Synchrotron FTIR imaging of OH in quartz mylonites

Andreas K. Kronenberg1,*, Hasnor F.B. Hasnan1a, Caleb W. Holyoke III1b, and Richard D. Law3, Zhenxian Liu1, and Jay B. Thomas4

1 Center for Tectonophysics, Department of Geology and Geophysics, MS 3115, Texas A&M University, College Station, TX, 77843-3115, USA
2 Department of Geosciences, MC 0420, Derring Hall RM 4044, Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, USA
3 Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Rd., NW Washington, D.C., 20015, USA
4 Department of Earth Sciences, 204 Heroy Geology Laboratory, Syracuse University, Syracuse, NY, USA 13244, USA
a now at: Department of Advanced Geophysics, PETRONAS, Carigali Sdn. Bhd., PETRONAS Twin Towers, Kuala Lumpur City Centre, 50088 Kuala Lumpur, Malaysia
b now at: Department of Geosciences, University of Akron, Akron, OH, USA 44325-4101, USA
Author Correspondence Information:

Corresponding Author:
Andreas K. Kronenberg  
kronenberg@geo.tamu.edu  001 (979) 845-0132
FAX: 001 (979) 845-6162

Hasnor F.B. Hasnan  
hasnorfarhana@gmail.com

Caleb W. Holyoke III  
cholyoke@uakron.edu  001 (330) 972-7632  FAX: 001 (330) 972-7611

Richard D. Law  
rdlaw@vt.edu  001 (540) 231-6685  FAX: 001 (540) 231-3386

Zhenxian Liu  
zxliu@bnl.gov  001 (631) 344-7199

Jay B. Thomas  
jthom102@syr.edu  001 (315) 443-2672
Abstract

Methods of measuring OH absorption bands of fluid inclusions and hydrogen defects in deformed quartz-rich rocks at high spatial resolution are described, using synchrotron infrared IR radiation coupled with a Fourier transform infrared FTIR microscope, and applied to imaging OH in mylonites from the footwall of the Moine Thrust (from the Stack of Glencoul, NW Scotland Caledonides) and hanging wall of the Main Central Thrust (Sutlej Valley, Himalaya of NW India).

Previous measurements of water in deformed quartzites using conventional FTIR instruments, through apertures of 50-100 µm for specimens ~100 µm in thickness have shown that water contents of larger grains vary from one grain to another. However, the non-equilibrium variations in water content between neighboring grains and within quartz grains cannot be interrogated further without greater measurement resolution, nor can water contents be measured in finely recrystallized grains without including absorption bands due to fluid inclusions, films, and secondary minerals at grain boundaries.

Synchrotron IR radiation is brighter and more collimated than offered by conventional FTIR globar light sources, and we have been able to distinguish and measure OH bands due to fluid inclusions, hydrogen point defects, and secondary hydrous mineral inclusions through an aperture of 10 µm for specimens > 40 µm thick. Doubly polished IR plates can be prepared with thicknesses down to 4-8 µm, but measurement of small OH bands is currently limited by strong interference fringes for samples < 25 µm thick, precluding measurements of water within individual, finely recrystallized grains. By translating specimens under the 10 µm IR beam by steps of 10 to 50 µm, using a software-controlled x-y stage, spectra have been collected over specimen areas of nearly 4.5 mm². Integrated absorbance of the broad OH band at 3400 cm⁻¹ due to fluid inclusions was mapped and water content contoured, after subtracting the 3600 cm⁻¹ band due to micas.
Maps of the 3600 cm\textsuperscript{-1} band absorbance show concentrations of micas at grain boundaries, as well as finely dispersed mica inclusions within quartz grains. Mylonitic Cambrian quartzites deformed under greenschist facies conditions in the footwall to the Moine Thrust exhibit a large and variable 3400 cm\textsuperscript{-1} band absorbance, and maps of water content corresponding to fluid inclusions show that inclusion densities correlate with deformation and recrystallization microstructures. Water contents of quartz grains in these mylonites are comparable to those of wet quartz varieties deformed in laboratory experiments. OH absorption bands of large clear quartz grains of mylonitic orthogneisses and paragneisses deformed under lower-upper amphibolite facies conditions in the hanging wall to the Main Central Thrust are much smaller, and dominated by sharp bands at 3595 cm\textsuperscript{-1} to 3379 cm\textsuperscript{-1} due to hydrogen point defects that appear to have uniform, equilibrium concentrations in the driest samples. The broad OH band at 3400 cm\textsuperscript{-1} in these rocks is much less common. The lack of detectable water in highly sheared Main Central Thrust mylonites offers a challenge to our understanding of quartz rheology. However, where water absorption bands can be detected and compared with deformation microstructures, OH concentration maps provide information on the histories of deformation and recovery, and evidence for the introduction and loss of fluid inclusions, and water weakening processes.

*Keywords:* FTIR Mapping, Water weakening, Dislocation Creep, Quartz
1 Introduction

Quartz mylonites sheared at middle to lower levels of the continental crust exhibit microstructural and textural evidence of dislocation creep, a process that is widely believed to require water weakening in framework silicates. The effects of water on dislocation creep of quartz, including the nucleation, glide, climb and recovery of dislocations, and recrystallization are well known from: 1) experimental studies of natural crystals, in which water was introduced into grain interiors (e.g., Griggs, 1967; Blacic, 1975, 1981; FitzGerald et al., 1991), 2) studies of synthetic and natural quartz varieties with large initial water contents (e.g., Griggs and Blacic, 1965; Hobbs, 1968; Baeta and Ashby, 1970; Kekulawala et al., 1978; Kirby and McCormick, 1979; McLaren et al., 1983; Linker et al., 1984; Gerretsen et al., 1989; Muto et al., 2011; Holyoke and Kronenberg, 2013; Stünitz et al., in press), and 3) quartzites and polycrystalline quartz aggregates with water added or removed before or during experiments (e.g., Jaoul et al., 1984; Kronenberg and Tullis, 1984; Tullis and Yund, 1989; Hirth and Tullis, 1992; Gleason and Tullis, 1995; Post et al., 1996; Chernak et al., 2009). In addition to the parametric approach taken to study water weakening in deformation experiments, key insights into water weakening come from infrared IR spectroscopy of quartz samples that have been deformed in the lab under varying hydrothermal conditions, explicitly adding or removing water or changing the fugacity of H$_2$O at fixed temperature and/or strain rate. OH absorption bands characteristic of different hydrogen defects and forms of molecular water can be identified and their size used to determine concentration (e.g., Kats, 1962; Griggs and Blacic, 1965; Aines and Rossman, 1984; Aines et al., 1984; Stipp et al., 2006).

Water weakening in the continental crust is inferred because of the high laboratory strengths exhibited by quartz and feldspars in the absence of water (Griggs, 1967; Heard and Carter, 1968; Tullis and Yund, 1977, 1980; Tullis, 1983; Blacic and Christie, 1984) and the postulated effects of water on point defects and...
disruptions of fully linked Si-O bonds (Griggs, 1974; Hirsch, 1979; Hobbs, 1981; Paterson, 1989). With the advent of Fourier transform infrared FTIR spectroscopy and IR microscopes, water and hydrogen defects in naturally deformed quartz have been reported with OH contents of 300 ppm to >10,000 ppm (molar H/10^6 Si, Kronenberg and Wolf, 1990; Kronenberg et al., 1990; Nakashima et al., 1995; Gleason and DeSisto, 2008; Seaman et al., 2013; Finch et al., 2016), comparable to those required for water weakening in laboratory experiments. In small granitic shear zones deformed at greenschist conditions, water contents of quartz grains appear to correlate with finite strain (Kronenberg et al., 1990; Gleason and DeSisto, 2008), and in the much larger Median Tectonic Line of Japan, intragranular water contents increase towards its center (Nakashima et al., 1995). However, OH concentrations of quartz of granitic rocks deformed at higher temperatures can be much lower (20 - 100 ppm; Han et al., 2013; Kilian et al., 2016), with IR spectra dominated by small sharp OH bands of hydrogen point defects (Kilian et al., 2016) that are not thought to weaken quartz. Moreover, quartz water contents have been reported that show a trend of decreasing OH content towards the center of a high grade shear zone (Finch et al., 2016). Maps of OH content, constructed from FTIR spectra of deformed granitic rocks (Seaman et al., 2013) show compelling relationships between water content and microstructures generated during deformation, suggesting that water contents are reduced during recrystallization and partial melting.

Much as deformation microstructures and textures provide a link between our understanding of deformation mechanisms activated in deformation experiments at high laboratory strain rates and the mechanisms governing plasticity and creep of shear zones at low natural strain rates (Snoke et al., 1998; Heilbronner and Barrett, 2014), IR spectroscopy can provide a link between our understanding of water weakening in the lab and in nature. In this paper, we report on methods of FTIR spectroscopy to characterize OH absorption bands and image OH contents in quartz (and other nominally anhydrous minerals) at higher
resolution than is possible using conventional instruments, coupling synchrotron IR radiation with FTIR spectroscopy. We then apply these methods to mylonitic quartzites in the footwall to the Moine Thrust in the NW Scotland and to mylonitic quartz-rich orthogneisses and paragneisses in the hanging wall to the Main Central Thrust in NW India. OH absorption bands are readily measured through an aperture of 10 μm for samples > 40 μm thick, sufficient to measure water contents in highly strained quartz grains (ribbons) and less deformed porphyroclasts and augen of the Moine Thrust mylonites. However, water contents of small individual recrystallized grains of the Moine Thrust mylonites could not be measured since spectra of doubly polished IR specimens < 25 mm thick display strong interference fringes. OH absorption bands can be measured for the larger grains of the Main Central Thrust mylonites, including original and recrystallized grains.

Images of intragranular water content in Moine Thrust and Main Central Thrust mylonites, based on contours of integrated absorbance of the broad OH band at 3400 cm⁻¹ correspond to populations of fluid inclusions, and to deformation and recrystallization microstructures. Planar arrays of secondary fluid inclusions within quartz grain interiors provide evidence of increases in water during brittle microcracking, followed by crack healing and processes of fluid inclusion evolution and redistribution. Contoured integrated absorbances of the sharper band at 3600 cm⁻¹ due to OH in micas show their spatial distributions at quartz grain boundaries and interiors.

2 Selected quartz mylonites

The quartz mylonites selected to test synchrotron FTIR spectroscopy and imaging of OH come from the footwall of the Moine Thrust at the Stack of Glencoul, NW Scotland (Christie, 1963; Law et al., 1986, 2010) and the hanging wall of the Main Central Thrust exposed in the Sutlej Valley, NW India (Law et al., 2013; Stahr,
Both of these thrust faults are orogen-scale shear zones with penetrative deformation on the Moine Thrust accommodating shortening at the foreland edge of the Caledonian orogeny (e.g., Peach et al., 1907; Elliot and Johnson, 1980; Law et al., 1986, 2010; Butler, 2010; Law, 2010; Law and Johnson, 2010; Dewey et al., 2015) and penetrative shear strains on the Main Central Thrust accommodating southward directed extrusion/exhumation of the overlying Greater Himalayan slab (e.g., Grujic et al., 1996; Grasemann et al., 1999; Godin et al., 2006; Law et al., 2013). Mylonitic grain shape foliations are well developed in rocks of both fault zones and mineral stretching lineations are parallel to the fault transport directions. Deformation microstructures and textures of quartz in these mylonites indicate that dislocation creep was the predominant deformation mechanism involving both basal and prism slip systems, internal recovery and dynamic recrystallization.

Structural distances of samples below the Moine Thrust and above the Main Central Thrust, together with available information on deformation temperatures and temperatures/pressures of metamorphism, are summarized in Table 1. All samples from the footwall to the Moine Thrust are mylonitic Cambrian quartzites. Samples from the hanging wall to the Main Central Thrust on the NW Sutlej transect are penetratively deformed orthogneisses in which intensities of grain shape fabrics, traced downwards towards the thrust surface, increase (associated with the transition from grain boundary migration to subgrain rotation recrystallization) and dynamically recrystallized grain sizes decrease (Law et al. 2013; their fig. 6). Samples from the more hinterland-positioned Eastern Sutlej transect are less obviously foliated paragneisses with more granular textures due to extreme quartz grain boundary mobility. At a given distance above the Main Central Thrust, samples from the more hinterland positioned Eastern Sutlej transect have much larger recrystallized grain sizes than on the NW Sutlej transect (compare figs. 15 and 6 in Law et al. 2013).
Mylonitic Cambrian quartzites in the footwall to the Moine Thrust at the Stack of Glencoul (Assynt region) display highly flattened relict grains aligned parallel to foliation, with grain shape aspect ratios up to 50:1 to 100:1 and smooth undulatory extinction between crossed polarizers that have been described as quartz ribbons (Bonney, 1883; Christie, 1960, 1963; Weathers et al., 1979; Law et al., 1986). At the margins of the larger quartz grains, more equant, finely recrystallized grains overprint these elongate high-strain grains, with the proportion of new to old grains increasing structurally upwards towards the Moine Thrust plane (Christie, 1960; Weathers et al., 1979; Law et al., 1986). Rare grains of feldspar and quartz aligned in “mechanically strong” orientations are relatively equant, and appear as augen or globular quartz grains. Quartz c-axes exhibit strong lattice preferred orientations in both deformed old grains and recrystallized grains, with symmetrical Type 1 (Lister, 1977) cross-girdle fabrics at distances > 150 nm beneath the thrust plane and increasingly asymmetric cross-girdle to single girdle fabrics closer to the thrust plane (Law et al., 1986, 2010). These fabrics reflect general flattening strains accommodated by quartz basal and prism slip, with variations in estimated flow vorticities and partitioning of strain between original and recrystallized grains (Law et al., 2010; Law 2010). Micas are highly aligned parallel to foliation, with coarse muscovite grains at quartz grain boundaries and fine, dispersed micas within quartz grain interiors. Optical microstructures show evidence of quartz recrystallization by bulge nucleation and subgrain rotation with relatively uniform mean recrystallized grain sizes of ~15 µm (Christie et al., 1954; Weathers et al., 1979). Microstructures imaged by transmission electron microscopy TEM show dense arrays of curved free dislocations, subgrain walls, and fine fluid inclusions that decorate dislocations (Weathers et al., 1979; Ord and Christie, 1984). Earlier FTIR measurements of Moine Thrust mylonites from a number of locations in the Assynt region revealed large OH absorption bands characteristic of milky quartz with OH contents of 1500 to 7500 ppm (Kronenberg and Wolf, 1990).
Quartz-rich Greater Himalayan Series orthogneisses and paragneisses in the hanging wall to the Main Central Thrust exposed in NW and Eastern Sutlej transects, respectively, include quartz mylonites, quartz-mica schists and quartz-garnet schists (Vannay and Grasemann, 1998; Grasemann et al., 1999; Law et al., 2013). Quartz grain shapes are not as highly elongate as observed in the Moine Thrust mylonites, owing to their extensive recrystallization, with mean grain sizes on the NW transect that vary with structural level from 200-250 μm (grain boundary migration microstructures) at ~1000 m above the Main Central Thrust to 75-95 μm at 200-750 m above the thrust, and 35-60 μm (dominantly subgrain rotation microstructures) at ~75 m above the thrust surface (Law et al., 2013). As noted above, quartz recrystallized grain sizes are much larger at a given structural height above the thrust plane on the hinterland-positioned Eastern transect with grain sizes commonly ranging from 250 - >1000 μm (0.25-1.0 mm) at ~ 25 m above the thrust to >1-2 mm at 200 m and higher above the thrust. Quartz grain interiors on the Eastern transect display mild undulatory extinction with highly aligned subgrain boundaries that give the appearance of chessboard extinction and irregular, non-planar grain boundaries that envelope neighboring mica grains, suggestive of high grain boundary mobilities at the time of peak metamorphism and deformation. Quartz c-axes show strong lattice preferred orientations with symmetrical and slightly asymmetrical cross-girdle fabrics on both transects, providing evidence of simultaneous basal and prism slip during plane strain deformation, with varying amounts of pure shear and simple shear (Law et al., 2013). Coarse-grained muscovite and biotite are highly aligned parallel to foliation, both at the boundaries of quartz grains and within quartz grain interiors.

While both the Moine Thrust and the Main Central Thrust mylonites were deformed by dislocation creep, their deformation temperatures were very different and the mechanisms of recrystallization, accommodating dislocation creep differ accordingly. Deformation temperatures for the Moine Thrust footwall mylonites at the Stack of Glencoul are estimated at between 300° and 350°C based on illite...
crystallinity (Johnson et al., 1985). Opening angles of c-axis fabrics measured separately on old and recrystallized grains (Law et al., 2010) indicate far higher apparent deformation temperatures using the Kruhl (1998) fabric opening angles thermometer (390°-440°C and 475°-530°C, respectively) than are compatible with their prehnite-pumpellyite to lower greenschist (chlorite) facies phyllosilicates (Law, 2014). Deformation temperatures for Main Central Thrust hanging wall mylonites range between ~535°-610°C on the NW Sutlej transect, using the Kruhl (1998) opening angle thermometer, and ~ 610° - >735°C based on fabric opening angles and petrologic constraints on the Eastern Sutlej transect (Table 1; Law et al., 2013; Stahr, 2013).

Dynamic quartz recrystallization microstructures in the Moine Thrust mylonites are similar to microstructures developed under experimental Regime II creep conditions as defined by Hirth and Tullis (1992), with a combination of bulge nucleation recrystallization (BLG) at grain boundaries and subgrain rotation recrystallization (SGR) within quartz grain interiors, and they are consistent with deformation under greenschist facies conditions (Stipp et al., 2002, 2010; Law, 2014). Quartz microstructures in the Main Central Thrust mylonites (particularly on the Eastern Sutlej transect and at large distances above the thrust on the NW transect) indicate more internal recovery and more extensive grain boundary migration (GBM) than is apparent in the Regime III creep experiments of Hirth and Tullis (1992). The microstructures are more similar to those observed by Stipp et al. (2002; 2010) in quartz veins deformed at natural strain rates and the equivalent of middle-upper amphibolite facies conditions (~550°-700°C; see review by Law, 2014).

The small recrystallized quartz grain sizes (16-9 μm), subgrain sizes, and dislocation densities of the Moine Thrust footwall mylonites at the Stack of Glencoul imply large differential stresses (40-250 MPa) during shearing (Weathers et al., 1979; Ord and Christie, 1984); differential stresses of ~ 55-85 MPa are recalculated using these grain sizes and the recrystallized grain size...
piezometer of Stipp et al. (2006) modified by the stress correction of Holyoke and Kronenberg (2010). In contrast, quartz recrystallized grain sizes for Main Central Thrust mylonites on the NW Sutlej transect of 60-35 µm at 75 m above the thrust to 95-75 µm at 750-200 m above the thrust indicate lower differential stresses of 19-30 MPa and 13-16 MPa, respectively, using the Stipp et al. (2006) grain size piezometer, adjusted by the same stress correction (Francsis, 2012; Law et al., 2013). Flow stresses inferred for the Eastern Sutlej transect mylonites would presumably be even lower than for mylonites of the NW Sutlej transect, but their grain sizes are far greater than those encompassed by any experimental grain size piezometer.

3 Methods

IR spectroscopy has been an important tool for studying OH defects in nominally anhydrous minerals and, in coordination with deformation experiments, to study the effects of water and hydrogen defects on mechanical properties (e.g., Kats, 1962; Griggs and Blacic, 1965; Kekulawala et al., 1978, 1981; Aines and Rossman, 1984; Cordier and Doukhan, 1991; Mackwell and Kohlstedt, 1991; Bai and Kohlstedt, 1996; Kohlstedt et al., 1996). With the introduction of efficient FTIR spectrometers and IR microscopes, studies of intragranular water and hydrogen defects in naturally deformed rocks have been enabled using apertures of 50-100 µm (Kronenberg and Wolf, 1990; Nakashima et al., 1995; Gleason and DeSisto, 2008; Finch et al., 2016; Kilian et al., 2016) as well as FTIR mapping of OH contents (Seaman et al., 2013). Molecular water contents of naturally deformed quartz commonly have large grain-to-grain variations at this scale of observation, and it has not been possible to measure OH contents of dynamically recrystallized grains smaller than ~75-130 µm, without including absorption bands of fluid inclusions, fluid films, secondary minerals, and hydrogen species at grain boundaries.
Synchrotron-generated IR radiation is much brighter (~1000x) than conventional globar sources of commercial FTIR instruments, and high quality IR spectra can readily be measured through small (10 \( \mu \)m) apertures (Lobo et al., 1999; Carr et al., 2008; Ma et al., 2013). By coupling synchrotron radiation to an FTIR instrument and IR microscope, OH absorption bands can be measured through a 10 \( \mu \)m aperture with higher signal-to-noise ratio than through a 100 \( \mu \)m aperture using a standard FTIR. We describe methods of preparing thin unsupported doubly polished IR samples and we compare IR spectra of quartz grains of deformed mylonites collected by FTIR spectroscopy using conventional and synchrotron IR sources. We also describe methods of scanning samples using a 10 \( \mu \)m IR beam, integrating absorbance of selected OH bands (due to fluid inclusions in quartz grains and micas at quartz grain margins and interiors) to form high-resolution images of OH in deformed and recrystallized mylonites. The ability to measure OH bands in finely recrystallized grains is not limited by aperture size or spectral quality for very thin (4-8 \( \mu \)m) samples. Rather, measurements for very thin IR plates are limited by internal reflections that give rise to interference fringes of increasing magnitude with decreasing sample thickness. In practice, measurements of the small OH bands of nominally anhydrous minerals are not possible for IR plate thicknesses of < 25 \( \mu \)m.

### 3.1 Preparation of IR plates

Doubly polished IR plates of uniform thickness were prepared perpendicular to foliation and parallel to lineation for Moine Thrust and Main Central Thrust mylonites. Images of large IR plates were collected using a high resolution (4000 dpi) Nikon slide scanner (Coolscan 8000 ED), with and without polarizing filters on both sides of the sample. Images of smaller IR plates were recorded with a Zeiss Axioplan 2 petrographic microscope and AxioCam HRc imaging system (Fig. 1). Image contrast was enhanced digitally (using Adobe Photoshop) for
crossed-polarized light images of ultrathin samples with small optical retardations. Throughout the preparation of IR plates, impregnation of samples by epoxy or other insoluble resins was avoided to prevent the introduction of OH or CH absorption bands of mounting media, which might be difficult to distinguish from OH bands of samples. While central regions of the IR plates remain fragile, metal frames were mounted to IR plate extremities for mechanical support, to avoid catastrophic loss and facilitate handling.

Oriented rock chips were first mounted on a glass thin section plate using CrystalBond 509 (supplied by Aremco, NY) and a low-temperature hot plate. The top surfaces of samples were ground by hand against large glass plates using a sequence of silicon carbide (400 mesh size) and alumina powder slurries of decreasing particle size (600 mesh and 9.5 µm). Grinding with each grit size was carried out until the thickness of the sample, measured by a micrometer, was reduced by three times the grit dimension of the previous step (e.g., 3 µm grit was used to remove 3 x 9.5 µm = 29 µm). Samples were cleaned ultrasonically before advancing to the next grit size. Ground surfaces were then polished using polishing cloths (Buehler Texmet and Microcloth) mounted on high-speed laps and a sequence of alumina powder slurries with particle sizes of 3 and 0.3 µm, using the same measurement technique and testing the finish at each step by visual inspection.

Polished specimens were removed from the glass plate and remounted, this time on their polished surfaces, applying gentle pressure to sample centers to promote uniform thickness of the CrystalBond mounting medium (~20 µm). Sample plates were cut parallel to the first surface, and the second (cut) surface was ground and polished by the same methods outlined above. For the second surface, a micrometer was used to measure the compound thickness of sample, glass plate, and mounting medium, checking thickness at sample extremities, to adjust the grinding procedure for thickness uniformity. Sample thicknesses were determined from the compound sample-glass plate thickness, the glass plate
thickness measured prior to mounting, and estimated CrystalBond layer thickness. In addition to micrometer measurements, sample thicknesses were tested during grinding, using interference colors for thicker samples (first order colors for quartz plates 50-90 µm thick) and maximum detectable birefringence (grey-white scale) while polishing ultrathin (< 20 µm) samples.

Before removing doubly polished samples from the glass thin section plate, metal frames were mounted to sample extremities using a thin bead of epoxy resin to provide support. For larger (> 10 mm) samples with thicknesses of 25 - 100 µm, metal frames made of Ni wire (1.15 mm diameter) were custom fit to each sample. For thin samples (< 25 µm), several metal frames normally used to mount TEM samples (3 mm outer diameter copper rings or slot rings with 1 x 2 mm internal dimensions; supplied by Ted Pella, Inc.) were mounted on each polished sample. Once the metal frames were attached and the epoxy hardened, samples were removed from the glass thin section over a low-temperature hot plate, and the CrystalBond resin removed using acetone.

Once quartz IR plates, 4 to 150 µm thick, are removed from the glass thin section plate, they are very fragile, and we found that they did not tolerate ultrasonic agitation. As a result, we soaked samples in acetone baths several times, dissolving CrystalBond resin for 30 minutes for each bath, exchanging the acetone in the beaker and repeating this procedure three times. Even without agitation, some samples did not survive when air bubbles were caught beneath them, leading to specimen warping and disintegration. However, with sufficient care, loss rates were low, and doubly polished IR plates were prepared without impregnating resins with thicknesses of 150 µm to 4 - 8 µm.

3.2 FTIR spectroscopy

IR absorption spectra were collected for quartz mylonites of varying plate thickness using a Nicolet Magna 560 FTIR with Omnic software, a conventional
globar source and NicPlan IR microscope (at Texas A&M University), and using a 
Bruker Hyperion FTIR spectrometer, OPUS software, and IR microscope at the 
U2A synchrotron beamline of the National Synchrotron Light Source NSLS I (at 
Brookhaven National Laboratory). Both the Nicolet and Bruker instruments make 
use of liquid nitrogen-cooled MCT detectors capable of absorbance measurements 
at wavenumbers of 7400 to 400 cm$^{-1}$, but we did not routinely store data beyond 
4000 to 2000 cm$^{-1}$. We chose to collect spectra at a wavenumber resolution of 4 
cm$^{-1}$ on both instruments, compiling 512 scans for each spectrum, adjusting to 
larger numbers of scans with the Nicolet FTIR when needed to reduce noise in the 
spectrum. For purposes of comparison, all absorbances shown in spectra for 
quartz grains of varying thickness have been normalized to a common thickness of 
1 mm.

Representative IR spectra of individual quartz grains from Moine Thrust 
and Main Central Thrust samples measured with the Nicolet FTIR (100 µm 
aperture) exhibit OH absorption bands of variable size and character (Fig. 2). 
Moine Thrust quartz spectra show a broad OH stretching band at 3400 cm$^{-1}$ of 
large but variable magnitude (Fig. 2a), characteristic of molecular water in fluid 
inclusions of milky quartz (Kekulawala et al., 1978; Aines and Rossman, 1984; 
Stünitz et al., in press). In addition to this absorption band, some quartz grains 
from Moine Thrust samples show an additional absorption band (or subtle 
shoulder) at ~3600 cm$^{-1}$ (Fig. 2b) due to fine scale micas (sometimes visible 
optically and sometimes too fine to resolve) dispersed within quartz grains. Main 
Central Thrust quartz spectra tend to have smaller OH absorption bands (Fig. 2c), 
with some grains showing small sharp bands at 3595, 3482, 3431, 3408, and 3379 
cm$^{-1}$ due to hydrogen interstitial defects (Kats, 1962; Aines and Rossman, 1984) 
and less common grains with a larger broad band at 3400 cm$^{-1}$. Finely dispersed 
micas are less common in these coarser-grained mylonites, but some quartz grains 
also exhibit a 3600 cm$^{-1}$ OH band due to micas (Fig. 2d).
Aside from differences in the Nicolet and Bruker FTIR instruments and software, the most significant difference between these facilities is the IR source, so that OH absorption measurements with the Nicolet FTIR and its conventional IR source could not practically be made with apertures < 50-100 µm, while OH absorption bands could routinely be made with the Bruker FTIR and synchrotron IR source through a 10 µm aperture. In both cases, the IR sources are nearly isotropic, leading to differences in those OH absorption bands that are dichroic in quartz and mica grains of varying orientation. Small sharp OH bands due to hydrogen interstitials of quartz between 3595 cm\(^{-1}\) and 3379 cm\(^{-1}\) absorb most strongly for vibrational directions perpendicular to the quartz c axis (Kats, 1962), and these bands vary according to the c-axis orientation of each quartz grain relative to the unpolarized IR beam. OH absorption bands at ~3600 cm\(^{-1}\) of micas are strongly dichroic (Beran, 2002), and they vary according to mica grain orientations relative to the unpolarized IR beam. However, the primary OH band of interest for water-weakening of milky quartz, at 3400 cm\(^{-1}\), is broad and isotropic (Kekulawala et al., 1978; Aines et al., 1984), and associated with finely dispersed fluid inclusions. Variations in absorbance of this band for neighboring quartz grains represent real variations in water content and not variations in quartz grain orientation.

IR microscope stages are not purged as effectively as sample chambers of FTIR spectrometers that are evacuated or operate at positive nitrogen pressures, and some of our spectra show evidence of atmospheric contamination. We attempted to minimize absorption bands due to H\(_2\)O vapor and CO\(_2\) by making spectral measurements of samples and the background (without the sample in the IR beam) at similar times after the last sample change or disturbance at the microscope stage. However, atmospheric absorptions were not always cancelled completely, with the appearance of “noise” between 3940 and 3420 cm\(^{-1}\) due H\(_2\)O vapor vibrations (Fig. 2a, Grain 26; Fig. 2b, Grains 11B and 39) and absorptions at 2337 and 2361 cm\(^{-1}\) due CO\(_2\), which were either under- or over-corrected by
subtracting the measured background (Fig. 2a, Grain 26 and Fig. 2b, Grains 11B and 39, and Fig. 2d, Grain 4 show examples of CO₂ band under-correction; Fig. 2c, all grains show negative deflections at 2337 and 2361 cm⁻¹ due to over-correction of CO₂ absorptions).

Direct comparisons of intragranular water of a given quartz grain using the two FTIR facilities and a common aperture size could not be made because of 1) the poor signal-to-noise ratio of spectral measurements through a 10 µm aperture with the broad globar IR radiation, and 2) the inability to make spectral measurements for a 100 µm-apertured area with the narrow synchrotron IR beam (which is not much broader at the microscope stage than the 10 µm aperture).

Samples with uniform OH contents might serve as standards to compare OH absorption bands for different spectrometers, irrespective of aperture size, but our observations indicate that OH contents of the quartz grains in the mylonites we measured are highly variable. Measurements through finer apertures led to larger variances in OH absorption bands, within grains as well as between neighboring grains.

We also observed larger amplitude interference fringes in spectra measured with the synchrotron IR source than those observed in spectra measured with the globar IR source for a given sample. These fringes are caused by internal reflection within doubly polished, parallel-sided IR plates, and they have larger magnitudes for the highly collimated IR synchrotron beam than for the broad, confocal globar IR radiation.

### 3.3 Interference fringes

The appearance of interference fringes in spectra can be useful to determine the optical path length in thin samples, as long as their amplitude is small compared with vibrational absorption bands of interest, or they are distinguishable from absorption bands by their wavenumber spacing. Interference fringes are present in
many spectra we collected for quartz mylonite plates (Fig. 2c, Grains 1 and 8), that are of manageable size for our thicker samples and problematic for thinner samples.

Interference fringes were routinely observed for all samples measured with synchrotron IR radiation and the Bruker FTIR instrument. We therefore made use of these fringes to determine local sample plate thicknesses. For sample plates with large interference fringes, we attempted to reduce their size by tilting samples by 45° in the IR beam or using a Cassegrain objective lens with large numerical apertures (0.6). However, neither of these methods was effective in reducing amplitudes of some of the very large interference fringes sufficiently to detect small OH absorption bands. We had greater success reducing interference fringes by fitting them where the baseline was free of absorption bands, using DatLab software (similar to fringe modeling of Clark and Moffatt, 1978; Pistorius and DeGrip, 2004; Konevskikh et al., 2015), and subtracting the model fringes from the spectral data. This improved the quality of spectra when interference fringes had modest amplitudes, but interference fringes for thin samples were very large and resulting backgrounds sufficiently irregular that we could not resolve small OH absorption bands.

3.4 IR plate thickness and OH absorbance determinations

IR plate thicknesses were determined by focusing on imperfections in the top and bottom specimen surfaces, and recording the numerical graduation on the focusing knob of the Nicolet FTIR microscope for each surface. The focusing knob graduations were calibrated for vertical translation using the same procedure for a thick (~3 mm) quartz specimen that had been measured with a micrometer. Local IR plate thicknesses were also determined from interference fringes measured in spectra collected with the synchrotron-Bruker FTIR microscope system, where thickness $t$ is given by
\[ t = \frac{1}{(2n\delta\nu)} \]  \hspace{1cm} (1)

where \( n \) is the mean refractive index of quartz (\( n = 1.55 \)) and \( \delta\nu \) is the measured peak-to-peak fringe spacing (Stuart et al., 1996; Griffiths and de Haseth, 2007). The two measures of thickness were in agreement within resolution (~ 5%) for a given IR plate and location within the specimen, with thick IR specimens (~100 \( \mu m \)) showing real variations in local thickness of ± 10 \( \mu m \) and thin samples varying in local thickness from 4 to 8 \( \mu m \).

IR spectra were collected and integrated absorbances of OH bands were measured above an assumed straight-line background, where backgrounds were fit and integration limits were chosen at the same wavenumber values, from ~3705 cm\(^{-1}\) to 2880 cm\(^{-1}\) for OH bands of quartz grains and ~3702 cm\(^{-1}\) to 3544 cm\(^{-1}\) for OH bands of micas (Fig. 3a). We have confidence in our ability to separate OH absorption bands due to fluid inclusions in quartz and due to micas in Moine Thrust samples, because IR spectra of coarse muscovite grains in Moine Thrust mylonites consist of a single OH absorption band at 3620 cm\(^{-1}\) (Fig. 3b). This strong OH stretching band is well known from multiple spectroscopic studies of muscovite (Beran, 2002; Tokiwa and Nakashima, 2010a,b; Kallai and Lapides, 2015).

Our ability to distinguish OH absorbance due to fluid inclusions and micas in Main Central Thrust samples, by contrast, is poor. In addition to the primary OH absorption bands of muscovite (Fig. 3c) and biotite (Fig. 3d) grains at 3638 cm\(^{-1}\) and 3614 cm\(^{-1}\), respectively, Main Central Thrust muscovite spectra show smaller OH bands at 3815, 3311, 3146, and 3035 cm\(^{-1}\) and biotite spectra show shoulders at both sides of the primary OH absorption band (at ~3679 cm\(^{-1}\) and ~3561 cm\(^{-1}\)) and significant OH bands at 3258, 3043, and 2829 cm\(^{-1}\). All of these OH bands are anisotropic, and complexly so. OH band absorbances of micas will therefore vary with crystallographic orientation within an unpolarized IR beam.
The primary OH band of Main Central Thrust muscovite at 3638 cm\(^{-1}\), measured in polarized IR radiation, is strongest when the vibration direction E is parallel to the basal plane (001), consistent with idealized hydrogen positions in dioctahedral micas and the polarization of OH bands normally reported for muscovite (Beran, 2002). However, our polarized IR measurements of muscovite OH bands at 3311, 3146, and 3035 cm\(^{-1}\) indicate that they are more nearly isotropic. The primary OH band of Main Central Thrust biotite grains at 3614 cm\(^{-1}\) is strongest when E is perpendicular to (001), consistent with hydrogen positions of trioctahedral micas and OH band polarizations observed for phlogopite (Beran, 2002). However, the OH bands at 3258, 3043, and 2829 cm\(^{-1}\) are only weakly polarized and in the opposite sense of the primary 3614 cm\(^{-1}\) band.

As a result, we only feel confident in our determinations of OH absorbances of quartz grains in Main Central Thrust mylonites (Fig. 2c), when mica inclusions are absent (3600 cm\(^{-1}\) band is undetectable). When the 3600 cm\(^{-1}\) band is present (Fig. 2d), we cannot readily interpret absorption bands of molecular water or hydrogen defects in quartz; at best, quartz OH contents are overestimated.

Integrated absorbances of OH bands of quartz were used to determine OH contents based on the Beer-Lambert relation (Stuart et al., 1996; Griffiths and Haseth, 2007),

\[
A = k \cdot c \cdot t
\]

where integrated absorbance \(\Delta = A/t\), determined in cm\(^{-2}\), is related to the concentration \(c\) of OH, assuming that \(k\) for the broad isotropic OH band at 3400 cm\(^{-1}\) due to fluid inclusions in milky quartz is the same as for the broad isotropic OH absorption band of molecular water in wet synthetic quartz (Aines et al., 1984);
To the extent that spectra include sharp OH absorption bands due to hydrogen point defects, this calibration will overestimate OH concentrations due to H interstitials, given that the value of k for these bands is larger than for molecular water (Kats, 1962; Thomas et al., 2009) for quartz grains oriented for maximum OH absorbance (vibrational directions perpendicular to the c axis). However, apparent OH concentrations due to H interstitials will appear smaller for quartz grains oriented for minimum OH absorbance in unpolarized IR radiation. These errors are not serious for quartz grains with large molecular water contents that dominate over hydrogen point defect concentrations. However, we expect that our determinations of OH concentrations for dry quartz grains (< 100 ppm) with spectra dominated by sharp dichroic OH bands are not as accurate as for wet quartz grains with spectra dominated by isotropic broad OH bands. We also acknowledge that the calibration for molecular water absorption of synthetic quartz used here differs from the calibration of the 3400 cm\(^{-1}\) OH band absorbance reported by Stipp et al. (2006) for milky quartz grains with fluid inclusions. If this alternative calibration is correct, OH contents reported here are smaller by a factor of 0.56. The calibration of Stipp et al. (2006) is based on FTIR measurements of individual grains of a pure quartzite and independent Karl Fischer titration of disaggregated quartz particles, and we do not understand the source of discrepancies in absorbance calibrations.

Integrated absorbances \(\Delta (A/t \text{ in } \text{cm}^{-2})\) were also measured for the 3600 cm\(^{-1}\) OH band of micas but no attempt was made to convert these to OH concentrations. Muscovite grains of Moine Thrust samples show simple OH absorption spectra with one prominent band at \(~3600\text{ cm}^{-1}\) (Fig. 3b), but integrated absorbances for this band cannot be converted to muscovite (or OH) content without polarized IR spectral measurements and detailed knowledge of muscovite grain orientations. Integrated absorbances of OH bands of muscovite and biotite
grains in Main Central Thrust samples at wavenumbers of 3800 cm\(^{-1}\) to 2830 cm\(^{-1}\) are more complicated to interpret. In addition to the need for polarized IR measurements and grain orientation information, integrated OH absorbances due to unseen (below optical resolution) mica inclusions will depend on whether the micas consist of muscovite or biotite, or both.

### 3.5 Mapping OH absorption bands

Integrated areas of OH were measured as a function of spatial x and y dimensions within IR plates measured on the Bruker FTIR system, separating absorbances of OH bands due to fluid and mica inclusions to the extent that this was possible. Samples were translated under the 10 µm IR beam using a motorized x-y stage, controlled by OPUS software, and spectra were collected for each translation step, usually moving the stage by 10 µm. In those cases where we mapped coarse-grained samples over large regions (up to ~4.5 mm\(^2\)), we increased the step spacing to 30 or 50 µm, in order to limit total step-scan measurement times and the number of required steps (our software version could not compile > 99 steps in a single row of measurements). Integrated absorbance measurements were made over 3705 - 2880 cm\(^{-1}\) (to include the 3400 cm\(^{-1}\) broad band of milky quartz) and 3702 - 3544 cm\(^{-1}\) (to determine the 3600 cm\(^{-1}\) mica band) for each scanned area (compiling absorbance measurements for 660 to 4950 spectra). The integrated absorbances of the 3600 cm\(^{-1}\) mica band were subtracted from the first of the two integrated absorbances, saving the result as a representative measure of the OH bands of molecular water and hydrogen defects of quartz.

Given that the same IR background was used to reference all spectral measurements made during x-y mapping of OH bands, long step-scan mapping projects were susceptible to changes in aperture and condenser lens centering, IR beam drift and beam outages while the synchrotron ring was refilled. As a result, we modified our IR absorbance measurement methods for step-scan mapping to
obtain reasonably accurate integrated absorbances of broad OH bands without requiring high resolution or precision measurements of small, sharp OH bands, with the goal of limiting total measurement times.

IR spectra used to map OH bands were made at a wavenumber resolution of 8 cm\(^{-1}\), reducing the interferometer mirror translation times with no detectable degradation in integrated absorbance measurements. More significantly, we reduced the number of scans to measure each IR spectrum from 512 to just 16, resulting in measurement times for each spectrum of only ~10 s, including the time for stage translation. This number of scans was chosen on the basis of tests for a given quartz grain of Moine Thrust sample SG-10 with an absorbance of 36 cm\(^{-1}\) measured over 3705 - 2880 cm\(^{-1}\) (or \(\Delta = 3000\) cm\(^{-1}\) for a sample thickness \(t\) of 120 \(\mu m\)), determining integrated absorbances for spectra compiled for 512, 256, 128, 64, 32, 16, and 8 scans. Integrated absorbances of the broad 3400 cm\(^{-1}\) band varied by less than 4% for measurements made with 512 - 32 scans, while the absorbance measurements for 16 and 8 scans were within 8% and 12%, respectively, of the mean of the other determinations. OH maps were thereby constructed for sample areas of 0.066 mm\(^2\) (22 x 30 = 660 spectra) to nearly 4.5 mm\(^2\) (50 x 99 = 4950 spectra) requiring measurement times of 110 minutes to nearly 14 hours, respectively. The larger step-scan maps include some poor spectral data corresponding to beam drift or interruption of radiation; these spectra were identified and removed from the data set.

Maps of integrated OH absorbance were contoured (using SigmaPlot) to form images of water contents and micas, and superposed on optical micrographs of the measured regions, to look for correlations between OH content and microstructure. OH contents of quartz, due primarily to the broad 3400 cm\(^{-1}\) OH band of fluid inclusions and secondarily to sharp hydrogen defect bands, were mapped as molar ppm (OH/10\(^6\)Si), while the OH absorption band at ~3600 cm\(^{-1}\) due to micas was mapped in units of integrated absorbance (cm\(^{-2}\)). Logarithmic contour intervals of \(\log_{10}(\text{OH}/10^6\text{Si})\) were chosen to image water contents in quartz.
over a wide range of concentrations, and to provide visual images of water
distributions at low (and high) values. OH contents were contoured in color with
blue (and other cool colors) corresponding to large water contents, and red (and
other warm colors) corresponding to low water contents. Logarithmic contours
were also chosen to image distributions of micas, plotting $\log_{10}(\Delta$ in cm$^{-2}$) for the
integrated absorbance of the ~3600 cm$^{-1}$ OH band, using a similar key for the
contour interval, where cool colors correspond qualitatively to high mica contents
and warm colors correspond to low mica contents.

4 Results

Synchrotron radiation coupled with the FTIR spectrometer and microscope at the
NSLS I has enabled spectral measurements for sampling volumes that are smaller
by a factor of 100 than is possible with a conventional FTIR microscope system.
OH band measurements for quartz through a 10 $\mu$m aperture are comparable to
OH band measurements made using a conventional FTIR spectrometer-
microscope system through a 100 $\mu$m aperture. The ability to measure OH bands
of individual recrystallized quartz grains is currently limited by IR plate thickness,
not because of signal-to-noise problems, but because of internal reflections in
ultrathin IR plates. Water contents of quartz grains, and OH contents associated
with micas and other hydrous phases, can be measured spatially by translating
samples under the 10 $\mu$m-apertured beam and contouring integrated OH
absorbance over chosen wavenumber intervals. High-resolution images, formed
in this way, can be compared with optical deformation microstructures, providing
a means of studying the role of water in deformation and changes in water content
during deformation and recrystallization.

4.1 Synchrotron FTIR Measurements
IR spectra of quartz in Moine Thrust and Main Central Thrust samples measured with the synchrotron-FTIR system through a 10 µm aperture exhibit OH absorption bands of similar character at the same wavenumbers as measured for samples of the same thickness (~100 µm) using a conventional FTIR spectrometer-microscope system through a 100 µm aperture. OH bands of Moine Thrust quartz grains generally include a large broad absorption band at 3400 cm\(^{-1}\) due to dispersed fluid inclusions, with some grains showing a secondary absorption band at 3600 cm\(^{-1}\) due to mica inclusions (Fig. 4a), just as those measured for larger sampling volumes (Fig. 2a, b). Given the more intense IR radiation of the synchrotron source, we did not encounter any losses in spectral quality due to signal-to-noise ratios for the smaller sample volumes measured. However, interference fringes were more apparent using the synchrotron-FTIR microscope system associated with internal reflections from the parallel-sided IR plates and the lower divergence of the synchrotron beam. Synchrotron FTIR measurements of Main Central Thrust samples through a 10 µm aperture show the same sharp OH bands due to hydrogen point defects as measured through a 100 µm aperture. With the exception of some unusual grains, broad OH bands at 3400 cm\(^{-1}\) in Main Central Thrust samples are small to negligible.

Integrated absorbances of the broad 3400 cm\(^{-1}\) OH band measured with a 10 µm aperture are highly variable spatially, yielding water contents for individual spots within quartz grains for a given Moine Thrust sample (SG-10) of 280 to 9000 ppm, with a comparable mean (2430 ppm) but more variance among individual measurements than measured with a 100 µm aperture (from 1130 to 8590 ppm for 45 measurements). For dry Main Central Thrust samples (S09-71B), OH contents of quartz measured using a small (10 µm) aperture varied from 50 to 300 ppm while OH contents measured with the larger (100 µm) aperture varied from 85 to 240 ppm. For unusually wet Main Central Thrust samples (S09-35), OH contents of quartz measured using a small (10 µm) aperture varied from 150 to 7500 ppm while OH contents measured with the larger (100 µm) aperture varied from.
varied from 160 to 4620 ppm. The variations in size of sharp OH bands associated with hydrogen point defects, by comparison, are much smaller. The sizes of these dichroic absorption bands may be explained by differing quartz grain orientations without calling upon any variations in hydrogen point defect concentrations (Thomas et al., 2009).

4.2 Limits of IR plate thickness

IR spectra of quartz were measured through a 10 μm aperture, varying sample plate thickness from ~100 μm to 4-8 μm, with the hope that we might be able to measure the OH bands of individual recrystallized grains in ultrathin IR plates. Owing to the coarse recrystallized grain sizes of Main Central Thrust mylonites, we were able to measure IR spectra of most quartz grains in these samples for plate thicknesses of >50 μm. However, our IR measurements of individual grains in Moine Thrust samples (with recrystallized grains of ~10-15 μm) are limited to larger porphyroclastic and deformed ribbon quartz grains. While the signal-to-noise ratio of our measurements continue to be acceptable to measure the small OH absorption bands in very thin IR plates, interference fringes increase in size as the IR plate thickness $t$ is decreased. Interference fringes become very large at $t < 25$ μm and OH bands cannot be detected at $t = 13$ μm and 6.5 μm (Fig. 4b, c).

The magnitude of interference fringes can be modified by tilting the sample within the IR beam and increasing the numerical aperture of the Cassegrain objective on the IR microscope. However, with peak-to-trough fringe magnitudes $10^4$ greater than the OH bands in our mylonite samples, the modest reductions in fringe amplitude realized by these methods are not significant for the measurement of OH absorptions. Our efforts to model interference fringes were largely successful, reducing their magnitudes by a factor of ~100, but the resulting backgrounds were not flat enough at the scale of the known OH absorption bands of the Moine Thrust (or Main Central Thrust) samples to allow absorption band
measurements for our thinnest sample plates. Interference fringes vary in magnitude according to IR plate thickness, surface polish, and scattering by internal flaws, but OH absorption bands could only be measured for samples of ~40 µm thickness or greater.

4.3 Optical microstructures and plate thickness

Although the painstaking efforts to prepare ultrathin IR plates were not rewarded by spectral measurements of OH content within individual, finely recrystallized grains, optical imaging of deformation and recrystallization microstructures in ultrathin samples was improved over that using conventional thin sections. Optical microstructures of 100 µm-thick IR plates are poorly resolved by comparison with those imaged in 30 µm-thick sections (Fig. 1c, d), with interference colors that reflect greater optical retardation, grain boundaries that are not as clearly defined, and greater numbers of overlapping grains. Remarkably, ultrathin IR plates of quartz mylonites, just 4-8 µm thick (Fig. 1f), continue to exhibit contrast between grains and within grains, with first-order black to grey birefringence that can be enhanced by increasing image contrast.

High magnification optical micrographs of ultrathin Moine Thrust mylonites reveal microstructures (Fig. 5) that correspond better to TEM observations (Weathers et al., 1979; Ord and Christie, 1984) than to optical microstructures of conventional thin sections. While highly flattened ribbon quartz grains observed in 30 µm sections show smoothly varying undulatory extinction, ultrathin sections exhibit well developed subgrains within grain interiors, with sharply defined changes in extinction marking the locations of distinct subgrain walls (Fig. 5a). Prior TEM of Moine Thrust mylonites revealed significant densities of free dislocations that have been associated with smooth changes in extinction. However, TEM observations also show dense, sharply defined subgrain walls (Weathers et al., 1979; Ord and Christie, 1984) that are
often not resolved as optical microstructures of normal thin sections. These observations suggest that ultrathin sections may be useful to distinguish smooth changes in extinction (due to free dislocations and strains internal to subgrains) from discrete changes in extinction of overlapping and neighboring subgrains. Recrystallized grains are apparent at some sutured grain boundaries in Moine Thrust samples (Fig. 5a) with grain sizes that are significantly smaller than the dimensions of subgrains within the ribbon quartz grains. Microstructures of these new grains suggest that they form by grain boundary bulge mechanisms. Newly recrystallized grains surrounding other grains (Fig. 5b) have sizes in common with nearby subgrains, and microstructures suggest that these recrystallized grains develop by subgrain rotation. While prior optical examination of Moine Thrust mylonites using 30 µm thin sections has led to the conclusion that both BLG and SGR recrystallization were important during deformation (Law, 2014), quantitative evaluations of these processes and their contributions to dislocation creep could be improved by the higher microstructural resolution offered by ultrathin sections.

4.4 High-resolution imagining of OH

By translating IR plates under the 10 µm apertured IR beam and measuring spectra over many steps (spaced by 10 to 50 µm) we were able to compile integrated absorbances over spatial areas of up to 4.455 mm² (50 x 99 = 4950 spectra, step size = 30 µm). Integrated absorbances of OH bands were determined for the collection of spectra, choosing limits of 3705 cm⁻¹ to 2880 cm⁻¹ to include the broad OH band at 3400 cm⁻¹ and sharp OH bands between 3595 cm⁻¹ and 3379 cm⁻¹ due to fluid inclusions and hydrogen defects, respectively, within quartz grains. Integrated absorbances of the 3600 cm⁻¹ OH band of micas were determined between 3702 cm⁻¹ to 3544 cm⁻¹, and this value, ΔOH_musc was subtracted from the
first integrated absorbance (as illustrated in Fig. 3a) to represent the best measure of absorbance $\Delta \text{OH}_{\text{qtz}}$ of water and hydrogen defects of quartz grains.

These values were plotted spatially for Moine Thrust and Main Central Thrust samples, and contoured on common logarithm scales, to form high-resolution images (Figs. 6 - 9) of OH absorbance of quartz (converting to molar ppm, OH/10^6 Si) and OH absorbance of micas ($\Delta \text{OH}_{\text{musc}}$ in cm$^{-1}$). In all cases, we superposed the contoured OH maps on optical micrographs to make sense of OH distributions in terms of fluid inclusions, defects, and micas, and their relationships to deformation and recrystallization microstructures. Images of the 3600 cm$^{-1}$ mica OH absorbance were placed over plane light micrographs that highlight scattering (and sometimes color) due to micas, grain boundaries, and fluid inclusions, while images of OH absorbance due to fluid inclusions (principally the broad 3400 cm$^{-1}$ band at large integrated absorbances) and lesser hydrogen defects of quartz were placed over cross-polarized light micrographs that emphasize undulatory extinction, deformation microstructures and recrystallization of quartz grains.

FTIR maps of OH of quartz grains show that water contents of deformed mylonites (Figs 6 - 8) are extremely heterogeneous when absorbance is dominated by the 3400 cm$^{-1}$ band, with water contents that vary from 300 ppm to >10,000 ppm between neighboring grains and within grain interiors. This result helps explain the wide variations in water contents measured by conventional FTIR spectroscopy through a 100 µm aperture. OH contents of quartz grains of relatively dry mylonites (Fig. 9) are more nearly constant (50 - 150 ppm) when IR spectra are dominated by sharp OH bands of hydrogen point defects. FTIR maps of mylonite samples, constructed for the 3600 cm$^{-1}$ OH absorbance, show that micas are heterogeneously distributed, with concentrations apparent at quartz grain boundaries in optical micrographs (Figs. 6 - 9) and finely dispersed micas within quartz grain interiors (Figs. 7, 8), some of which can be difficult to detect.
optically. We show these relationships in several contoured OH maps, focusing on different types of quartz grains and deformation microstructures.

While most quartz grains in Moine Thrust mylonites are highly deformed, some quartz grains remained nearly equant (globular grains or quartz augen with $c$-axes aligned perpendicular to foliation; Law et al., 1986), despite their high original OH contents in the form of fluid inclusions (Fig. 6). The lack of 3600 cm$^{-1}$ OH absorbances within globular quartz grains indicate that finely dispersed micas in original relict quartz grains are absent, while large 3600 cm$^{-1}$ OH absorbances at quartz grain extremities indicate that micas are localized at quartz grain boundaries (Fig. 6a, b). Broad band OH contents of quartz of >1000 ppm, thought to be sufficient for water weakening, are present in undeformed and deformed ribbon quartz grains (Fig. 6c, d) with very large water contents (>10,000 ppm) marking a healed crack in the quartz augen, made up of a planar array of fluid inclusions. OH contents due to fluid inclusions are also very large at the globular augen quartz boundaries, coincident with high mica concentrations, and in some ribbon and recrystallized quartz grains. With a sample plate thickness of 56 µm, these maps represent OH absorbances within the interiors of larger quartz grains, while OH absorbances of fine micas and recrystallized quartz represent composite spectra of polycrystalline fault rock. However, we are confident that the quartz OH contents reflect fluid inclusions, even in these fine-grained regions, because of the simple spectral quality of muscovite (Fig. 3) in the Moine Thrust samples and our ability to distinguish between the 3400 cm$^{-1}$ and 3600 cm$^{-1}$ OH absorbances.

High-strain ribbon quartz grains in the Moine Thrust samples have large OH contents (>1000 ppm) comparable to those of water-weakened synthetic and milky quartz (samples SG-10 and SG-8, Figs. 7 and 8, respectively), with some reductions in OH at recrystallized margins of original grains. Micas, as imaged by the 3600 cm$^{-1}$ OH absorbance (Fig. 7a, b), continue to be highly localized at the grain boundaries of deformed quartz grains, with a mixture of fine-grained mica...
and quartz grains providing evidence for some redistribution during recrystallization (Fig. 8a, b). The broad 3400 cm\(^{-1}\) OH absorbance in marginal recrystallized regions surrounding ribbon quartz grains are locally smaller than those of the original deformed quartz grains in some regions (Fig. 7c, d) while broad OH absorbances of recrystallized quartz continue to be large where mica contents (as evidenced by the 3600 cm\(^{-1}\) band absorbance) are large (Fig. 8c, d).

FTIR maps of coarse-grained Main Central Thrust mylonites yield spectral measurements of individual grains of quartz, muscovite and biotite, even for relatively thick IR plates and larger step sizes (Fig. 9). Small, sharp absorption bands of quartz grains yield OH contents of ~100 ppm, with only local regions of quartz with larger OH contents near contacts with coarse-grained muscovite and biotite grains. Quartz grain interiors generally lack the absorbance band at 3600 cm\(^{-1}\); thus, there is no evidence for finely dispersed micas within these coarse-grained deformed (and recrystallized) quartz grains. Contours of integrated OH absorptions at 3400 cm\(^{-1}\) are considerably larger for coarse-grained micas and near their contacts with quartz grains. However, these bands cannot be attributed to fluid inclusions where they coincide with large 3600 cm\(^{-1}\) mica bands, given that muscovite and biotite grains in the Main Central Thrust samples exhibit complex secondary OH bands between 3311 and 2829 cm\(^{-1}\).

5 Discussion

Our IR spectra collected from quartz-rich mylonites in the footwall to the Moine Thrust (Scottish Caledonides) and the hanging wall to the Main Central Thrust (Himalaya of NW India) using synchrotron IR radiation through a 10 \(\mu\)m aperture are comparable to IR spectra we collected for the same samples using a conventional FTIR-microscope system through a 100 \(\mu\)m aperture. The broad OH band and large water contents of the Moine Thrust mylonites deformed at 300 - 350°C are in line with previous FTIR studies of OH in quartz deformed under...
greenschist facies conditions. The sharp OH bands and low water contents of the Main Central Thrust mylonites deformed at 570 - 610°C are consistent with FTIR studies of quartz in other shear zones deformed at amphibolite conditions (Han et al., 2013; Kilian et al., 2016).

This study adds to an emerging impression that quartz tectonites deformed at greenschist temperatures and natural strain rates are wet. Water contents of quartz mylonites from other locations of the Moine Thrust deformed at greenschist facies conditions vary from 1400 to 7500 ppm (Kronenberg and Wolf, 1990). Water contents of deformed quartz across the Median Tectonic Line (Japan) vary from 300 to 2500 ppm (Nakashima et al., 1995), depending on metamorphic grade and shear displacement. Water contents of quartz deformed in granitic shear zones and mylonites at greenschist conditions reach values of 1100 ppm and >10,000 ppm (Gleason and DeSisto, 2008; Kronenberg et al., 1990).

Our measurements of water in quartz grains in Main Central Thrust mylonite samples build on the results of Nakashima et al. (1995), Han et al. (2013) and Kilian et al. (2016), which suggest that quartz deformed at amphibolite temperatures and natural strain rates may be relatively dry. Han et al. (2013) report water contents of just 10 to 110 ppm for quartz grains of granitic mylonites deformed at 400-500°C within the Longmenshan tectonic zone (Sichuan, China). Kilian et al. (2016) measured OH contents of just 20 to 100 ppm for quartz grains of granitic mylonites deformed at upper amphibolite conditions (Truzzo meta-granite, Central Alps, Italy), with IR spectra dominated by sharp OH bands due to hydrogen point defects and no detectable broad band due to molecular water.

Significant water contents (1400-4400 ppm) have been observed for quartz deformed at amphibolite conditions in mylonites of the El Pichao shear zone (NW Argentina), though reductions in water content are evident with progressive deformation (Finch et al., 2016). Fluid inclusions may be lost and intragranular water contents reduced during high temperature deformation by a variety of processes, from pipe diffusion (Bakker and Jansen, 1990, 1994; Hollister, 1990;
Cordier et al., 1994; Mavrogenes and Bodnar, 1994) to recrystallization and grain boundary sweeping (Faleiros et al., 2010; Seaman et al., 2013; Finch et al., 2016; Kilian et al., 2016), and partial melting (Seaman et al., 2013).

5.1 Wide variations in OH content

All previous FTIR studies of quartz mylonites have revealed large variations in water content for different grains of the same fault rock, and FTIR mapping of OH (Seamon et al., 2013, and this study) has revealed significant variations within grains. Given that the broad OH band of quartz at 3400 cm\(^{-1}\) is isotropic, the grain-to-grain variations (at large water contents) are real, not owing to variations of dichroic OH band absorbance with quartz grain orientation for a uniform concentration of structurally incorporated hydrogen defects. Our FTIR measurements of quartz OH contents using a 10 \(\mu\)m aperture show that these variations depend on sampling volume, as observed by Kilian et al. (2016) who showed that broad OH band absorptions scale with size of the measurement area due to the inhomogeneous distributions of fluid inclusions.

The large and variable water contents of quartz mylonites are far above equilibrium solubilities (e.g., Paterson, 1986; Kronenberg et al., 1986; Cordier and Doukhan, 1989), and the variations in non-equilibrium OH contents probably reflect some part of the history of water migration during deformation. Images of contoured OH absorbances of the broad 3400 cm\(^{-1}\) band for quartz and the 3600 cm\(^{-1}\) bands of micas constructed for Moine Thrust and Main Central Thrust samples show relationships with optical deformation and recovery microstructures that suggest mechanisms by which water is incorporated in quartz grain interiors, how water becomes redistributed during deformation and recovery, and how water is lost from quartz grain interiors.

OH contours within relatively undeformed quartz augen of the Moine Thrust reveal planar zones of high water content that correspond to secondary
fluid inclusions at healed microcracks (Fig. 6). We know little of this early brittle
deformation, but these fluid inclusion arrays have microstructures similar to those
generated during hydrothermal diffusional healing of cracks (Smith and Evans,
1984; Beeler and Hickman, 2015). As a result, early brittle deformation,
infiltration of water along open cracks, and crack healing appear to be important
to the early introduction of water to quartz grain interiors (Kronenberg et al., 1986,
1990, 2001; Diamond et al., 2010; Tarantola et al., 2010, 2012; Stünitz et al., in
press).

OH contours in plastically deformed regions of Moine Thrust samples are
complex and water contents appear to vary with strain patterns and
recrystallization (Figs. 6 - 8). Clearly defined planar arrays of course fluid
inclusions are absent from these regions, although the measured high water
contents indicate redistribution of water within quartz grains rather than the loss of
water. Processes of fluid inclusion decrepitation under deviatoric stresses have
been studied experimentally (Diamond et al., 2010; Tarantola et al., 2010, 2012,
Stünitz et al., in press), and they include simultaneous shrinkage of coarse (> 10
µm, optical-scale) inclusions, generation of dislocations at fluid inclusion walls,
and formation of a new population of very fine (< 100 nm) fluid inclusions (visible
only by transmission electron microscopy), which reside at dislocations and
resemble water clusters and inclusions of deformed and heat-treated synthetic
quartz (McLaren and Hobbs, 1972; White, 1973; Kirby and McCormick, 1979;
Christie and Ord, 1980). The loss of coarse fluid inclusions and growth of fine
inclusions requires diffusive transport, which may occur along interconnected and
mobile dislocations (McLaren et al., 1983; 1989; Cordier et al., 1988, 1994;
Bakker and Jansen, 1990, 1994; Hollister, 1990; Kronenberg et al., 1990, 2001;
Tarantola et al., 2010, 2012; Stünitz et al., in press). Once formed, very fine fluid
inclusions may also coarsen by pipe diffusion and processes documented by
McLaren et al. (1983) and Cordier et al. (1988), leading to continuous changes in
inclusion densities and size distributions.
Some regions of recrystallized quartz grains in Moine Thrust samples appear to have somewhat lower OH contents than original ribbon quartz grains (Figs. 7), while highly recovered and recrystallized quartz grains in the Main Central Thrust samples have little or no detectable molecular water (Fig. 9).

Reductions in intragranular water during dynamic recrystallization have been attributed to sweeping of fluid inclusions by mobile grain boundaries and losses of water from the fault rock by rapid grain boundary diffusion (Faleiros et al., 2010; Seaman et al., 2013; Finch et al., 2016; Kilian et al., 2016).

5.2 Limits on measurement volume

While synchrotron IR radiation has enabled spectral measurements through small (10x10 µm) apertured areas, we have not succeeded in measuring OH absorption bands for ultrathin samples when their interference fringes are larger than the absorption bands. Interference fringes due to internal reflections can be modeled (e.g., Clark and Moffatt, 1978; Pistorius and DeGrip, 2004; Konevskikh et al., 2015), but they become increasingly large as thickness of the doubly polished sample is reduced. For samples < 25 µm thick, we were unable to execute fringe corrections with sufficient confidence to measure OH spectra of individual, recrystallized quartz grains of the Moine Thrust.

The physical means by which we attempted to reduce interference fringes (rotating the sample within the IR beam, and changing numerical aperture of the IR objective) were also unsuccessful. However, interference fringes might be reduced in future studies by a number of other methods. Interference fringes could be eliminated if ultrathin samples are mounted on a substrate with a matching refractive index \(n\) (personal communication, Sina Marti). Such a substrate would need to be infrared-transparent, facilitate bonding between the sample and substrate (by low temperature melting or casting, to eliminate any residual air gaps between the sample and substrate), and lack OH bonds of its own. Alternatively,
internal reflections could be reduced if thin samples are immersed in polychlorotrifluoroethylene oil (n = 1.41), which exhibits strong absorption bands at <2500 cm\(^{-1}\) but has only small bands (between 3600 and 3200 cm\(^{-1}\)) that might interfere with OH absorptions of the sample (personal communication, Jed Mosenfelder and George Rossman). Internal reflections could also be reduced if only one surface of the ultrathin IR plate is polished, leaving the other surface precision-ground for a given plate thickness t (as employed by Woodhead et al., 1991). Spectra measured with just one polished surface will suffer some signal loss and spectra will need to be corrected for background. Another method of reducing interference fringes that obscure OH absorption bands might be developed by focused ion beam (FIB) milling of one side of a doubly polished sample to eliminate reflections at that surface over the IR wavenumbers of interest (personal communication, Roy Christoffersen).

5.3 Water weakening in nature?

The water contents of Moine Thrust samples and other quartz mylonites deformed at greenschist conditions are large and variable, comparable to (and even larger than) those of wet varieties of synthetic and natural milky quartz (350-4000 ppm) that exhibit water weakening in laboratory studies (e.g., Griggs and Blacic, 1965; Kekulawala et al., 1978; Stünitz et al., in press). Highly deformed ribbon quartz grains, less deformed quartz augen, and recrystallized quartz grains of the Moine Thrust exhibit OH bands of similar character to those of quartzites deformed in laboratory experiments, a result that validates applications of wet quartzite rheologies to evaluate rates of dislocation creep in middle to upper crustal shear zones (e.g., Hirth et al., 2001; Behr and Platt 2011; Law, 2014).

In contrast, water contents of highly sheared and recrystallized quartz in the hanging wall of Main Central Thrust samples and other mylonites deformed at upper amphibolite conditions are much smaller than measured for wet varieties of...
quartz. The large shear strains accumulated over ~150-250 km of displacement along the Main Central Thrust (e.g., Srivastava and Mitra, 1994; Hodges, 2000; Mitra et al., 2010; Tobgay et al., 2012; Law et al., 2013) and quartz OH contents (50 - 150 ppm) far lower than required for water weakening challenge our understanding of dislocation creep and the role of water in deformation deep in the continental crust. With only few exceptions, IR spectra of Main Central Thrust samples have OH bands of the same character and size as dry natural quartz crystals, which are strong and have not been deformed by dislocation processes in laboratory experiments (e.g., Heard and Carter, 1968; Blacic, 1975; Blacic and Christie, 1984). Given sufficiently high temperatures, it is possible that quartz may deform at tectonic strain rates without critical hydrogen defects at dislocations and water weakening (Kilian et al., 2016). However, this implies that we have not measured flow laws for appropriately dry quartzites that we can apply to amphibolite conditions and natural strain rates. Alternatively, water may have been lost from quartz interiors following deformation. It is also possible that hydrogen defects that enhance dislocation motion at high temperatures and natural strain rates may be sourced from grain boundaries or micas, diffusing over longer distances than are possible at greenschist conditions or laboratory strain rates.

Spatial variations in OH content of quartz in natural shear zones, as mapped in this study, may provide key insights into the role of water weakening, and changes in water content during deformation and recrystallization. High resolution FTIR imaging of OH in Moine Thrust and Main Central Thrust samples show that water contents are increased, fluid inclusions are redistributed, and water contents are decreased during brittle deformation, plastic creep, recovery, and recrystallization. Changes in OH contents of quartz mylonites and the history of fluid migration during deformation may lead to changes in governing flow laws, non-steady rates of creep, and shifting zones of localized shear.

6 Conclusions
The brightness of synchrotron IR radiation enables measurement of IR spectra for much smaller sampling volumes than is possible using conventional globar IR sources of FTIR instruments. In this study, we have used this improvement in signal to characterize and measure small OH absorption bands in quartz mylonites with an aperture size of 10 \( \mu \text{m} \) and to map water contents spatially. The ability to measure IR spectra for small, individual recrystallized grains by methods described in this study is limited by samples that must be > 40 \( \mu \text{m} \) thick to avoid internal reflections that lead to interference fringes that are larger than OH absorption bands. High-resolution images of OH in quartz mylonites, based on spectra collected through a 10 \( \mu \text{m} \) aperture as samples are translated under the beam, reveal large variations in OH content that correspond to the distributions of fluid inclusions and layer silicates, and to deformation and recrystallization microstructures. The OH contents of quartz in Moine Thrust mylonites deformed at greenschist conditions are comparable to wet quartzites deformed in the laboratory by processes of water weakening. By comparison, OH contents of quartz in Main Central Thrust mylonites deformed at upper amphibolite conditions are small, and molecular water, as required to deform quartz at experimental strain rates, is absent. What role water plays in deformation at these conditions is unclear, calling for further studies of water weakening in natural shear zones. High-resolution FTIR mapping of OH offers a new method of tracking changes in water content during deformation, recovery, and recrystallization.

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patience were invaluable to our work. We are indebted to Randy Smith of Brookhaven National Laboratory for sharing his expertise with OPUS imaging subroutines and teaching us how to compile and analyze integrated absorbances for multiple IR spectra collected over large scanned areas. Many thanks go to the leadership and staff of Brookhaven National Laboratory for operating the National Synchrotron Light Source NSLS I and awarding access to the U2A Beamline and Bruker Hyperion-2000 FTIR microscope. We thank the Consortium for Materials Properties Research in Earth Sciences COMPRES for their coordination of Earth science pursuits with other sciences done at NSLS. The National Science Foundation funded this work through a collaborative research grant awarded to the PIs at Virginia Tech (NSF EAR 1220345), Texas A&M University (NSF EAR 1220138), and Rensselaer Polytechnic Institute (transferred to Syracuse University, NSF EAR 1543627); their support is gratefully acknowledged.

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Paterson, M.S.: The thermodynamics of water in quartz, Phys. Chem. Minerals,


Srivastava, P., and Mitra, G.: Thrust geometries and deep structure of the outer and lesser Himalaya, Kumaon and Garhwal (India): implications for evolution


Table Captions

Table 1. Structural distances of samples below the Moine Thrust at the Stack of Glencoul (Law et al., 1986, 2010) and above the Main Central Thrust on the NW and Eastern Sutlej transects (Law et al., 2013). Deformation temperatures estimated by Law et al. (2013) using the Kruhl (1998) quartz c-axis fabric opening angle thermometer, and temperatures and pressures of metamorphism estimated by Stahr (2013) using THERMOCALC multi-equilibria thermometry (Powell and Holland 1994) are indicated.

Figure Captions

Figure 1. Doubly polished IR plates of Moine Thrust mylonites prepared perpendicular to foliation and parallel to lineation. (a) Low magnification image of large IR plate prepared from Stack of Glencoul sample SG-10 (unpolarized light imaged in high resolution Nikon slide scanner), with a mean thickness \( t = 120 \mu m \). (b) Same IR plate of SG-10 shown in (a) but with crossed-polarized light. The Moine Thrust transport direction is shown in the plane of the IR plate.
(top to the left, in the geographic WNW direction). (c) Higher magnification optical micrograph of large IR plate of sample SG-10, with crossed polarized light and local plate thickness (117 µm) determined from IR interference fringes. (d) Optical micrograph of Stack of Glencoul sample SG-7 in crossed-polarized light (normal 30 µm section thickness), illustrating deformation and recover microstructures with higher resolution than in thick IR plates, with undulatory extinction in ribbon quartz grains, fine recrystallized grains and aligned muscovite grains localized at quartz grain boundaries. (e) Low magnification image of ultrathin IR plate of Stack of Glencoul sample SG-7-5 (crossed-polarized light) mounted on a copper TEM slot ring (t = 4-8 µm, based on IR interference fringes).

(f) Higher magnification optical micrograph of the same IR plate SG-7-5 (crossed-polarized light) as shown in (e) with deformation and recrystallization microstructures shown more clearly than in normal 30 µm thin section.

Figure 2. IR spectra of quartz grains in mylonites from the Moine Thrust (Stack of Glencoul) and the Main Central Thrust (Sutlej Valley) using conventional FTIR with globar IR source through a 100 µm aperture. (a) Absorbance spectra of quartz grains of Moine Thrust IR plate SG-10 (shown in Fig. 1, t = 120 µm) showing broad OH band at 3400 cm⁻¹ associated with fluid inclusions in milky quartz. (b) Absorption spectra of Moine Thrust quartz grains of the same IR plate (SG-10) showing the same broad OH band due to fluid inclusions in addition to an OH absorption band (or shoulder) at 3600 cm⁻¹ due to mica inclusions. (c) Absorbance spectra of quartz grains of Main Central Thrust IR plates S09-30 (t = 121 µm), S09-35 (t = 74 µm), and S09-58 (t = 145 µm), with many grains showing small sharp OH absorption bands at 3595, 3482, 3431, 3408, and 3379 cm⁻¹ due to hydrogen point defects, and less common grains with a large broad absorption band at 3400 cm⁻¹. (d) Absorption spectra of quartz grains of Main Central Thrust sample S09-30 (t = 121 µm) with a prominent OH band at 3600 cm⁻¹ due to mica inclusions and smaller OH bands at lower wavenumbers. Absorbance values...
plotted vertically are normalized to represent their values for a uniform sample thickness of 1 mm.

**Figure 3.** OH absorption bands due to fluid inclusions and hydrogen defects in quartz grains and those due to mica inclusions. (a) Integrated absorbances of OH bands at 3400 cm\(^{-1}\) (due to fluid inclusions) and 3595 to 3379 cm\(^{-1}\) (due to hydrogen interstitials) of quartz grains (\(\Delta_{\text{OH,qtz}}\) in cm\(^2\)) can be separated from the integrated absorbance of the 3600 cm\(^{-1}\) OH band of mica inclusions (\(\Delta_{\text{OH,mica}}\)), depending on the IR absorption spectra of the micas. The integrated absorbance \(\Delta\) of the 3600 cm\(^{-1}\) OH band of micas can be determined over 3702 cm\(^{-1}\) to 3544 cm\(^{-1}\), fitting a straight line between these values. In order to evaluate the remaining OH absorbance of the spectrum, the value of \(\Delta\) determined for the 3600 cm\(^{-1}\) band is deducted from value from the integrated absorbance \(\Delta\) due to all OH absorptions over 3705 cm\(^{-1}\) to 2880 cm\(^{-1}\), again fitting the background by a straight line. This procedure works well to distinguish OH absorbances due to muscovite inclusions (\(\Delta_{\text{OH,musc}}\)) from those of fluid inclusions and hydrogen defects of Moine Thrust quartz grains (\(\Delta_{\text{OH,qtz}}\) determined for SG-10, Grain 2, \(t = 120\ \mu\text{m}\)), given that (b) the absorption spectrum of muscovite grains in Moine Thrust samples is very simple, with one prominent OH absorption band at 3620 cm\(^{-1}\) (\(t = 8\ \mu\text{m}\), absorbance normalized to \(t = 0.1\ mm\)). OH absorption spectra of (c) muscovite and (d) biotite grains of Main Central Thrust mylonites (S09-63, \(t = 155\ \mu\text{m}\)) are more complex than displayed by muscovite grains of the Moine Thrust. The prominent OH band of muscovite grains in Main Central Thrust samples appears at 3638 cm\(^{-1}\) with smaller OH bands at 3815, 3311, 3146, and 3035 cm\(^{-1}\). The primary OH band of biotite grains in Main Central Thrust samples appears at 3614 cm\(^{-1}\) (with shoulders at 3674 and 3561 cm\(^{-1}\)) and secondary OH bands at 3258, 3043, and 2829 cm\(^{-1}\). The OH bands of all micas at ~3600 cm\(^{-1}\) are highly anisotropic; absorbances at ~3600 cm\(^{-1}\) for muscovite grains measured in polarized IR radiation are maximized when the vibration direction E is parallel to...
the basal (001) plane, while principal OH absorbances for biotite grains are maximized when E is perpendicular to (001). However, secondary OH bands of muscovite and biotite grains of the Main Central Thrust show significant variations from the dichroism displayed by the primary OH bands of each of these micas. The complex nature of these secondary OH bands presents significant difficulties in separating OH absorptions of quartz grains due to molecular water and hydrogen defects and those due to mica inclusions dispersed within quartz grains. All absorption spectra shown here were measured using unpolarized IR radiation with a conventional FTIR spectrometer and a 100 μm aperture.

Absorbances for all spectra but (b) are normalized to a uniform thickness t of 1 mm.

**Figure 4.** IR spectra of quartz grains in Moine Thrust mylonite samples (Stack of Glencoul), measured with synchrotron-FTIR system using a 10 μm aperture with varying IR plate thicknesses (a) $t = 113 \, \mu m$ (BSG 10, local plate thickness determined from interference fringes), (b) $t = 13 \, \mu m$ (SG-10.2t), and (c) $t = 6.5 \, \mu m$ (BSG 7.3, sample plate SG-7-1). For doubly polished sample plates of ~100 μm, IR spectra measured using the coupled synchrotron-FTIR spectrometer system through a 10 μm aperture are similar to those measured using a conventional FTIR spectrometer through a 100 μm aperture. (a) IR spectra of Moine Thrust sample (SG-10) show OH absorption bands of similar character at the same wavenumbers for a 10 μm aperture as OH bands measured through a larger (100 μm) aperture, including a large broad absorption band at 3400 cm$^{-1}$ due to dispersed fluid inclusions (both BSG 10.1 and BSG 10.3) and a sharper band at 3600 cm$^{-1}$ due to mica inclusions (shown by BSG 10.3). Interference fringes in samples ~100 μm thick are apparent, allowing determination of local IR plate thickness, but they do not obscure the OH absorption bands. (b) Interference fringes for samples < 25 μm thick are large, and make detection of small OH absorption bands difficult. The only detectable absorbance bands in sample SG-
10.2t (t = 13 µm) are due to strong primary Si-O vibrations (at υ < 2200 cm⁻¹);
OH absorption bands cannot be resolved. (c) Interference fringes are very large
for thin IR plates (t = 6.5 µm; SG-7-1); OH absorption bands are not observed,
even after attempts to model them and remove fringes numerically. All
absorbance values (and apparent absorbance values of interference fringes
exhibited by SG-7) are normalized to a uniform sample thickness of 1 mm.

**Figure 5.** Ultrathin IR plates (t = 4-8 µm) exhibit deformation microstructures in
crossed-polarized light with greater clarity than those of conventional thin sections
(t = 30 µm). (a) Deformed ribbon quartz grains of Moine Thrust sample SG-7-6 (t
= 6-8 µm) show distinct subgrains with sharply defined subgrain walls, while
extinction in conventional thin sections of ribbon quartz is smoothly varying and
subgrain boundaries are difficult to detect. Finely recrystallized quartz grains at
sutured grain boundaries are smaller than subgrains within large deformed quartz
grains. (b) Less deformed quartz porphyroclast of Moine Thrust sample SG-7-5 (t
= 5-6 µm) with internal subgrains, and surrounding recrystallized quartz grains of
similar dimensions to those of internal subgrains.

**Figure 6.** OH absorbance maps of Moine Thrust sample SG-7 constructed from
900 IR spectra (SG-7t-1map, 30 x 30 steps, 10 µm/step) for a doubly polished
plate prepared (56 µm thick) perpendicular to foliation and parallel to the transport
direction (lineation horizontal in all panels). (a) Plane-polarized micrograph of IR
plate SG-7t showing nearly equant globular augen quartz grain surrounded by
highly deformed ribbon and recrystallized quartz grains. Light scattering is mostly
due to micas and fluid inclusions. Outlined box is the region imaged by integrated
IR absorbances. (b) The same plane-polarized light micrograph as in (a) with
superposed map of OH absorbance of the 3600 cm⁻¹ band due to micas (OH of
micas given in integrated area cm⁻²). Contours are given in log_{10}(Δ in cm⁻²) for the
integrated absorbance of the ~3600 cm⁻¹ OH band. (c) Cross-polarized light
Figure 7. OH absorbance maps of Moine Thrust sample SG-10 constructed from 3600 IR spectra (SG-10-XY2, 60 x 60 steps, 10 µm/step) for a doubly polished plate prepared (117 µm thick) perpendicular to foliation and parallel to the transport direction (lineation horizontal in all panels). (a) Plane-polarized micrograph of IR plate SG-10-2 showing deformed ribbon quartz grains surrounded by recrystallized quartz grains. Light scattering is mostly due to micas and fluid inclusions. Outlined box is the region imaged by integrated IR absorbances. (b) The same plane-polarized light micrograph as in (a) with superposed map of OH absorbance of the 3600 cm\(^{-1}\) band due to micas (OH of micas given in integrated area \(\Delta\) cm\(^{-2}\) and contoured as \(\log_{10} \Delta\)). (c) Cross-polarized light micrograph of the same region of IR plate SG-10-2 as shown in (a), with undulatory extinction of deformed ribbon quartz grains, incipient recrystallized grains at quartz ribbon margins, and recrystallized matrix grains shown by first-order interference colors. (d) The same cross-polarized light micrograph as in (c) with superposed map of OH absorbance of the broad 3400 cm\(^{-1}\) band due to molecular water in fluid inclusions (and smaller OH bands due to hydrogen defects) of quartz grains (OH of quartz in molar ppm, OH/10\(^6\) Si and contoured as \(\log_{10} OH\)). OH contents of quartz and those associated with micas...
are contoured in color with blue (and cool colors) corresponding to large water (OH) contents, and red (and warm colors) corresponding to low water (OH) contents.

Figure 8. OH absorbance maps of Moine Thrust sample SG-8 constructed from 1800 IR spectra (SG-8t-map1, 30 x 60 steps, 10 µm/step) for a doubly polished plate prepared (73 µm thick) perpendicular to foliation and parallel to the transport direction (lineation horizontal in all panels). (a) Plane-polarized micrograph of IR plate SG-8t showing deformed ribbon quartz grains and regions of finely dispersed mica and recrystallized quartz grains. Light scattering is mostly due to micas, fluid inclusions, and grain boundaries. Outlined box is the region imaged by integrated IR absorbances. (b) The same plane-polarized light micrograph as in (a) with superposed map of OH absorbance of the 3600 cm⁻¹ band due to micas (OH of micas given in integrated area Δ cm⁻² and contoured as log₁₀ Δ). (c) Cross-polarized light micrograph of the same region of IR plate SG-8t as shown in (a), with undulatory extinction of deformed ribbon quartz grains and regions of recrystallized grains shown by first-order interference colors. (d) The same cross-polarized light micrograph as in (c) with superposed map of OH absorbance of the broad 3400 cm⁻¹ band due to molecular water in fluid inclusions (and smaller OH bands due to hydrogen defects) of quartz grains (OH of quartz in molar ppm, OH/10⁶ Si and contoured as log₁₀ OH). OH contents of quartz and those associated with micas are contoured in color with blue (and cool colors) corresponding to large water (OH) contents, and red (and warm colors) corresponding to low water (OH) contents.

Figure 9. OH absorbance maps of Main Central Thrust sample S09-63 constructed from 1200 IR spectra (S09-63-map1, 30 x 40 steps, 50 µm/step) for a doubly polished plate prepared (155 µm thick) perpendicular to foliation and parallel to the transport direction (lineation horizontal in all panels). (a) Plane-
polarized micrograph of IR plate S-09-63 showing coarse, clear quartz grains, and coarse muscovite and biotite grains with readily distinguishable color and pleochroism. Scattering of light is primarily due to grain boundaries, with little evidence for dense fluid inclusions or finely dispersed micas.Outlined box is the region imaged by integrated IR absorbances. (b) The same plane-polarized light micrograph as in (a) with superposed map of OH absorbance of the 3600 cm\(^{-1}\) band due to micas (OH of micas given in integrated area \(\Delta \text{ cm}^{-2}\) and contoured as \(\log_{10} \Delta \)). (c) Cross-polarized light micrograph of the same region of IR plate SG-09-63 as shown in (a), with high-temperature deformation and recovery microstructures (in higher order interference colors) that are characterized by subtle (to absent) undulatory extinction of quartz, subgrain walls, and coarse recrystallized grains. (d) The same cross-polarized light micrograph as in (c) with superposed map of OH absorbance over 3705 and 2880 cm\(^{-1}\) to capture the broad and sharp bands of quartz, deducting the large 3600 cm\(^{-1}\) band of micas, but including smaller OH bands of micas between 3311 and 2920 cm\(^{-1}\). Contours in this absorbance can only be attributed unambiguously to fluid inclusions and hydrogen defects in quartz where micas (and their 3600 cm\(^{-1}\) absorbances) are absent. OH contents of quartz and those associated with micas are contoured in color with blue (and cool colors) corresponding to large water (OH) contents, and red (and warm colors) corresponding to low water (OH) contents.
Table 1  Synchrotron FTIR Imaging of OH  Kronenberg et al

Moine Thrust - Stack of Glencoul mylonitic quartzites

<table>
<thead>
<tr>
<th>Sample</th>
<th>Distance below MT</th>
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<tbody>
<tr>
<td>SG.7</td>
<td>2.5 m</td>
</tr>
<tr>
<td>SG.8</td>
<td>2.9 m</td>
</tr>
<tr>
<td>SG.10</td>
<td>4.6 m</td>
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Main Central Thrust - NW Sutlej transect orthogneisses

<table>
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<th>Sample</th>
<th>Distance above MCT</th>
<th>T</th>
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<tbody>
<tr>
<td>S09-30</td>
<td>~ 750 m</td>
<td>~ 600°C¹</td>
</tr>
<tr>
<td>S09-35</td>
<td>75 m</td>
<td>~ 540°C²</td>
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</table>

Main Central Thrust - Eastern Sutlej transect paragneisses

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<th>Distance above MCT</th>
<th>T</th>
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<td>735°C²</td>
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<td>~1500 m</td>
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<tr>
<td>S09-71B</td>
<td>25 m</td>
<td>610°C¹</td>
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</tbody>
</table>

¹Deformation temperature estimated from quartz c-axis fabric opening angle (Law et al. 2013).

²Temperature and pressure of metamorphism estimated from THERMOCALC multi-equilibra thermobarometry (Stahr 2013, p. 67; Law et al., 2013).
Figures  Synchrotron FTIR Imaging of OH  Kronenberg et al

Fig. 1a

Fig. 1b
Fig. 2a

![Graph of Quartz Grain Spectra, Mylonite, SG-10, Moine Thrust, 100 µm aperture, t = 120 µm, showing absorbance vs. wavenumber (cm⁻¹).]

Fig. 2b

![Graph of Quartz Grain Spectra, Mylonite, SG-10, Moine Thrust, 100 µm aperture, t = 120 µm, with mica inclusions, showing absorbance vs. wavenumber (cm⁻¹).]
Fig. 2c

Quartz Grain Spectra  Mylonites S09 series
Main Central Thrust
100 \mu m aperture

S09-35 Grain 8
S09-30 Grain 2
S09-58 Grain 4
S09-35 Grain 1

t = 74-145 \mu m

Wavenumber (cm\(^{-1}\))

Absorbance

Fig. 2d

Quartz Grain Spectra  Mylonite S09-30
with mica inclusions  Main Central Thrust
100 \mu m aperture

Grain 1
Grain 4

t = 121 \mu m

Wavenumber (cm\(^{-1}\))

Absorbance
Fig. 4a

![Spectra Graph with labels for Quartz Grain Spectra, Mylonite SG-10, Moine Thrust, 10 µm aperture, and t = 113 µm.]

Fig. 4b

![Spectra Graph with labels for Quartz Grain Spectra, Mylonite SG-10, Strong Interference Fringes, Moine Thrust, 10 µm aperture, and t = 13 µm.]
Fig. 4c
Fig. 5a

Fig. 5b
Fig. 6

Fig 7

SG-7

SG-10
Fig. 8

![Image of Fig. 8](image1)

Fig. 9

![Image of Fig. 9](image2)