the studies by Song and Ree (2007) and Krabbendam et al. (2003) exhibit slightly different quartz grainsize correlations to the Zener parameter. The Sunchang shear zone data display a shallower trend than the Glen Golly transect in Zener space (Fig. 2.12); indicating that the Sunchang quartzites have a stronger dependence on mica content and size (Song and Ree, 2007). Where the Naxos dome quartz-graphite tectonites display a strong correlation to the Zener parameter, they
Fig. 2.12. Comparison of quartz-based Zener space trends. Mica-bound quartz, this study; Song and Ree (2007), Sunchang shear zone, Korea; Krabbendam et al. (2003), quartz-graphite tectonite from Naxos dome. See text for details. Adapted from Herwegh et al. (2011; their Fig. 13).
exhibit a similar trend to the Glen Golly transect (Krabbendam et al., 2003).

Comparisons of quartz grainsizes between the Sunchang, Naxos, and Glen Golly transects are difficult, however, because the data overlap in Zener space while deformation conditions vary considerably (Fig. 2.12). Because the Zener parameter only considers 2nd mineral phase grainsize and content, it is possible for samples from widely different geologic contexts (strike-slip shear zone, gneiss dome, thrust nappe) to produce similar Zener values, while quartz grainsize will be modified according to the ambient conditions. Deformation temperatures from the three quartz tectonite studies range from greenschist to upper-amphibolite facies (375—650 °C) and quartz recrystallization microstructures, at least correlated with the Stipp et al. (2002b) quartz recrystallization microstructural thermometer, reflect these changes in deformation conditions.

Mineral specific maps of Zener space, so called ‘grainsize evolution maps’ or ‘grain coarsening maps,’ attempt to document the dynamic relation between the matrix phase grainsize (e.g. quartz, calcite, olivine) and the 2nd phase grainsize/content over all deformation conditions (Herwegh et al., 2005; Herwegh et al., 2011 and references within). Grain-size evolution maps have been calibrated for calcite and olivine illustrating two main data trends in Zener space: 1) a positive correlation between matrix grainsize and the Zener parameter (2nd phase controlled recrystallization) and, 2) constant grainsize with increasing Zener values (dynamic recrystallization controlled; Herwegh et al., 2005; Linckens et al., 2011). As noted in Section 4, 2nd phase controlled recrystallization depends primarily on 2nd phase content and deformation temperature, whereas dynamic recrystallization controlled grainsize (as defined for calcite by Herwegh et al. (2005)) is solely dependent on deformation temperature. The dynamic recrystallization controlled grainsize field for olivine is primarily dependent on deformation temperature, and secondarily dependent on the Zener parameter (Linckens et al., 2011). Note that the boundary between the Zener trends is not at a constant Zener value for all matrix grainsizes. For calcite deforming between ~345—470 °C (steady state, uninhibited grainsizes between ~10—200 μm), the Zener value
dividing the two trends is \(~ 50—1000 \mu m\), respectively (Herwegh et al., 2011). This field boundary is different for olivine (Linckens et al., 2011) and is expected to also be different for quartz. From the combined quartz studies, it is apparent that both types of Zener space trends are observed in quartz-rich tectonites, but it is not clear what the primary control on quartz grainsize in the dynamic recrystallization field is (Fig. 2.12). Variations in differential stress, which can drive dynamic recrystallization and produce systematic matrix grain-sizes, are not explicitly addressed during the construction of grainsize evolution maps, and are expected to be important.

The Stipp and Tullis (2003) quartz grainsize piezometer produces stress estimates in dynamically recrystallized quartz-rich rocks (see Section 5 for details). Differential stress estimates from the Sunchang shear zone range from 12—37 MPa, although, the specific structural relation of each sample is not known and so any identified stress profile is completely without context (Song and Ree, 2007). Note that stress estimates from the Sunchang shear zone should generally be regarded as maximum estimates, due to the obvious mica-pinning influence on quartz grainsize. From a single outcrop in the Naxos dome, and presumably near identical deformation conditions, stress estimates of 16—26 MPa are estimated (Krabbendam et al., 2003). Due to graphite pinning, the smallest quartz grainsizes should produce maximum stress estimates while the largest quartz grainsizes, uninhibited by graphite particles, may produce average stress estimates. The mica-free quartz grain population from the Glen Golly transect yields differential stress estimates of 7-37 MPa over a structural distance of \(~2300 m\).

Structural context is of the upmost importance when considering the relative control of strain-energy-driven grain boundary migration (dynamic recrystallization driven by differential stress) on the microstructures of polyphase rocks. Hence, samples from the Sunchang shear zone of Song and Ree (2007) cannot be further considered. Structural context is well resolved in the Naxos gneiss dome. However, because only one outcrop was studied by Krabbendam et al. (2003), the samples cannot be placed into a larger kinematic frame-
work. Structural context in the calcite-based Zener literature has been addressed by Herwegh et al. (2008) across the Alpine Doldenhorn thrust. Plotted against structural distance, calcite grain size abruptly decreases from a constant ~ 20 µm in the hanging wall to < 5 µm within 10 m structural distance of the thrust (Herwegh et al., 2008; their Fig. 10). In the dynamic recrystallization controlled field of Zener space, the data plot chaotically, suggesting that differential stress, rather than temperature, is the primary control of recrystallized calcite grain size (Herwegh et al., 2008; their fig. 4). This is relatively unsurprising given that calcite grain size has been documented both experimentally and naturally to be modified by temperature and differential stress (e.g. Rutter, 1995). The Glen Golly transect captures microstructures across a 2.3 km thick thrust nappe, and mica-free quartz grain sizes track the spatial evolution of uninhibited quartz domains which have been used as a proxy for differential stress. While there is a strong correlation between the Zener parameter and mica-bound quartz grain size (Fig. 2.8), there is also a fairly strong correlation between structural distance from the Moine thrust and the Zener parameter (Fig. 2.13). This suggests that mica size/content still controls quartz grain size, but it does not rule out a differential stress control as differential stress is interpreted to increase towards the Moine thrust (Fig. 2.9). As mentioned above, experimental work on quartz piezometers suggests no temperature control on grain size evolution (Stipp et al., 2006). However, theoretical studies on dynamically recrystallized quartz grain size indicate that temperature has a minor input (Shimizu, 2008; Platt and Behr, 2011). If temperature plays a slight or negligible role in the evolution of dynamically recrystallized quartz grain sizes, then differential stress must be taken into account while interpreting grain size profiles and may unknowingly already be implicitly involved in Zener space, as interpreted in calcite studies.

As compiled for calcite-rich mylonites (Herwegh et al., 2011; their fig. 4c and references within), grain size evolution maps contain data from multiple 'representative elementary volumes' (REV) in individual samples. Each REV in a sample is obviously deformed at identical deformation conditions and where a sample contains a large range of Zener values
Fig. 2.13. Plot of mica-bound quartz Zener parameter against structural distance above/below the Moine thrust.
the two typical Zener space trends, 2\textsuperscript{nd} phase affected and uninhibited grains, will emerge. At high enough Zener values (i.e. in the dynamic recrystallization field of Zener space), matrix grains can grow unabated until an equilibrium grainsize, where temperature-driven grain growth and differential stress-driven grain reduction equilibrate. If equilibrated matrix grains exhibit dynamic recrystallization then grainsize piezometers can record differential stress levels. Differential stress estimates from grainsize piezometers only require grainsize inputs so it is unclear where differential stress estimates should plot in Zener space. Certainly the Zener levels will not be correlated to differential stress estimates, except for the need for the Zener parameter to be large, and likewise the Zener parameter is not expected to show much correlation to structural distance. In the Zener analysis of the Doldenhorn thrust, Herwegh et al. (2008; their Fig. 4) illustrated very little correlation between grainsize and the Zener parameter from different REV’s in samples at low structural distances. This suggests that very localized (thin-section scale) perturbations in differential stress modify calcite grains in a particular REV. Variations in differential stress at slightly higher structural distances produce a swath of grainsizes, indicating that either differential stress varies locally or the size of each REV is not large enough to capture the full range of grainsizes in a given sample. This distribution of grainsizes, which increase with increasing structural distance, implies that differential stress estimates decrease away from the thrust. We now return to the Glen Golly transect in order to interpret the Zener space distribution in light of the previous discussion.

7.3 Zener space interpretation of Glen Golly samples

While there is a strong correlation between Zener parameter and quartz grainsize in the Glen Golly samples (Fig. 2.8), multiple interpretations are possible without the guidance of a Zener space calibration for quartz. In order to illustrate the various possible data interpretations, a set of strongly correlated data for a hypothetical mineral assemblage are plot-
ted in Zener space shown in Figure 14. Because the data are strongly correlated between matrix grainsize and the Zener parameter, an intuitive assumption would be that the data lie along the boundary between the 2nd mineral phase controlled and the dynamically controlled grainsize fields in Zener space. If that assumption holds, then the data may either lie at their ultimate equilibrium grainsize or below it. Grainsize measurements and natural extrapolations from grainsize measurements, such as differential stress estimates, taken from data lying on the Zener space field boundary at an ultimate equilibrium grainsize will provide true measures of rock parameters (Red dashed line in Fig. 2.14). However, if data lie below final equilibrium grainsizes, all measurements or estimates taken from those grains must be minima (green dashed line in Fig. 2.14). A third interpretation requires the apparent strong correlation between matrix grainsize and the Zener parameter to be completely serendipitous and all data points lie off of the field boundary in the dynamically recrystallization controlled Zener space field (blue dashed line in Fig. 2.14). In this last case, grain measurements and estimates would again provide meaningful results, however, this scenario is particularly unlikely to occur in nature and we disregard it. Based on the first two hypothetical cases, we regard all mica-bound quartz grainsize measurements as being minima measures of the final, equilibrium grainsize, thus the resulting differential stress estimates are maxima.

In order to control for differential stress-driven grainsize reduction, the mica-free quartz grain population must be approximately equal to the equilibrium grainsize. The two different quartz grain populations do not exhibit drastically different grainsizes (Fig. 2.4, Tables 1 & 2) as would be intuitively expected if the mica-bound quartz grains lie on the Zener space field boundary. Five of the Glen Golly transect samples display a slightly larger average quartz grainsize in the mica-free population, relative to the mica-bound population. However, in all cases, the errors associated with grainsize measurements overlap between the two quartz grain populations. This similarity in grainsize may be at least partially caused by an unintentional biasing of the mica-free quartz grainsize population towards
Fig. 2.14. Hypothetical Zener space and three possible interpretations given a linear distribution of data (black circles; equivalent to mica-bound quartz population). Red and green circles are equivalents of the mica-free quartz grain population for a given scenario. Red dashed lines and circles illustrate a case where measured data lie on the Zener field boundary and is at the equilibrium quartz grainsize for a given Zener value. Green dashed lines and circles illustrate a case where measured data lie on the Zener field boundary, but is less than the equilibrium quartz grainsize for a given Zener value. Blue dashed line indicates the expected second mineral phase controlled Zener space trend for a case where the black circles lie in the dynamic recrystallization controlled field. See text for details.
smaller grainsizes. Measuring of this population of quartz grains was geometrically forced
to focus on smaller grainsizes with less grain boundary surface area, and hence less of a
chance to be in contact with a bounding mica lathe. It is also possible that the mica-free
quartz grain population is bounded by mica out of the thin section plane which would lead
to a real decrease in grainsize (as opposed to an apparent decrease caused by biased mea-
surements). However, measured grain shape (long/short axis, Fig. 2.5) differences in the
quartz grain populations suggest that the mica-free population may not be bound by mica
in the third dimension. Mica-bound grains in all but one sample exhibit larger grain shape
factors than mica-free grains, implying that the mica-free grain boundaries are relatively
uninhibited in at least 2 dimensions. While acknowledging the potential mica-free grain-
size bias, we argue that the mica-free quartz population is, at least to the first order, a true
grainsize and therefore, the mica-bound quartz grainsizes may be very close (within ~ 20
μm) to true grainsizes as well.

The Zener parameter of the mica-free quartz population is effectively infinite be-
cause of the selective sampling methodology. Plotting the mica-free quartz grainsize
against an effectively infinite Zener value of $10^4$ μm and correlating to the mica-bound
quartz population allows for a rough, first-order calibration of quartz/mica Zener space
(Fig. 2.15). Mica-bound grainsizes are generally within 15 μm of the equilibrium grainsize,
suggesting either that mica does not completely dominate the resulting measurements,
or the presence of differential stress acts to keep mica-free grains relatively small through
dynamic recrystallization. Accepting that the mica-free quartz grains provide true grainsize
values, the resulting estimations of differential stress and strain-rate can be further ana-
lyzed.

Differential stress estimates of mica-free quartz grains increase towards the Moine
thrust, reaching peak levels of ~ 35 MPa in the immediate foowall (Fig. 2.9). Such a distri-
bution is expected from a Type II shear zone (Means, 1995) where strain is continuously lo-
calized and low-strain, marginal rocks record earlier deformation conditions. Peak stresses
Fig. 2.15. Preferred Zener space interpretation of the Glen Golly transect. Mica-free quartz grain population are nominally assigned a Zener value of $10^5$ μm (effectively infinite). Quartz grain size difference is generally < 15 μm between the mica-free and mica-bound population, suggesting mica-bound quartz grains are near the equilibrium grain size. See text for details.
in quartz-rich crust have been estimated at ~ 150 MPa near the brittle-ductile transition (Behr and Platt, 2011). However, extrapolated deformation temperatures at the base of the Moine nappe indicate temperatures of ~ 430 °C, or ~ 100 °C above the typical temperature range of brittle quartz deformation. Stresses inferred from quartz flow laws at ~ 430 °C are typically < 75 MPa and decrease to < 25 MPa at 550 °C, though the exact correlation depends on strain rate (e.g. Hirth et al., 2001). This reaffirms the assumption that the mica-free grainsizes and associated estimates are typical of mid-crustal environments.

Strain rate estimates using the mica-free differential stress and c-axis fabric temperature estimates are within normal geologic strain rates, but produce an unusual profile against structural distance (Fig. 2.11). Traced down from the top of the Moine nappe to ~ 300 m structural distance, strain rates decrease about half an order of magnitude. The two footwall samples both indicate faster strain rates than are observed in the lower half of the Moine nappe. This profile is likely caused by the steep and inverted thermal gradient and its interplay with differential stress estimates in the Hirth et al. (2001) quartz flow law.

7.4 Final comment on quartz Zener space interpretations

As illustrated by the discussion above, the limitations of this Zener space study are substantial. Quartz grainsizes, mica grainsizes, and mica contents for the Glen Golly transect have been measured throughout whole thin sections and have not focused on multiple ‘representative elementary volumes’, as in Herwegh et al. (2011). This methodology produces only one Zener space data point per sample and hinders the full exploration of Zener space for quartz. However, as noted above, most samples contain homogeneous distributions of mica and therefore the Zener parameter is not expected to vary considerably for a particular sample. Mica content, the strongest control on the Zener parameter, is always larger than 18.0 modal percent which may be great enough to significantly affect the microstructures and recrystallization mechanism. Song and Ree (2007) postulated a change in
quartz deformation mechanisms at mica contents as low as 3 percent. Likewise, the calcite-based Zener space literature consistently finds a 2nd phase content of ~ 2 percent to inhibit calcite grainsizes (Herwegh et al., 2005; Ebert et al., 2007; Ebert et al., 2008; Herwegh et al., 2011). Without a true Zener space calibration for quartz (e.g. as for calcite Herwegh et al., 2005) thorough interpretation of the Glen Golly data is not much more than speculation.

Clearly what is needed is a true Zener space calibration for quartz, as has been created for calcite and olivine (Herwegh et al., 2011; Linckens et al., 2011). Potential sample candidates for such a calibration may include the Stack of Glencoul quartzites in the immediate footwall to the Moine thrust 20 km south of the Glen Golly transect (Fig. 1; Law et al., 1986; Law et al., 2010) or the Harkless quartzites surrounding the Papoose Flat pluton of eastern California (Law et al., 1992). Both areas provide pervasively dynamically recrystallized quartzites with changing modal percentages of mica. Most importantly, however, is that both sites have extremely well documented structural and kinematic frameworks, as well as well studied thermal histories.

8. Conclusions

1. Two populations of quartz grainsizes, mica-free and mica-bound, have been measured in a 2.3 km thick structural transect across the Moine nappe in NW Scotland. Mica-bound quartz grains are almost always smaller (19—140 μm) than the mica-free population (26—203 μm). Mica grain size and content was analyzed in all samples; grainsize varied between 12—106 μm and modal mica percentage ranged from 18—47%.

2. First order Zener space analysis of the two populations of quartz grainsizes suggests that while mica size/content appears to control both the mica-bound and mica-free quartz grainsize, the mica-free grainsizes reflect the final, equilibrium between temperature-driven grain growth and differential stress-driven dynamic recrystal-
lization. Thus, the microstructures, grainsizes, differential stresses, and strain rates calculated from the mica-free quartz grain population are assumed to be true, average estimates.

3. Utilizing the mica-free quartz grainsize population, differential stress was estimated with a state-of-the-art quartz grainsize piezometer (Stipp and Tullis, 2003; Holyoke and Kronenberg, 2010). Differential stress estimates ranged from 7—37 MPa and generally increase down structural section, with highest stress magnitudes in the immediate footwall of the Moine thrust.

4. Deformation temperatures from quartz c-axis fabric (Kruhl, 1998) and microstructural (Stipp et al., 2002b) thermometers indicate an inverted thermal gradient within the Moine nappe. Temperature estimates from structurally highest samples are 575 °C and 610 °C based on the Kruhl (1998) quartz fabric opening angle thermometer. Along strike, N and S of the Glen Golly transect, unpublished temperature data from the base of the Moine nappe (Law, 2012) indicates deformation temperatures of ~ 430 °C. A linear best fit between the highest and lowest temperature data produces an inverted apparent thermal gradient of ~ 80 °C/km.

5. Strain rates were estimated using the Hirth et al. (2001) dislocation creep quartz flow law and combined differential stress and deformation temperature data. Strain rate estimates range from $1.52 \times 10^{-14}$ s$^{-1}$ to $1.78 \times 10^{-13}$ s$^{-1}$ and decrease traced towards the Moine thrust. Additional microstructural, grainsize, and differential stress data from Thigpen et al. (2010a, b) projected along the base of the Moine nappe to our sample transect further constrains the strain rate profile; which exhibits an overall kink shape, first decreasing from the top of the nappe to ~ 300 m structural distance above the Moine thrust and then increasing about one order of magnitude traced towards the thrust. Recovery-dominated quartz microstructures at the top of the Moine nappe indicate that the movement on overlying Ben Hope thrust is not recorded, thus, differential stress and strain rate estimates from these rocks are
minima and are associated with the general regional deformation conditions.
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