

**WATER CONTENTS OF QUARTZ MYLONITES OF THE SOUTH  
TIBETAN DETACHMENT AND THE ROLE OF WATER WEAKENING  
IN HIMALAYAN CHANNEL FLOW**

An Undergraduate Research Scholars Thesis

by

LYNNA JEZEK

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Dr. Andreas Kronenberg

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## ABSTRACT

Water Contents of Quartz Mylonites of the South Tibetan Detachment and the Role of Water Weakening In Himalayan Channel Flow

Lynna Jezek  
Department of Geology and Geophysics  
Texas A&M University

Research Advisor: Dr. Andreas Kronenberg  
Department of Geology and Geophysics  
Texas A&M University

OH absorption bands due to water in deformed quartz mylonites from the low-angle Lhotse Detachment (of the South Tibetan Detachment System, Rongbuk Valley north of Mount Everest) have been measured by Fourier Transform Infrared (FTIR) Spectroscopy. Previous work has shown that these rocks were deformed by dislocation creep at high temperatures (Law *et al.*, 2004) and middle to lower crust (upper Amphibolite) conditions. Despite the depths from which these fault rocks come,  $^{18}\text{O}$  studies suggest significant influx of meteoric water is synchronous with mylonitic deformation and exhumation of the region (Gébelin *et al.*, 2013). OH absorption bands at  $\sim 3400\text{ cm}^{-1}$  of quartz mylonites from the footwall of the Lhotse Detachment fault are large, with the character of the molecular water band due to fluid inclusions in milky quartz. Mean water contents depend on structural position relative to the core of the Lhotse Detachment, from  $\sim 1000\text{ ppm}$  ( $\text{OH}/10^6\text{ Si}$ ) at 420 m below the fault to  $11,350 (\pm 1095)\text{ ppm}$  near its center. This gradient implies influx of meteoric water along the Lhotse Detachment from the Tibetan surface to mid-crustal depths and significant fluid penetration into the extruding Himalayan slab by intergranular, permeable fluid flow processes. Increased water contents of

quartz may also be responsible for continued deformation and strain localization on the South Tibetan Detachment System.

Dislocation creep in quartz is facilitated by water in laboratory experiments, and the water contents of the Lhotse fault rocks are similar to water contents of synthetic hydrated quartz. Penetration of meteoric fluids to mid-crustal depths could help explain why Lhotse rocks have much higher intragranular water content than quartz mylonites of the Main Central Thrust (with OH contents of just 170 ppm) deformed at greater crustal depths in the Himalayan slab below the South Tibetan Detachment System. Existing knowledge of water weakening in quartz has been mainly derived from laboratory experiments, and this study will examine its importance in nature.

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# CHAPTER I

## INTRODUCTION

### Background

Detachment systems like the South Tibetan Detachment System (STDS) are suites of regional-scale, low-angle normal faults, and they are common features of extensional tectonic settings (Schulz *et al.*, 2017). The Lhotse Detachment is a single detachment part of a larger suite of north-dipping faults that make up the greater STDS. Samples collected at varying depths beneath the Lhotse detachment suggest that this fault served as a fluid conduit for meteoric (rain) water synchronous with mylonitic deformation and exhumation of the STDS caused by extensional tectonism of the region at ~15.5 Ma. Measurements of oxygen isotopes in this fault zone are comparable to those with meteoric water, suggesting penetration of water up to depths of 20 km during the Himalayan mountain building event (Gébelin *et al.*, 2013).

Hydrogen resides on the surfaces, within, and along grain boundaries of quartz and exists in its crystal lattice as hydrogen defects and molecular water (Kronenberg, 1994). These hydrogen atoms, acting as part of a water molecule or as point defects that correct charge for impurity cations, influence the physical and chemical properties of quartz and encourage processes of inelastic deformation by replacing strong silicon-oxygen bonds with SiOH complexes are hydrogen bonded together. When the siloxane bonds are broken and replaced with hydrogen bonds, the strength of quartz is diminished. It is well-known that water and fluids on faults greatly reduces the strength of the surrounding crust, and at depths where plastic deformation is the primary mechanism of deformation, quartz is greatly weakened by water via dislocation creep. The samples used for this study were determined previously to have been

deformed at Upper Amphibolite facies conditions ( $T > 500^{\circ} \text{C}$ ,  $P$  corresponding to depths of the mid- to lower crust) via Regime II dislocation creep mechanisms (Law *et al.*, 2004).

The STDS served previously as a large, ductile shear zone, and evidence from other shear zones such as one in central Sierra Nevada studied by Kronenberg, Segall, and Wolf (1990), shows that hydrogen content (ppm  $\text{H}/10^6 \text{Si}$ ) varies substantially within quartz grains based on position inside or outside of the shear zone. Water contents in these rocks can be compared to those determined from wet/dry quartz experiments, where hydrogen concentrations in the shear zone are similar to weak (hydrated) synthetic quartz, and the quartz grains measured outside of the shear zone have water contents comparable to dry Brazilian quartz used in laboratory experiments (Kronenberg, 1994). Water contents of the Lhotse rocks indicate they are very wet, with water contents similar to (and even larger than) values determined from the wet/dry quartz experiments described previously.

## **Research Objectives**

Existing knowledge of hydrolytic weakening mechanisms suggests a contradictory role that water content plays in shear zones with respect to depth below Earth's surface, and it is theorized that water may be less important for weakening rocks deep in the continental crust. The Main Central Thrust, the fault that forms the basal boundary of the Himalayan slab (the STDS makes up the top boundary), has very little water content and was deformed at depths greater than those from the Lhotse rocks collected from meters above. A few studies of water have been executed for only thrust faults, and this study is the first to make observations of water weakening in natural rock samples taken from a normal fault.

## CHAPTER II

### METHODS

#### Hydrogen Speciation in Quartz Aggregates

When quartz-bearing rocks are deformed by water weakening, the strong siloxane bonds are replaced by silanol groups whose hydrogen bonds are easy to break during motion of crystal defects. This continuous movement of dislocations to sites of lower energy (located at grain boundaries) actually deforms the rock by rearranging the size and orientation of the grain boundary as bonds are broken and reformed. Infrared (IR) spectroscopy is used because of its strong sensitivity to concentrations of water due to the strong polarity of OH ions and H<sub>2</sub>O molecules that create vibrational stretching seen as distinctive absorption ranges in the IR. Data derived from spectroscopy studies of quartz grains can provide information of not only what type of OH species resides in the grain, but also give insight as to how much water is concentrated within the grain being measured.

For hydrogen point defects, these appear as sharp absorption peaks at different wavenumbers reflecting multiple sites that the defects exist. OH absorption spectra for fluid inclusions (liquid water) are broad bands centered at wavenumbers approximately 3400 cm<sup>-1</sup> over a range of ~3600 cm<sup>-1</sup> to ~2500 cm<sup>-1</sup> (Kronenberg, 1994). These values were derived in part from studies of the synthetic (hydrated) quartz that proved to be much weaker in rock deformation experiments than did the natural, dry Brazilian quartz under same amounts of stress. The spectroscopic analysis of other more hydrous SiO<sub>2</sub> polymorphs (e.g. citrine, milky quartz, or opal) in Kronenberg's study also yields broad OH absorption due to the presence of liquid water



within the crystal lattice, suggesting that water plays a significant role in weakening one of the most important mineral constituents of Earth's crust.

## Procedure

A Fourier transform infrared (FTIR) spectrometer coupled to an Infrared (IR) microscope (shown in **Figure 1**) was used to measure the magnitude of broad OH absorption for eight samples collected at varying depths below the Lhotse detachment. Samples were prepared approximately 100  $\mu\text{m}$  thick and grain measurements were collected at low temperature (77 K; cooled with liquid nitrogen) in a 100  $\mu\text{m}^2$  window using the IR microscope.



**Figure 1.** An FTIR bench coupled to an IR microscope. The microscope is cooled to 77 K before collecting measurements. Low temperatures increase the radiation produced by vibrational stretching of polar ions and molecules in the IR, which improves the quality of the spectra by enhancing absorption features characteristic and specific to certain compounds. For quartz in reference to this study, it would be the broad band absorption of OH centered at  $\sim 3400\text{ cm}^{-1}$ .

Grains selected for FTIR study were chosen based on their similarity to microstructures corresponding to those described in Regime II dislocation creep, as well as their actual measurability due to size and orientation of the grain and the grains around it. Under Regime II, subgrain rotation is the primary mechanism by which dislocation creep occurs. When dislocations travel to sites of lower energy at subgrain boundaries to form a high-angle grain boundary during dynamic recrystallization, the process creates a distinct set of optically-visible microstructures specific to quartz aggregates (Hirth and Tullis, 1992). The presence of intragranular micas and elongate quartz grains are both characteristics of Regime II plastic deformation, though they pose challenges to selecting grains that fit these microstructural qualifications with respect to the microscope's narrow  $100\ \mu\text{m}^2$  field of view. Areas within some of the samples were contaminated with epoxy and were selectively avoided to reduce error caused by the interference of CH absorption bands caused by the epoxy with the OH absorption of molecular water.

## CHAPTER III

### RESULTS

The eight samples collected below the Lhotse detachment vary in depth over a vertical range of 407 m, with most of the samples collected at depths less than 150 m from the core of the shear zone (top of the detachment). Measurements were collected for 132 quartz grains in total, where each sample yielded one to two dozen absorption spectra due to wide grain to grain variations, depending on the sample.

Before analyzing the data, the integrated area (magnitude) of the OH absorption spectrum for each grain was subtracted for areas over wavenumber ranges corresponding to any micas that exist in the grain. The injection of epoxy into the samples (from previous study) created unwanted absorption in some grains due to the vibrational stretching of CH that needed corrections for, and this was done similarly by subtracting the magnitude CH from the total magnitude of OH absorption. The final integrated area for each grain was then used to determine the mean intragranular water content of the eight samples. Some grains were excluded based on high epoxy content/CH concentration whose integrated area of OH absorption, if used, would interfere with the accuracy of the data caused by the overlap of CH wavenumbers with those ranges corresponding to liquid water. The final integrated absorbance values after correcting for mica and epoxy are thought to be representative of liquid water that exists either optically or sub-optically within each grain as fluid inclusions determined by the broad characteristic absorption spectrum.

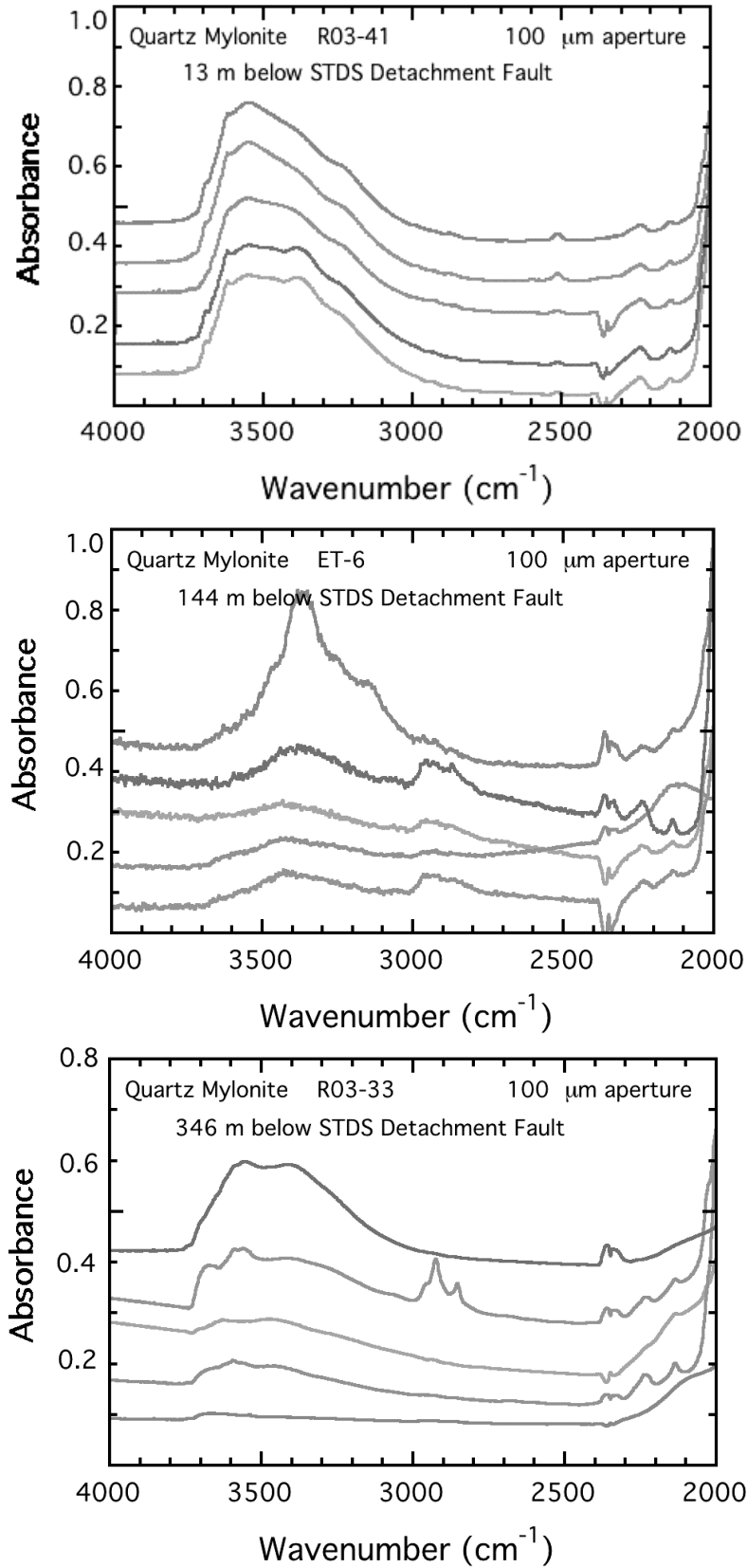
The Calib, Aines, and Rossman calibration shown below (1) was used to determine the value ( $c$ ), concentration of OH, from the integral absorbance caused due to OH stretch ( $A^*$ ) and the IR path length ( $l$ ) through the specimen (Kronenberg, 1994).

$$(1) \quad c \text{ (ppm H/10}^6 \text{ Si)} = (1.05)(A^*/l)(\text{cm}^{-2})$$

This calibration is chosen based on hydrogen extraction measurements performed on the experimental (hydrated) synthetic quartz that have an integral absorption coefficient (described by the Beer-Lambert relation) closer to that of liquid water, described by Kronenberg in his study. This was used against a calibration for water that is more useful when studying hydrogen point defects, where the resulting value would yield a much lower OH concentration relative to thickness of the sample and actual water contents within the grain. Although some absorption spectra for Lhotse quartz grains do imply the existence of hydrogen as point defects, they exist as small peaks atop the broad band of molecular water absorption, therefore the Calib, Aines, and Rossman calibration is best suited for this study. Further evidence that the Lhotse quartz mylonites contain significant concentrations of water can be seen through the IR microscope as bubbles of fluid inclusions that would also be visible with an optical microscope. Samples that are drier based on magnitude of broad OH still show the presence of liquid water as the broad absorption spectrum centered at  $\sim 3400 \text{ cm}^{-1}$ , implying the existence of sub-optically visible fluid inclusions.

The absorption spectra of five grains for three different samples are shown in order of increasing distance from the top of the Lhotse detachment (**Figure 2**). The three samples were selected to represent the trend of the data set based on their position below the STDS, starting near the core of the fault zone at 13 m below the Lhotse detachment and moving to greater depths at 346 m below, with an intermittent depth of 144 m below the fault zone.

Figure 2. Absorption spectra showing variable OH concentrations among three samples. The nature of the broad band molecular water changes as water contents decrease moving away from the STDS.



Mean intragranular water contents for the remaining samples were evaluated as a function of structural position relative to the core of the Lhotse Detachment using the Calib, Aines, and Rossman calibration explained previously. The eight mylonite samples range in mean intragranular water content from just ~1000 ppm at 420 m below the fault to 11,350 ( $\pm 1095$ ) ppm near its center, 13 m below the fault (**Table 1**).

**Table 1. Mean intragranular water contents for each sample collected from below the Lhotse detachment.**

| Sample | Depth (m) | Mean OH (ppm H/10 <sup>6</sup> Si) |
|--------|-----------|------------------------------------|
| R03-32 | 420       | 988                                |
| R03-33 | 346       | 1523                               |
| R03-39 | 46        | 1840                               |
| R03-40 | 20        | 9738                               |
| R03-41 | 13        | 11347                              |
| ET-6   | 144       | 1742                               |
| ET-7   | 144       | 6179                               |
| ET-8   | 94        | 1313                               |

The mean OH contents determined using this method are comparable to synthetic (hydrated) quartz that was measured to have high OH concentration in laboratory experiments. It seems necessary that rain water has travelled along fractures via permeable, intragranular fluid flow processes and penetrated along the fault plane deep into the Earth's crust for <sup>18</sup>O studies to imply the source of the water is surficial. The increased concentrations of meteoric water at depths near the top of the fault are indicative of water successfully penetrating the country rock up to depths of 20 km, but the mechanisms by which the water travelled to these depths is not entirely known.

## CHAPTER IV

### DISCUSSION

#### Synthesis

The gradient of decreasing water content with depth into the STDS suggests that the Lhotse serves as a conduit for rainwater via the Tibetan surface, with meteoric water reaching depths as great as the middle to lower crust. When all samples are plotted of their mean water contents against their structural location below the Lhotse detachment, there is a trend of significantly increased water at depths up to 20 km below the detachment, consistent with results from Gébelin *et al.* (2013), suggesting that meteoric water penetrated the fault downward distances up to 20 km.

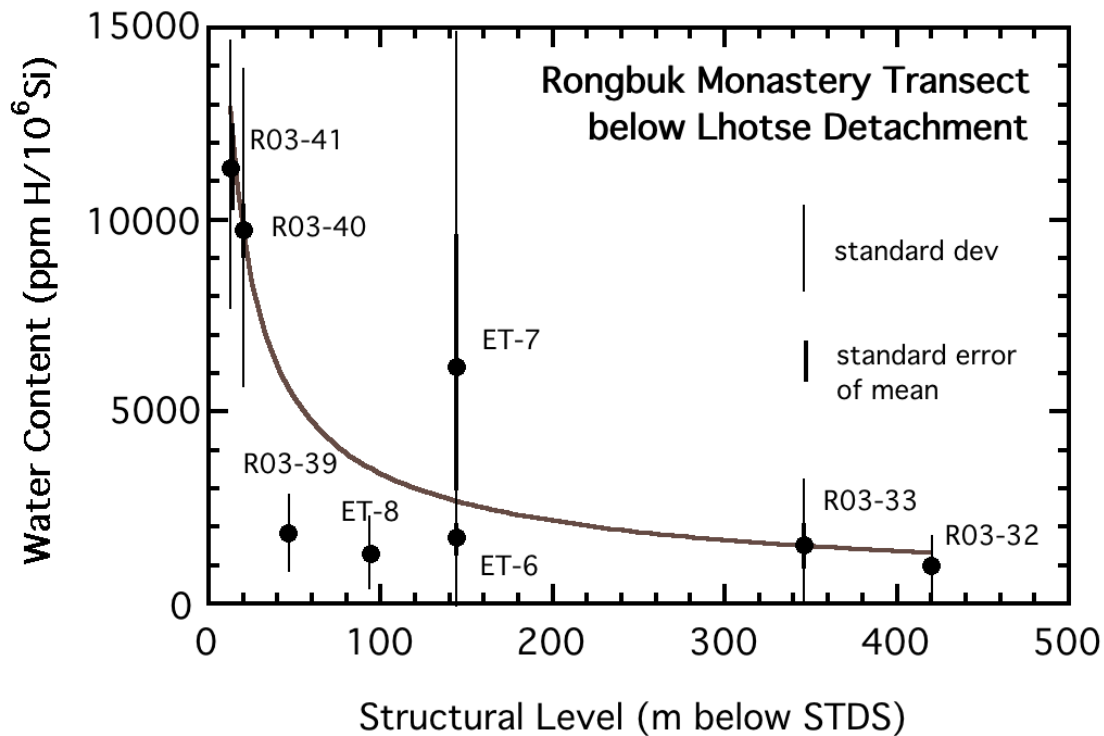


Figure 3. Samples collected from the Lhotse Detachment show a relationship with their respective depth below the fault. The Main Central Thrust (below the STDS) bounds the Himalayan slab at its base deep in the crust, having mean intragranular water contents of only ~170 ppm, which is nowhere near the concentrations observed in the Lhotse fault rocks.

In addition to the standard deviation (shown as thin lines in **Figure 3**), the standard error of mean was used when evaluating the samples and their position in Earth's crust relative to the STDS. The standard error of mean is the sample standard deviation divided by the root of the number of observations ( $n = \text{grains measured per sample}$ ), and this value uses the sample mean to give an estimate of the population mean. In the case of this study, that would mean more grain measurements collected for the same sample would result in a new mean that falls within range of the error of mean, shown by the thick lines on the curve.

Even accounting for complications and corrections in the study due to mica and epoxy, there is a discernable trend of increasing water content with depth into the fault zone and rapidly decreasing water away from it. Knowledge of how water weakening behaves in thrust fault systems, such as the Main Central Thrust, suggest that water content is reduced at the core of the fault zone, opposite the trend observed in this study. It is no doubt the STDS has been a conduit by which meteoric water penetrated the country rock to depths up to 200 m, but the contradictory evidence that exists for thrust faults as conduits may mean that they are pushing water out of the rock via other intragranular, fluid flow mechanisms while normal faults are allowing water to percolate downward into them. Perhaps this could be a factor causing the continued deformation and strain localization of the STDS, where water weakening will speed the process of any subsequent deformation.

## **Future Research**

Previous literature has disputed whether or not faults serve as conduits or seals for fluids, and it is clear in this case that the STDS is acting as a conduit for water to penetrate into the rock



up to depths in the middle and lower crust. This study is the first using FTIR spectroscopy to evaluate the water contents of rocks collected from a large, normal detachment from a regional-scale tectonic setting important to understanding the climactic and geologic history of the past ~20 Ma. Most of the existing knowledge of water weakening in quartz aggregates has been derived from laboratory experiments, and there is a lot to learn about how these mechanisms are operating in nature, not only extensional settings but collisional systems as well.. Future research could aim to evaluate water contents in other normal fault systems of different locations and sizes to see if there is significant evidence suggesting the penetration of rainwater to mid-crustal depths in former ductile shear zones.

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