

ABSTRACT

The Bancroft Shear Zone is an extensional collapse structure that formed in the Grenville Province due to the over thickening and resulting crustal weakening during the Ottawa orogeny, ~1030-1070 Ma (Cosca *et al.*, 1995). The shear zone was active late in the orogenic cycle, ~1045 to 1030 Ma (Metzger *et al.*, 1991), forming very fine-grained mylonites with textures indicating that deformation occurred well below peak metamorphic temperatures (van der Pluijm, 1991). These mylonites mainly consist of calcite, along with minor amounts of other minerals including graphite. The $^{13}\text{C}/^{12}\text{C}$ ratios of coexisting calcite and graphite are sensitive to temperature. Expressed as $\delta^{13}\text{C}_{(\text{cal})} - \delta^{13}\text{C}_{(\text{gr})} = \Delta^{13}\text{C}_{(\text{cal-gr})}$, the Δ -values correspond to temperature, presumably peak metamorphic temperature. Carbon diffusion rates are relatively fast in calcite, but extraordinarily slow in graphite, such that carbon equilibration appears to require graphite crystallization (Valley, 2001). So unless graphite is recrystallized, the Δ -values provide an estimate of the peak metamorphic temperature (Valley and O'Neil, 1981).

In this study marble mylonites from six localities within the Bancroft Shear Zone were analyzed to determine whether the Δ -values were reset from the regional metamorphic temperature down to the lower temperature of shearing. Previous work shows peak regional temperatures to be ~650-700°C (van der Pluijm and Carlson, 1989). The protomylonite Δ -values range from 3.12 to

4.80‰, which correspond to a similar mean temperature of 677°C (n=13) using the calibration of Kitchen and Valley (1995). Two localities for which I have the most data, gave a mean protomylonite temperature of 686°C (n=4), a mean mylonite temperature of 600°C (n=4), and a mean ultramylonite temperature of 642°C (n=5). The data indicated no significant difference in temperature due to the locality ($p=0.598$) or due to the extent of mylonitization ($p=0.326$). We therefore conclude that mylonites within the shear zone retain the isotopic signature from the previous peak regional metamorphism, rather than from the subsequent shearing at temperatures lower than graphite can recrystallize.

Calcite-Graphite Isotope Thermometry of Marble Mylonites in the Bancroft Shear Zone

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INTRODUCTION

The purpose of this study is to evaluate the behavior of the calcite-graphite isotope geothermometer in the Bancroft Shear Zone (BSZ) of the Grenville Province in southern Ontario. During the development of this shear zone, the marbles within the shear zone experienced mylonitization, forming finer grained marbles that range from protomylonites to ultramylonites. In order to test whether the carbon isotope system in these marbles was reset during shearing, I applied calcite-graphite thermometry to marble samples that experienced various degrees of mylonitization from multiple localities along the shear zone.

I will start by providing some background about the geology of the Grenville Province, the Ottawa Orogeny, and the formation of the Bancroft Shear Zone. I will explain the concepts behind calcite-graphite isotope thermometry and explain how this thermometer was calibrated. I will also provide background about the regional peak metamorphic temperatures of the study region. I will then discuss previous studies that have used calcite-graphite thermometry in the region and on marbles within the shear zone. Finally, I will describe my methods, results, and interpretations in the context of previous research that has been conducted in the Grenville Province, and discuss how my results improve our understanding of the calcite-graphite isotope thermometer.

Three possible outcomes could result from this study. If the calcite-graphite thermometer was not reset during shearing, then there will not be a difference between the $\Delta^{13}\text{C}_{\text{cal-gr}}$ values of the marbles outside the shear zone and the $\Delta^{13}\text{C}_{\text{cal-gr}}$ values of the various stages of mylonitized marbles within the shear zone. However, if the isotopic signature of the marble mylonites was reset during shearing, the $\Delta^{13}\text{C}_{\text{cal-gr}}$ values should increase as the extent of mylonitization increases, since lower temperatures produce larger $\Delta^{13}\text{C}_{\text{cal-gr}}$ values. The third possibility is that the $\Delta^{13}\text{C}_{\text{cal-gr}}$ values could be equally scattered above and below the regional $\Delta^{13}\text{C}_{\text{cal-gr}}$ values, indicating that during shearing the displacement of graphite away from the calcite that it originally established equilibrium with prior to extensional shearing occurred, rendering the $\Delta^{13}\text{C}_{\text{cal-gr}}$ data useless for determining temperature during either event. By determining which possible outcome occurred, we will increase our understanding of the calcite-graphite geothermometer and its potential uses in geothermometry studies.

BACKGROUND

History of the Grenville Province and Bancroft Shear Zone

The Grenville Province of Ontario, Canada consists of the Central Gneiss Belt, the Central Metasedimentary Belt, and the Central Granulite Terrain progressing from approximately west to east as shown in Figure 1 (Wynne-Edwards, 1972). Numerous periods of metamorphism occurred in the Grenville Province as multiple terranes accreted onto Laurentia (Carr *et al.*, 2000). The most recent, and generally the most pervasive, period of regional metamorphism in southern Ontario is the Ottawa Orogeny, which occurred episodically between approximately 1090-980 Ma (Carr *et al.*, 2000). During this period of convergence, northwest-directed thrusting throughout the Grenville Province occurred (Carr *et al.*, 2000). Shear sense indicators within the rocks support northwest thrusting during this period (Carlson *et al.*, 1990). This thrusting led to the formation of an orogenic plateau with an estimated width of several hundred kilometers and an estimated thickness of over 60 kilometers (Rivers, 2012). The formation of this plateau is believed to have resulted in partial melting within the mid-crust. This crustal thickening and partial melting weakened the mid-crust, resulting in orogenic collapse (Rivers, 2012).

The collapse led to the formation of the Bancroft Shear Zone, which is a late-stage extensional shear structure (van der Pluijm, 1991; Cosca *et al.*, 1995). This ductile shearing produced marble mylonites within the shear zone (Cosca *et al.*, 1995). The Bancroft Shear Zone is located within the Central Metasedimentary Belt, which is divided into five domains. The Bancroft domain is located in the northwestern most region of the Central Metasedimentary Belt, with the Elzevir, Mazinaw, Sharbot Lake, and Frontenac occurring proceeding to the southeast (Cosca *et al.*, 1995; Carr *et al.*, 2000). The Bancroft domain consists of middle to upper amphibolite grade gneisses and marbles and abundant igneous intrusions of various ages. The Elzevir domain consists of greenschist to lower amphibolite grade rocks including marbles, gneisses, and metavolcanics, as well as igneous intrusions (Wynne-Edwards, 1972; Carr *et al.*, 2000). The Bancroft Shear Zone occurs between the Bancroft domain and the Elzevir domain (Figure 2). The Bancroft terrane is the footwall and the Elzevir terrane is the hanging wall of the shear zone which dips to the southeast at an angle of 30° to 40° (Carlson *et al.*, 1990). U-Pb sphene ages indicate activity of the Bancroft Shear Zone from approximately 1045 to 1030 Ma (Metzger *et al.*, 1991).

An extensional sense of shear within the Bancroft Shear Zone is supported by the presence of shear sense indicators including S-C structures, rotated clasts, and mica-fish structures (Carlson *et al.*, 1990). The Bancroft Shear Zone mainly consists of marble mylonite, though mylonitized granites, syenites, and other rocks also occur within the zone (van der Pluijm, 1991). The complete sequence

of mylonites, from protomylonites to ultramylonites, occurs within the Bancroft Shear Zone (van der Pluijm, 1991). The portion of the shear zone that outcrops at the surface today is estimated to have formed 20 kilometers below the surface based on estimates of the temperature during shearing and the geothermal gradient (van der Pluijm, 1991). The shear zone extends approximately 70 kilometers in length, with an average width of 10 to 15 meters (van der Pluijm, 1989). Outcrops of marble in various stages of mylonitization occur throughout the region to the southwest of Bancroft.

Carbon Isotopes and Fractionation

The calcite-graphite thermometer is based on the fractionation of carbon-13 between calcite and graphite and can be used in calcite marbles to determine peak metamorphic temperatures. Isotopes are versions of the same element that contain different numbers of neutrons. Two stable isotopes of carbon exist; carbon-12 and carbon-13. Carbon-12 constitutes 98.90% of these two stable isotopes and has a mass of 12.000000 amu. Carbon-13 is the remaining 1.10% of the stable carbon isotopes and has a mass of 13.003355 amu. This 8.36% difference in mass between the two stable isotopes allows fractionation to occur during various biological and chemical processes (Faure and Mensing 1973). Isotopic fractionation is any process where the amount of one isotope is increased relative to the amount of the other isotope. $\delta^{13}\text{C}$ is the parameter that expresses the stable isotope composition of carbon. The $\delta^{13}\text{C}$ value is defined as:

$$\left(\frac{R_{sample} - R_{standard}}{R_{standard}} \right) \times 10^3 \text{‰}$$

where R is the $^{13}\text{C}/^{12}\text{C}$ ratio. This equation is also used to determine the $\delta^{18}\text{O}$ where R is the $^{18}\text{O}/^{16}\text{O}$ ratio. According to this equation, a material is depleted in carbon-13 if its $\delta^{13}\text{C}$ value is negative and is enriched in carbon-13 if its $\delta^{13}\text{C}$ value is positive (Faure and Mensing 753).

The Vienna Pee Dee Belemnite (VPDB) standard is defined to have a $\delta^{13}\text{C}$ value of zero permil (0‰) (Faure and Mensing 753). This standard is a marine carbonate and so marine calcites, for example limestones, tend to have $\delta^{13}\text{C}$ values that are close to zero and range from approximately +5‰ to -5‰ depending on the period of Earth history during which they formed (Faure and Mensing 764-766). Meanwhile, the organic matter in sediments from which graphite is derived is depleted in carbon-13, and usually shows $\delta^{13}\text{C}$ values between -20‰ and -30‰ (Valley and O'Neil, 1981). Often, the $\delta^{13}\text{C}$ value of graphite within marble is greater than -10.0‰ but less than 0.0‰ (Valley and O'Neil, 1981). Graphite forms during metamorphism from organic material within the sediment (Dunn and Valley, 1992). If carbonates are present during this process, fractionation of the stable carbon isotopes can occur between the carbonates and the graphite (Dunn and Valley, 1992). The resulting fractionation is dependent on the peak temperature that the rock experienced during graphite crystallization, allowing it to be used as a geothermometer (Dunn and Valley, 1992).

Calcite-Graphite Thermometry

During prograde metamorphism, as the graphite crystallizes from organic material, it exchanges isotopes with the calcite in the rock, causing the $\delta^{13}\text{C}$ of the graphite to become heavier and the $\delta^{13}\text{C}$ of the calcite to become lighter. The $\delta^{13}\text{C}_{\text{cal}}$ and $\delta^{13}\text{C}_{\text{gr}}$ values are used to determine the $\Delta^{13}\text{C}_{\text{cal-gr}}$ value, which is the $\delta^{13}\text{C}_{\text{cal}}$ value minus the $\delta^{13}\text{C}_{\text{gr}}$ value (Valley and O'Neil, 1981). In the early, very low temperature stages of metamorphism, the exchange of carbon between calcite and the graphitic material is limited. Valley (2001) cites data showing that isotopic exchange can begin at 300°C. The amount of isotopic exchange between calcite and graphite increases as the metamorphic temperature increases, causing the difference between the $^{13}\text{C}/^{12}\text{C}$ ratio in calcite and graphite to decrease, resulting in smaller $\Delta^{13}\text{C}_{\text{cal-gr}}$ values at higher temperatures (Valley and O'Neil, 1981; Figure 3). This decrease in $\Delta^{13}\text{C}_{\text{cal-gr}}$ values at higher temperatures enables estimation of the peak metamorphic temperature. However, once the graphite is crystallized, carbon exchange between the calcite and graphite becomes difficult. Calcite-graphite thermometry is possible because carbon exchange within crystalline calcite occurs at temperatures as low as 350°C, while carbon exchange in crystalline graphite is negligible at temperatures up to 1000°C, making it difficult for this thermometer to be reset, allowing preservation of the isotopic signature from the peak metamorphic conditions (Valley 2001).

Due to the high temperature required for crystalline graphite to exchange by diffusion, experimental calibration of the calcite-graphite thermometer has

been unsuccessful (Dunn, 2005). Therefore the calcite-graphite thermometer was calibrated by relating the $\Delta^{13}\text{C}_{\text{cal-gr}}$ value to temperatures determined within rocks from the same area using other previously determined thermometers. Valley and O'Neil (1981) used K-feldspar-plagioclase feldspar and magnetite-ilmenite thermometry to determine the peak metamorphic temperatures of rocks sampled from the Adirondacks. The temperature estimates obtained from these thermometry methods were then compared to the $\Delta^{13}\text{C}_{\text{cal-gr}}$ values in order to calibrate the thermometer. This calibration resulted in a relationship in which $\Delta^{13}\text{C}_{\text{cal-gr}} = -0.00748T + 8.68$ where the temperature is measured in degrees Celsius (Valley and O'Neil, 1981).

Dunn and Valley (1992) continued to refine the calibration of the calcite-graphite thermometer through comparison with temperature estimates obtained from calcite-dolomite thermometry. This calibration resulted in a relationship in which $\Delta^{13}\text{C}_{\text{cal-gr}} = 5.81 \times 10^{-6}T^2 - 2.61$ where the temperature is measured in Kelvin (Dunn and Valley, 1992). The methods used by Dunn (2005) to determine temperature conditions using calcite-dolomite thermometry have a minimum uncertainty of $\pm 0.20\%$ for the $\Delta^{13}\text{C}_{\text{cal-gr}}$ value. At temperatures below 670°C , this corresponds to an uncertainty in temperature of $\pm 15^\circ\text{C}$ (Dunn, 2005). The Dunn and Valley calibration is the most reasonable calibration for temperatures below 600°C (Valley, 2001).

Kitchen and Valley (1995) also worked to calibrate the calcite-graphite thermometer. They sampled graphitic marbles from the Northwest Adirondacks

and the Central Adirondacks, forming a data set of 115 calcite-graphite fractionations (Kitchen and Valley, 1995), including data from Valley and O'Neil (1981). They compared this fractionation data to temperatures in these regions that had previously been determined in other studies using K-feldspar-plagioclase thermometry, magnetite-ilmenite thermometry, calcite-dolomite thermometry, and garnet-clinopyroxene thermometry (Kitchen and Valley, 1995). Through calibration with these other thermometers, they determined the equation $\Delta^{13}\text{C}_{(\text{cal-gr})} = 3.56 \times 10^6 T^{-2}$ for the calcite-graphite thermometer, where the temperature is expressed in Kelvin (Kitchen and Valley, 1995). Many other studies have also determined calibrations for the calcite-graphite thermometer (Figure 4), but the Kitchen and Valley (1995) calibration is generally agreed to be the most accurate thermometer at temperatures above 600°C (Dunn, 2005).

RAM Thermometers

The calcite-graphite thermometer is a useful thermometer because it is a RAM thermometer. RAM stands for refractory accessory mineral (Valley, 2001). A refractory accessory mineral is a mineral that constitutes a small proportion of the mode and has a slow diffusion rate (Valley, 2001). Since refractory accessory minerals have very slow rates of diffusion, they do not exchange isotopes with other minerals once they have crystallized (Valley, 2001). The other mineral used in a RAM thermometer also maintains its peak temperature isotope ratio because the refractory accessory mineral is ideally the only other mineral present that it would exchange with (Valley, 2001). RAM thermometry is most accurate when

the quantity of the refractory mineral is very small and no third phase is present with which exchange could occur (Valley, 2001). In order for RAM thermometry to be accurate, the refractory mineral should not undergo retrograde recrystallization, exhibit growth zonation, or have cryptic alteration (Valley, 2001).

Calcite-graphite thermometry is a RAM thermometer because although carbon exchange by diffusion within calcite can occur at temperatures as low as 350°C, carbon diffusion in graphite is negligible at temperatures up to 1000°C (Valley, 2001). Carbon has an extremely slow diffusion rate in graphite. Therefore, graphite recrystallization must occur in order for the calcite-graphite thermometer to be reset. Examination of the mineral textures in thin section can provide evidence of recrystallization (Dunn and Valley, 1992). Once the graphite has finished crystallizing or recrystallizing, isotopic exchange with calcite will essentially cease (Valley, 2001). If another carbonate mineral such as dolomite is present in a marble containing calcite and graphite, the temperature calculated from calcite-graphite thermometry methods must be corrected. If calcite and graphite are the only two carbon-bearing phases present, the thermometer will not be reset if only the calcite recrystallizes, because there is no other phase with which to exchange carbon.

However, it is also important to consider the complication that the isotope ratio may not always accurately reflect peak metamorphic conditions. If the graphite recrystallizes before the calcite and graphite attain isotopic equilibrium,

the isotope values will reflect some intermediate condition, rather than the true peak metamorphic temperature. Dunn (2005) states that below about 540°C, the thermometer becomes less reliable because calcite and graphite isotopic disequilibrium is possible. Therefore at temperatures below 540° the calcite and graphite may not be in isotopic equilibrium and so may not reflect the peak metamorphic temperature (Dunn, 2005).

Dolomite-Calcite Fractionation

The presence of dolomite within calcite marble samples must also be considered when using calcite-graphite thermometry. The presence of dolomite can be an issue because carbon isotope fractionation occurs between the coexisting calcite and dolomite. This is due to the fractionation of carbon isotopes being dependent on both temperature and magnesium concentration within carbonates (Dienes, 2004). Dolomite has a chemical formula of $\text{CaMg}(\text{CO}_3)_2$ while calcite has the formula CaCO_3 . The heavier carbon isotope is preferentially incorporated into carbonates that are higher in magnesium (Dienes, 2004). Therefore if a marble contains both calcite and dolomite, the heavier carbon isotope will be preferentially incorporated into the dolomite, causing the carbon isotope ratio of the calcite to be smaller than it would be in a pure calcite marble under those same temperature conditions (Dienes, 2004). The CO_2 released and analyzed in a marble containing both calcite and dolomite is a mixture derived from both of these carbonates. However, we only want the isotope value of the CO_2 that is released from the calcite for calcite-graphite thermometry. Therefore

if the presence of dolomite in a calcite marble were not corrected for, a sample high in dolomite would result in a lower temperature estimate than the true value.

Sheppard and Schwarcz (1970) used magnesium-calcite solvus thermometry to determine the fractionation of carbon isotopes between calcite and dolomite at temperatures between 100°C and 650°C. The fractionation that occurs is nonlinear and modeled by the equation $10^3 \ln \alpha = 0.18(10^6 T^{-2}) + 0.17$ where $\alpha = \frac{(^{13}C/^{12}C)_{Dol}}{(^{13}C/^{12}C)_{Cal}}$ and temperature is in degrees Kelvin (Sheppard and Schwarcz, 1970). Therefore at temperatures around 100°C the dolomite is 1.4‰ heavier than the calcite, while at 650°C the dolomite is only 0.4‰ heavier than calcite (Figure 5). Therefore the presence of dolomite has a much greater effect on calcite-graphite thermometry at low temperatures, and the presence of dolomite should be noted and corrected for when interpreting temperature estimates. In the temperature range of interest in this study, a small correction can be applied, though this is only necessary when the dolomite constitutes a significant proportion of the carbonate (>20%).

Mylonite Textures and Classification

It is clear from field relations that the protolith of the mylonites in the Bancroft Shear Zone is the adjacent coarse-grained marbles consisting of a matrix of calcite grains between 1 and 5 mm in diameter, with graphite grains between 1 and 5 mm in diameter between the calcite (Carlson et al., 1990). In the protolith, the calcite can be equant to irregular in shape, while the graphite is usually found as euhedral flakes and aggregates (Carlson et al., 1990). As the calcite grains

experience shearing conditions, they become progressively smaller until they reach 5 to 200 μm in the mylonites and less than 30 μm in the ultramylonites (van der Pluijm, 1991). The size of the graphite is reduced even further, with grains becoming submicroscopic within the ultramylonites (van der Pluijm, 1991). The extent of mylonitization reflects the differing amount of stress that the protolith experienced, with increased mylonitization reflecting increased stress (van der Pluijm, 1991). The reduced grain size that exists in mylonites is caused by the combination of high differential stress and low temperatures within the ductile shear zones where they form since small grains are typically more stable during dynamic recrystallization under these conditions (Passchier and Trouw, 1996).

Structures including lineations, foliations, mica fish, and S-C structures can provide information about the sense of shear within various mylonite stages. S-C structures are defined by the long axes of calcite grains occurring at an angle to the shear plane, which is often delineated by the foliation highlighted by sheared graphite (Figure 6). S-C textures are characteristic of dynamic recrystallization (Busch and van der Pluijm, 1995). Protomylonites can also contain abundant porphyroclasts, which are relict grains of calcite within which new grain boundaries are partially formed (Figure 7). These grains help to indicate that the marble was experiencing deformation and forming new grain boundaries during this process. Minerals other than calcite, including tremolite and diopside, can experience solid-state grain boundary adjustment, which is indicated by the presence of rounded grain corners (Vernon, 2004).

Van der Pluijm (1991) defines four different mylonite classifications; protomylonites, coarse mylonites, fine mylonites, and ultramylonites. He describes protomylonites as consisting of mainly equant calcite grains that exhibit twins. These calcite grains range from 2 mm to 6 mm with a mean size of 3.2 ± 1.1 mm. The graphite grains within the protoliths are randomly oriented and range from 1 mm to 20 mm. Protomylonites contain calcite grains with a mean grain size of 2.3 ± 1.0 mm, with some grains as small as 50 to 150 μm . Some calcite grains within protomylonites are elongate, exhibit undulose extinction, or have bent twins. The graphite grains in the protomylonites are oriented (van der Pluijm, 1995). Van der Pluijm (1991) defines two types of mylonites. Coarse mylonites have mean calcite grains of 153 ± 67 μm while fine mylonites have a mean grain size of 47 ± 22 μm . These mylonites have dark bands of fine graphite, and the fine mylonites have S-C textures. Ultramylonites are dark gray to black at the scale of the outcrop, and contain mean calcite grains of 22 ± 10 μm . The ultramylonites lack S-C structure (van der Pluijm, 1991). The gradational transition from protolith to ultramylonite is illustrated in Figure 8.

A similar classification scheme is described by Busch and van der Pluijm (1995). They define four different mylonite classifications within the Bancroft Shear Zone; protomylonites, coarse mylonites, S-C mylonites, and ultramylonites (Figure 9). They classify protomylonites as marbles consisting of coarse calcite porphyroclasts. The coarse grains are rimmed by finer calcite grains, have straight to curved grain boundaries, and exhibit undulose extinction (Busch and van der

Pluijm, 1995). Coarse mylonites are defined as recrystallized grains with sharp extinction, straight to slightly curved calcite grain boundaries, and a weak dimensional preferred orientation (Busch and van der Pluijm, 1995). S-C mylonites experience a continued decrease in grain size, straight to curved grain boundaries, and an S-C structure formed by elongate calcite grains. Coarser grains within S-C mylonites will often have sub-grains forming within them. Mylonites are characterized as having even smaller grain sizes, with a loss of the dimensional preferred orientation (Busch and van der Pluijm, 1995). I based my mylonite classification scheme off those described by van der Pluijm (1991) and Busch and van der Pluijm (1995).

Recrystallization Textures and Temperatures

If temperatures during or after shearing become too warm, mylonite and ultramylonite textures can be lost and are replaced by annealing textures (van der Pluijm, 1991). The presence of these annealing textures can help to provide limits on the temperature during shearing, since at temperatures above 500°C, carbonates anneal rapidly (van der Pluijm, 1991). Therefore carbonates that still exhibit a fine-grained texture must have experienced lower shearing temperatures at which annealing cannot occur. Deformation twinning occurs in calcite and the style of twinning can indicate the temperature at which deformation occurred (Vernon, 2004). Deformation twins are narrow and straight at temperatures below 200°C and widen as conditions approach 300°C (Passchier and Trouw, 1996). Bending and intersection of calcite twins occurs above 200°C, and above 250°C

calcite twin boundaries become serrated (Passchier and Trouw, 1996). The appearance of these different types of deformation twins are illustrated in Figure 10 and can be used to access the temperatures that marble mylonites were experiencing during at least a portion of their deformation.

In calcite rocks, dynamic recrystallization often begins at grain boundaries and then moves progressively further into the grain. In addition, it can begin along the twins within the calcite grains (Ferrill *et al.*, 2004). This recrystallization process results in calcite grains with serrate boundaries or core and mantle structures (Ferrill *et al.*, 2004). Amphibolite facies conditions are required for grain-boundary migration recrystallization to occur in calcite (Vernon, 2004). According to Vernon (2004), ductile deformation and dynamic recrystallization in calcite usually occur at the greenschist facies or at higher temperatures, but can occur as low as 150°C to 250°C. Ferrill *et al.* (2004) state that dynamic recrystallization of calcite can begin above 250°C; this is represented in thin section by the boundary between type III and type IV calcite twinning (Figure 10). Therefore while calcite recrystallization is probably most common at the greenschist grade and higher grades, some studies have indicated recrystallization is possible at temperatures as low as 150°C.

Previous Regional Thermometry in the Study Area

Mineral isograds and various geothermometers have been applied to the Grenville Province to determine the regional peak metamorphic temperatures produced during the Ottawa Orogeny. Diopside-grade marble occurs throughout

my area of study. The reaction tremolite + calcite + quartz = diopside + CO₂ + H₂O within the marbles indicates that the peak regional metamorphic temperature of the Ottawa Orogeny must have exceeded 575°C here (Dunn, 2005). Protolith (unsheared) marbles are reported by van der Pluijm and Carlson (1989) to have $\Delta^{13}\text{C}_{\text{cal-gr}}$ values of 3.3‰ to 4.2‰. According to the calcite-graphite thermometer calibrated by Kitchen and Valley (1995), these values correspond approximately to temperatures of 650°C to 720°C for the peak regional metamorphic temperature of the Ottawa Orogeny.

A study by Rathmell *et al.* (1999) compiles regional metamorphic temperatures from multiple studies and three different geothermometers including calcite-graphite, calcite-dolomite, and garnet-biotite thermometry (Figure 11). The garnet-biotite thermometry temperatures determined by Rathmell *et al.* (1999) can be used to approximate a 650°C isotherm that is located a few kilometers southeast of Bancroft and trends southwest just east of Apsley (Figure 11a). To the southeast of this isotherm, toward Madoc, the garnet-biotite thermometry indicates a decrease in temperature (Rathmell *et al.*, 1999). Rathmell *et al.* based the curvature of the isotherms near Apsley off the shape of the pelitic isograds determined by Carmichael *et al.* (1978) (Figure 11d). The lobate isotherm based on the pelitic isograds in this region is not strongly supported by the thermometry data (S. Dunn, personal communication, March 2015) and so the isotherms are probably more like those depicted in Figure 11b. The calcite-graphite thermometry (Figure 11c) conducted by Dunn (1989) and the calcite-

dolomite thermometry (Figure 11b) conducted by Dunn and Valley (1992) generally agree with the trend that peak metamorphic temperatures increase from Madoc to Bancroft (Rathmell *et al.*, 1999). Near Madoc, temperatures range from about 400°C to 500°C, while near Bancroft temperatures are typically between 550°C and 650°C, with a few samples indicating even higher temperatures (Figure 11).

Figure 12 shows a geologic map of the region depicting an approximation of the Bancroft Shear Zone (BSZ) and isotherms in the region (Dunn, personal communication, March 2015). The regional temperatures on this map are a combination of garnet-biotite thermometry and calcite-graphite thermometry from both published and unpublished work. This map is similar to Figure 11, with regional metamorphic temperatures increasing from Madoc past Bancroft and Apsley. Figure 12 introduces a 700° isotherm located to the northwest of the Cardiff, Cheddar, and Anstruther domes. Therefore protolith marbles in our study region would be expected to indicate temperatures in the 600°C to 700°C range, with the possibility of temperatures slightly greater than 700°C, based on Figure 11 and Figure 12. This is consistent with the study by van der Pluijm (1991) that generalized the Bancroft terrane as middle to upper amphibolite grade and the Elzevir terrane as greenschist to lower amphibolite grade.

Previous Studies on Resetting of the Calcite-Graphite Thermometer

A previous study by van der Pluijm and Carlson (1989) used calcite-graphite thermometry methods to try to determine the temperature at which

mylonites within the Bancroft Shear Zone deformed during extensional collapse and the development of the shear zone. Van der Pluijm and Carlson (1989) reported $\Delta^{13}\text{C}_{\text{cal-gr}}$ values of 4.7‰ to 9.5‰ for mylonites within this shear zone. These values correspond to temperatures of 620° to 420°C. However, only data for six samples of unsheared marble and six samples of sheared marble mylonites are reported in their study. Van der Pluijm (1991) reports data from nine mylonite and ultramylonites samples, some of which are from his previous study. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values from these samples range from 6.2‰ to 9.5‰, indicating temperatures from 450°C to 540°C (van der Pluijm, 1991). The data reported by van der Pluijm and Carlson (1989) and by van der Pluijm (1991) support the idea that the graphite within the shear zone recrystallized, allowing at least partial exchange of carbon between adjacent calcite and graphite, resetting the calcite-graphite thermometer to lower temperatures (~450°C) during the shearing event.

However, there is debate as to whether carbon isotope exchange is possible under these shearing conditions due to the extremely slow diffusion rate of carbon out of graphite at low temperatures (Valley and O'Neil, 1981). Dunn and Valley (1992) argue that the calcite graphite thermometer was not reset during nearby regional metamorphism at temperatures around 500°C. Rather, the temperatures from earlier contact metamorphism were preserved by the calcite-graphite thermometer, while the calcite-dolomite thermometer was reset to record the lower regional metamorphic temperatures (Dunn and Valley, 1992). However the marbles studied by Dunn and Valley (1992) did not experience shearing and

grain size reduction, which could be the factor that led to the resetting of the thermometer in the study by van der Pluijm and Carlson (1989). Therefore the current literature is inconclusive about the conditions that reset the calcite-graphite thermometer.

METHODOLOGY

Field and Petrography Methods

Over the course of four days during August 2014, Steven Dunn, Michelle Markley, and I sampled various marble mylonites from road cut outcrops along the Bancroft Shear Zone in the area around Bancroft, Canada. We collected samples from nine different localities from within three different quadrangles. I extracted enough graphite from samples for calcite-graphite thermometry analysis from the six localities shown on the map (Figure 12). The GPS coordinates for these localities can be found in Table 1. The longitude and latitude values for the sample localities are listed in degrees, minutes, and seconds. We determined these coordinates using Google Earth (Markley, personal communication, March 2015). At some locations, we collected multiple samples from along the same foliation.

We cut and stained thin sections with alizarin in order to be able to distinguish calcite from dolomite (Rathmell *et al.*, 1999). I estimated the mineral modes for each thin section in percent and noted the occurrence of accessory minerals (Table 2). I used reflected light to distinguish graphite from other opaque minerals. I estimated the mean calcite grain size range for each thin section. I made observations about the types of grain boundaries, the grain shapes and orientations, any intra-grain textures, and layering for each thin sample. We also analyzed thin sections of GM14-5-1, GM14-6-2, WF14-1-5B, GM14-1-1, and

BT14-1-3 on the scanning electron microscope at Mount Holyoke College to confirm the minerals present. We polished other thin sections in order to use reflected light to distinguish graphite from the other opaque minerals in thin section.

Methods: Calcite Analysis

I determined the stable carbon and oxygen isotope values for the calcite and graphite from the same billet of rock. I recorded the mass of each sample billet in grams. I scrubbed all samples clean to remove any soil or other materials. I crushed the sample billets into small pieces and then ground them down to a powder. I placed a small portion of the whole-rock powder in a labeled vial. I sent all the vials to the Department of Geosciences at the University of Massachusetts-Amherst in order to determine the stable carbon and oxygen isotope values of the calcite. The whole-rock calcite samples were reacted with concentrated phosphoric acid within the automated carbonate preparation system according to the methods of acid decomposition of carbonates described by McCrea (1950). This system was connected to a Finnegan Delta Plus XL ratio mass spectrometer, which runs eight cycles for each measurement. The Vienna Pee Dee Belemnite (VPDB) standard was used for the carbon R_{standard} and the Vienna Standard Mean Ocean Water (VSMOW) standard was used for the oxygen R_{standard} . The results are reported in standard delta notation where both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ equal $(R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$. The ratio of the minor to the major isotope is represented by R . We analyzed MHC calcite standards eight times.

Methods: Graphite Analysis

I obtained the graphite separate from the remainder of the whole-rock powder through flotation. Some samples did not have enough graphite to determine their $\delta^{13}\text{C}$. I poured the whole-rock powder in a large beaker and then added water to the beaker with enough force to froth the water and cause the graphite to float to the top. I used filter paper to scoop the floating graphite flakes out of the beaker. I rinsed the flakes off the filter paper into the vacuum filter and continued to scoop graphite until I removed the majority of the graphite from the beaker. I washed the 0.3 μm filter paper within the vacuum filter that was coated in graphite in hydrochloric acid in order to dissolve any calcite or dolomite present on the filter paper. Then I rinsed the graphite on the filter paper thoroughly with distilled water. I placed the filter paper in a covered glass petri dish and then heated it in the furnace for about 15 minutes at 120°C .

I combined approximately 0.5 mg of the graphite with at least fifty times that amount of copper oxide and then ground them together using a mortar and pestle. I wore gloves in order to prevent contamination of the samples. I poured this mixture into a quartz tube that had been cleaned of carbon by pre-firing it in the furnace at 950°C overnight. I then attached the quartz tube to the vacuum line and evacuated it. I fused the tube containing the evacuated sample shut using a torch and placed it in the furnace overnight at 950°C to produce carbon dioxide.

I then used cryogenic methods on the vacuum line to purify and extract the carbon dioxide produced from the graphite from the marble samples. First I

scratched the quartz tube containing the CO₂ in order to create a point of weakness along which I would break the tube. I then attached the tube to the vacuum line. Three quartz tubes and three 6 mm Pyrex tubes were attached to the vacuum line at one time. I opened all the valves where the tubes were connected to the vacuum line in order to pump out the air. I used a heat gun to evaporate any moisture within the tubes. I checked the pressure gauge to make sure that no air was leaking into the vacuum line. Once the line was airtight, I closed both ends of the line. I used liquid nitrogen to cool the U-trap. I cracked one quartz tube to allow the CO₂ to enter the vacuum line. I waited until the pressure gauge indicated that only non-condensables remained in the line. I recorded the quantity of non-condensables in millitorrs. I then released the non-condensables by slowly opening the valve and allowing the pressure gauge to return to zero. Then I closed the valve and opened a valve leading to one of the 6 mm Pyrex tubes. I quickly transferred the liquid nitrogen around the Pyrex tube while I placed pentane slush around the U-tube. This allowed the frozen CO₂ within the U-tube to thaw and re-condense within the Pyrex tube, while the unwanted gases remained frozen in the U-tube. When the gauge returned to almost zero, I torched off and labeled the Pyrex tube. I completed this process for the remaining two samples that were on the vacuum line. Then I thawed the U-tube with the heat gun and released the unwanted gasses.

I repeated this process twice for most graphite samples. The CO₂ in the Pyrex tubes was analyzed on the Finnegan Delta XL mass spectrometer at the

University of Massachusetts-Amherst. I obtained stable oxygen and carbon isotope data for the graphite using the same Finnegan Delta XL mass spectrometer at the University of Massachusetts-Amherst. We analyzed fourteen MHC graphite standards. The laboratory methods used in this study are based on the methods of Dunn and Valley (1992), and Dunn (2005).

Analytical Methods

I corrected the $\delta^{13}\text{C}$ values of the four samples that contained observable quantities of dolomite (GM14-5-1, GM14-6-2, GM14-6-3, WF14-1-1A). Between 500°C and 700°C, a sample that contains only dolomite as the carbonate must be corrected by 0.4‰ (Figure 5). Therefore I multiplied the modal amount of dolomite by 0.4‰ and subtracted this value from the measured $\delta^{13}\text{C}$ value of the sample to correct for the presence of dolomite. Most of the graphite $\delta^{13}\text{C}$ values used to calculate the $\Delta^{13}\text{C}_{\text{cal-gr}}$ values represent a two-sample mean. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values are the values used to determine the peak metamorphic temperature of the sample. I used the thermometer calibrated by Kitchen and Valley (1995) to calculate the temperature of the samples in this study because Dunn (2005) determined that it was the most accurate thermometer above 650°C.

I focused my analyses on the two outcrops that contained multiple mylonite stages. I used Excel to make tables and graphs of my data. I performed my statistical analyses in SPSS. I performed ANOVAs on the data to determine whether there was a significant difference in the temperature of the two localities and the different stages of mylonitization. I created plots of the standardized

residuals versus the predicted values to check that the residuals met the ANOVA assumptions.

RESULTS

Sample Textures and Petrography

Summary

I categorized each sample as a protomylonite, mylonite, or ultramylonite based on its mean grain size range and textural appearance (Table 3), in a similar scheme as that used by van der Pluijm (1991) and Busch and van der Pluijm (1995). The majority of the calcite grains in samples defined as **protomylonites** are larger than 1 mm, with grains as coarse as 6.4 mm and grains as fine as 10 μm in the rims around the coarse grains. The graphite grains in the protomylonites are usually mainly large grains, although in a few samples the graphite defines a very weak foliation. The calcite grain boundaries range from straight to serrate, but are typically straight or curved. The majority of the grains in the **mylonites** are an order of magnitude smaller, usually around a few hundred microns. The largest grains in the mylonites are about 2.8 mm but these grains usually show faint signs of sub-grain formation within their boundaries. The smallest grains in the mylonites are around 10 μm but these are usually found rimming coarser grains. Many of the calcite grains in the mylonites are no longer equant but instead have an aspect ratio of 2:1 or 3:1. The graphite in the mylonites occurs both as large grains and as sheared out wisps that define the foliation. The **ultramylonites** consist of the finest grains, which range in size from 5 μm to 70 μm . An S-C

structure is apparent in some of the ultramylonites. In some samples, a few coarse calcite grains remain but sub-grain formation is apparent within them. While some coarse graphite grains still remain in some samples, much of the graphite is finely sheared, defining the foliation. The calcite grain boundaries in the mylonites are typically straight to curved, and triple junction grain boundaries can be present.

Overall, the mineralogy of the marble samples in this study is relatively consistent. Most samples are mainly calcite, with non-trace amounts of diopside, tremolite, and phlogopite (the magnesium rich biotite end member). All except two of the samples for which I present isotope data contain at least 60% calcite. These low calcite samples are WF14-1-1A and WF14-1-3A. WF14-1-1A contains substantial amounts of dolomite. The other low (~55%) calcite sample, WF14-1-3A, contains a larger amount of K-feldspar and phlogopite relative to the other samples. Graphite and iron sulfides are present in low quantities (usually less than 10% combined) in most samples. A few samples from localities GM14-1, GM14-2, and BT14-1 contain serpentine. Many samples also contain 10% or less potassium feldspar in the form of microcline. Trace quantities of titanite also occur in many of the samples. Other minerals that are occasionally present in trace quantities in a few samples include ilmenite, apatite, quartz, and rutile. I am unable to find any mineral assemblages within my samples that could definitively be used to more narrowly constrain the metamorphic temperature.

GM14-1

Locality GM14-1 is along route 507 approximately 0.3 miles south of Gooderham, Ontario (Table 1). The marble contains anastomosing mylonite bands (Figure 13). Both serpentine and dolomite occur in the marble at GM14-1. The presence of serpentine may indicate that the marble used to contain forsterite that has since been hydrated. Forsterite is a high-grade mineral. We have five samples collected from GM14-1, and two of them yield isotope data; GM14-1-4 and GM14-1-5B. I also analyzed sample GM14-1-1 under the SEM and found serpentine intergrown with phlogopite and replacing tremolite (Figure 14).

Sample GM14-1-4 is a protomylonite with calcite grains of variable sizes that range from 100 μm to 1200 μm (Figure 15). Some calcite grains in this sample have serrate boundaries, while others are straighter with triple grain junctions. Twinning is not very distinct in many of the calcite grains and the twins are straight where they are present. The aspect ratio of the calcite grains is equant to 2:1. Other minerals in the sample include alkali feldspar and diopside. These minerals have curved boundaries, and the diopside appears altered in many places. The preferred orientation of sheared graphite and other opaques between the calcite grains defines the foliation. This foliation is very apparent at the scale of the thin section in sample GM14-1-4.

Sample GM14-1-5B is a protomylonite (Figure 16). The calcite grains in this sample range from 200 μm to 1600 μm , with some smaller sub-grains around other minerals. The calcite has straight to curved grain boundaries, and some

grains even have mildly serrate grain boundaries. Some calcite grains lack twinning while others show two directional twins. Many calcite grains have a 2:1 aspect ratio that is elongate parallel to the foliation. The preferred orientation of sheared graphite and the other opaques, which occur between the calcite grains, strongly defines the foliation at the scale of the thin section. Other minerals in this sample include alkali feldspar and diopside; these grains are commonly equant with curved grain boundaries.

GM14-2

Locality GM14-2 is located along route 507 approximately 2.2 miles south of Gooderham (Table 1). GM14-2 is essentially the type locality of the shear zone (van der Pluijm, 1991). Light gray to very dark gray calcite marbles occur at this outcrop. We focused on one area of the outcrop where thick regions of protomylonites, mylonites and ultramylonites all occur. We collected seven samples from this area of the outcrop. We collected approximately two samples from each mylonite stage, along the same foliation (Figure 17). We also collected two additional samples at a more southern point in the outcrop. We identified diopside, phlogopite, titanite, and graphite at the outcrop in some of the hand samples from this locality. I present isotope data from eight samples from this locality.

Sample GM14-2-1A is an ultramylonite. Most of the calcite grains in this sample range from 10 μm to 70 μm in length; these grains have straight to curved boundaries with triple-grain junctions (Figure 18). Some larger grains of calcite

are up to 700 μm long, show serrate grain boundaries and have low relief. The calcite grains do not exhibit twinning, have a 2:1 aspect ratio, and exhibit undulose extinction. The small calcite grains show a preferred orientation. Strands and wisps of sheared out graphite occur between calcite grains at an almost 45 degree angle to the long axes of the calcite grains. Thus, the calcite and graphite define an S-C structure. The preferred orientation of sheared graphite and other opaques strongly defines the foliation at the scale of the thin section. Graphite grains are as long as 150 μm and many grains are smaller than 10 μm . The other mineral grains in the samples, including alkali feldspar and diopside, are rounded and equant.

Sample GM14-2-2 is an ultramylonite that contains calcite grains that range from 5 μm to 40 μm with a few larger grains located in shadows around other minerals (Figure 19). The calcite grains have very narrow twins or lack twins. The calcite grains exhibit triple-grain junctions and undulose extinction. The calcite grains are equant or have a 2:1 aspect ratio. The preferred orientation of the finely sheared graphite and other opaques strongly defines the foliation at the scale of the thin section. These strands of sheared opaques bend around other minerals including feldspar and diopside.

Sample GM14-2-3B is an ultramylonite (Figure 20). The calcite in this sample is fine grained (5 μm to 60 μm). Rims of both coarser and finer calcite occur around other mineral grains. The calcite has mainly rounded grain boundaries with some triple grain junctions. The calcite has undulose extinction,

little to no twinning, and is equant. The preferred orientation of the finely sheared graphite and other opaques strongly defines the foliation at the scale of the thin section. These strands of sheared opaques bend around other minerals such as feldspar and diopside.

Sample GM14-2-4 is an ultramylonite (Figure 21). The majority of the calcite grains range from 10 μm to 50 μm , with finer grains localized within zones of sheared opaques and a few grains as large as 500 μm . One calcite grain is 1700 μm in length and has very undulose extinction. The majority of the calcite grains have straight to curved grain boundaries and many have triple grain junctions. These calcite grains are mainly equant, with a minority of grains showing a 2:1 aspect ratio. The coarser calcite grains have serrate boundaries. Some graphite grains are as long as 250 μm , but many grains are 20 μm or smaller. The preferred orientation of the finely sheared graphite and other opaques strongly defines the foliation at the scale of the thin section.

Sample GM14-2-6 is a mylonite (Figure 22). This sample contains calcite grains ranging from 20 μm to 1160 μm , with some of the larger grains showing straight twinning. The calcite grain boundaries are straight to lobate. The calcite grains range from equant to an aspect ratio of 3:1. The calcite grains show a weak shape preferred orientation with their long axes parallel to the foliation defined by the graphite. The calcite grains show undulose extinction. Some large mica grains show extremely curved cleavage and undulose extinction. Other minerals, including diopside and alkali feldspar, have rounded grain boundaries. The

preferred orientation of the sheared graphite and other opaques such as pyrrhotite strongly defines the foliation at the scale of the thin section. The graphite is located between the calcite grains and ranges from 20 μm to less than 5 μm in length.

Sample GM14-2-7 is a mylonite (Figure 23). The calcite grains in this sample are very variable in size, with grains ranging from 20 μm to 2800 μm in length. The calcite grain boundaries are lobate to serrate with only a few grains exhibiting triple grain junctions. The calcite grains have undulose extinction and some of the large grains have twins. The calcite grains vary from equant to an aspect ratio of 3:1. The preferred orientation of the sheared graphite and other opaques defines the foliation at the scale of the thin section. Other minerals in this sample include feldspars, tremolite, and diopside. These other grains tend to have curved boundaries.

Sample GM14-2-8 is an ultramylonite (Figure 24). This sample contains a majority of calcite grains ranging from 10 μm to 60 μm . Rims of fine calcite grains often occur around other minerals within the sample. The majority of the calcite grains have straight to lobate boundaries and many have triple grain junctions. The calcite grains range from equant, to an aspect ratio of 2:1 and have undulose extinction. Strands and wisps of fine, sheared out graphite occur between calcite grains at angles ranging from 0 degrees to almost 45 degrees to the long axes of the calcite grains indicating a weak S-C fabric. Some graphite grains are as long as 100 μm but many grains are 20 μm or smaller. The preferred

orientation of graphite and other opaques weakly defines the foliation at the scale of the thin section. Alkali feldspar, tremolite, and other minerals in the sample have curved grain boundaries.

Sample GM14-2-9 is a protomylonite (Figure 25). Calcite grains in this sample range from 560 μm to 5000 μm . The calcite has lobate to very serrate grain boundaries and lacks triple junctions. The calcite grains have bent and intersecting twins (type III twins) and exhibit undulose extinction. Fine-grained calcite ranging from 10 μm to 30 μm rims many of the large calcite crystals and other minerals such as phlogopite. Many phlogopite grains occur within this sample and tend to exhibit a preferred orientation, defining a weak foliation. Elongate grains of graphite occur in this sample and range from 70 μm to 350 μm in length.

GM14-5

Locality GM14-5 is located along route 503 approximately 1.2 miles west of Tory Hill (Table 1). This outcrop consists of coarse-grained marble with an approximately 1 cm thick vein of mylonite running through it (Figure 26). Below this coarse marble is a marble layer with abundant phlogopite. Three samples are from this locality; I present isotope data from two of these samples.

Sample GM14-5-1 is a protomylonite (Figure 27). This sample contains calcite grains ranging from 300 μm to 3000 μm . The calcite has lobate to very serrate grain boundaries and lacks triple junctions. The calcite grains have bent and intersecting twins and exhibit undulose extinction. Fine grained calcite

ranging from 10 μm to 200 μm rims many of the large calcite crystals and other minerals grains, or occurs within the larger calcite grains. Elongate grains of graphite range from 70 μm to 880 μm in length. These grains of graphite tend to share a preferred orientation, defining a weak foliation. Other minerals present in the sample include tremolite, phlogopite, titanite, and small amounts of dolomite. SEM backscattered electron images show that some phlogopite grains are rimmed with dolomite, and dolomite exsolution is visible in some of the calcite grains (Figure 28).

Sample GM14-5-4 is a protomylonite (Figure 29). This sample contains calcite grains ranging from 260 μm to 6400 μm . The calcite has lobate to very serrate grain boundaries and lacks triple-grain junctions. Many calcite grains have straight, intersecting twins and exhibit undulose extinction. The un-twinned grains exhibit even stronger undulose extinction. Finer grained calcite occurs between the boundaries of some of the large calcite crystals. Elongate grains of graphite range from 70 μm to 880 μm in length. Other minerals present in the sample include tremolite, phlogopite, titanite, and small amounts of dolomite.

GM14-6

Locality GM14-6 is located along route 118 approximately 0.3 miles east of Tory Hill (Table 1). This locality consists mainly of coarse-grained protomylonites. Some of the marble in this outcrop consists of dolomite in addition to calcite. Lineations are apparent in the marble at this outcrop (Figure 30). I present isotope data from all four of the samples from this outcrop.

Sample GM14-6-1A is a protomylonite with calcite grains that range from 30 μm to 2600 μm (Figure 31). The calcite has lobate to serrate grain boundaries and lacks triple junctions. Many calcite grains have straight to slightly bent, intersecting twins and exhibit undulose extinction. Fine calcite sub-grains sometimes occur between the boundaries of some of the larger calcite crystals. Other minerals present in the sample include tremolite, phlogopite, and diopside. These minerals usually have curved to lobate boundaries and frequently rim each other. Coarse elongate grains of graphite and iron sulfides occur in this sample.

Sample GM14-6-1B is a protomylonite with calcite grains that range from 100 μm to 1200 μm (Figure 32). The calcite has lobate to serrate grain boundaries and lacks triple junctions. Many calcite grains have straight to slightly bent, intersecting twins and exhibit undulose extinction. Finer calcite sub-grains sometimes occur between the boundaries of some of the larger calcite crystals. The calcite grains range from equant to an aspect ratio of 3:1. Other minerals present in the sample include tremolite, phlogopite, and diopside. These minerals usually have curved to lobate boundaries and frequently rim each other. Some of the phlogopite grains are kinked and show undulose extinction. The preferred orientation of sheared graphite and other opaques strongly defines the foliation at the scale of the thin section. The phlogopite grains tend to be oriented parallel to this foliation, while the angle between the graphite foliation and the long axes of the calcite grains varies.

Sample GM14-6-2 is a protomylonite with calcite grains that range from 60 μm to 4800 μm in length (Figure 33). Sub-grains are partially formed in many of the calcite porphyroclasts. The finer, newly formed calcite grains surround coarser calcite grains. The twinning in the large calcite grains ranges from type I to type III twins, and these grains exhibit undulose extinction. Some of the smaller calcite grains lack twins and have less pronounced undulose extinction. The calcite grain boundaries range from lobate to very serrate. Elongate grains of graphite range from 100 μm to 400 μm in length. Other minerals present in the sample include tremolite and phlogopite. Small amounts of dolomite, quartz, chlorite and rutile also occur in this sample. SEM backscattered electron images show quartz, rutile, and some dolomite inter-grown with or rimming grains of tremolite. These tremolite grains appear to be breaking down, possibly representing a retrograde process (Figure 34).

Sample GM14-6-3 is a protomylonite (Figure 35). This sample is a dolomite marble and so the isotope data for this sample had to be corrected. The dolomite grains range from 400 μm to over 4000 μm in length, with sub-grains beginning to form in some of the porphyroclasts. The dolomite grain boundaries range from lobate to very serrate. Many of the dolomite grains do not exhibit twinning and those that do have narrow to wider straight twins or intersecting twins that could be categorized as type I through type III twins. The dolomite grains have undulose extinction. The grains of graphite visible in the thin section

define a weak foliation. These elongate graphite grains range from 200 μm to 900 μm in length.

BT14-1

Sample locality BT14-1 is located along route 28 approximately 10 miles east of Bancroft near the bridge over the York River (Table 1). The outcrop consists of coarse foliated marble crosscut by thick planar zones of mylonite. The southeast dip of the foliation is noticeable at the scale of the outcrop (Figure 36). A biotite gneiss amphibolite is also present at this outcrop and exhibits a similar foliation as the foliation seen in the marble. We collected oriented samples from BT14-1. I present calcite-graphite isotope data from one sample from this locality, BT14-1-2.

Sample BT14-1-2 is a protomylonite (Figure 37). This sample consists mainly of coarse-grained calcite with grains sizes ranging from 200 μm up to 2200 μm . Rims and patches of fine-grained calcite ranging in size from 20 μm to 100 μm occur around larger calcite grains and other mineral grains. The calcite has bent and intersecting twins that could be described as type III twins. The calcite grains have serrate boundaries and exhibit undulose extinction. The calcite grains do not show a preferred orientation. The diopside and tremolite grains have curved grain boundaries. The rock is un-foliated at the thin section scale. The graphite grains range from 100 μm to 440 μm in length and sparsely are distributed throughout the sample between grains of calcite.

I also analyzed sample BT14-1-3 from this locality under the SEM. This sample is a calcite marble (~60%) with trace amounts of dolomite (>1%). Some regions of this sample contain substantial amounts of serpentine (~12%) that can be found rimming some phlogopite grains. Chlorite and a humite group mineral also occur in this sample (Figure 38). The serpentine and chlorite are probably secondary minerals that have replaced minerals such as forsterite or the humite group mineral.

WF14-1

Locality WF14-1 is a road cut outcrop along route 648 approximately 1.6 miles north of route 118 (Table 1). This outcrop consists of both marble protomylonites and mylonites. Thin anastomosing bands of mylonite go through much of the outcrop. Two thicker bands of mylonite are present in the outcrop. We collected samples from within and around these thicker bands (Figure 39). A southeast dip is apparent at the scale of the outcrop. Some of the samples taken from WF14-1 are oriented. I present isotope data from five samples from this locality.

Sample WF14-1-1A is a protomylonite with calcite grains that range from 10 μm to 2400 μm in length (Figure 40). Coarser calcite grains are adjacent to zones of finer calcite grains. The formation of sub-grains is apparent within some calcite porphyroclasts. The calcite grains exhibit undulose extinction and display a variety of twinning textures from type I through type III twins. The calcite grain boundaries range from lobate to extremely serrate. The calcite grains range from

equant to an aspect ratio of 3:1. The phlogopite grains show a preferred direction of elongation and exhibit undulose extinction. Some of the phlogopite grains are kinked. Some of the other mineral grains in the sample are rounded or have rims and replacement textures. Grains and wisps of sheared out graphite occur with a similar orientation to the phlogopite grains, defining the foliation at the thin section scale. The grains of graphite are up to 700 μm in length and can be less than 10 μm .

Sample WF14-1-3A is a mylonite with calcite grains that range from 10 μm to 300 μm in length (Figure 41). Many of the larger calcite grains are porphyroclasts in which smaller sub-grains are partially formed. The calcite grains range from equant to a 3:1 aspect ratio. The calcite grains have undulose extinction and serrate grain boundaries. Other minerals present in the samples include alkali feldspar, tremolite and diopside, and these minerals have rounded grain boundaries. Elongate phlogopite grains also occur within this sample. The phlogopite is sometimes kinked and is often parallel or at a slight angle to the long axes of the calcite grains. The opaques, which include graphite and iron sulfides, are very fine grained ($>20 \mu\text{m}$), relatively equant, and dispersed fairly evenly throughout the sample.

Sample WF14-1-3B is a protomylonite with calcite grains that range from 100 μm to 1800 μm in length (Figure 42). The calcite grains have undulose extinction and serrate grain boundaries. The calcite grains have straight twins of variable width and can be described as type I and type II twins. The calcite grains

range from equant to a 3:1 aspect ratio. Strands and wisps of opaques define a foliation at the thin section scale. The phlogopite grains show a similar preferred orientation to the wisps of opaques and are sometimes kinked. The diopside and tremolite grains present in the sample tend to have rounded grain boundaries.

Sample WF14-1-5B is a mylonite with calcite grains that range from 10 μm to 130 μm (Figure 43). The calcite grains have lobate to serrate boundaries and undulose extinction. They range from equant to a 2:1 aspect ratio. The calcite grains do not have twins. Iron sulfides and graphite are found both in sheared out wisps between calcite grains, defining the foliation at the scale of the thin section, and as rims around other minerals in the sample. Other minerals present within the sample include diopside, tremolite, phlogopite, and minor amounts of serpentine. In some places diopside grains are rimmed by tremolite and by lesser amounts of quartz and phlogopite. The phlogopite grains often have a similar orientation to the foliation defined by the opaque minerals and are sometimes kinked. SEM backscattered electron images show tremolite and phlogopite forming rims around diopside grains. These images also show phlogopite rims occurring around tremolite grains. In some places all three of these minerals are inter-grown, with the diopside appearing to be breaking down (Figure 44).

Sample WF14-1-6 is a protomylonite with calcite grains that range from 160 μm to 2400 μm (Figure 45). The calcite grains have straight to serrate grain boundaries and exhibit some triple grain junctions. Some of the calcite grains exhibit undulose extinction. The calcite twins vary in width and some twins are

straight while others are bent. The calcite grains range from equant to a 3:1 aspect ratio. The graphite and iron sulfides occur in sheared out wisps between the calcite grains and define the foliation at the scale of the thin section. The grains of graphite can be as long as 2000 μm all the way down to very fine grains. Rounded diopside grains are surrounded by rims of tremolite and phlogopite. The elongate phlogopite grains are usually oriented parallel to the foliation.

Isotope Results

A total of 22 samples yield isotope data; 13 protomylonite samples, 4 mylonite samples, and 5 ultramylonite samples. I replicated graphite in 18 of the samples; the mean of these values is used as the $\delta^{13}\text{C}$ value of the graphite for these samples. The other 4 samples did not have replicates and so the graphite $\delta^{13}\text{C}$ represents only a single isotope value. Protomylonites from all the localities yield isotope data. However, mylonites from only two localities (GM14-2 and WF14-1) and ultramylonites from only one locality (GM14-2) yield isotope data.

The $\delta^{13}\text{C}$ values of the graphite in the samples range from -4.48‰ to -0.24‰ and are located in Table 4. I corrected the $\delta^{13}\text{C}$ values of four of the samples for the presence of dolomite. The protomylonites have the greatest range in graphite $\delta^{13}\text{C}$ values, ranging from -3.19‰ to -0.24‰. The graphite $\delta^{13}\text{C}$ values for mylonites range from -3.17‰ to -2.56‰. The graphite $\delta^{13}\text{C}$ values for the ultramylonites range from -4.48‰ to -3.19‰. The $\delta^{13}\text{C}$ values of the calcite range from 0.17‰ to 4.07‰. Therefore the carbonate isotope values are within the typical range for marine carbonates (Faure and Mensing 753). The $\delta^{18}\text{O}$ -

SMOW values from the calcite range from 19.30‰ to 27.57‰ (Table 4). This range in $\delta^{18}\text{O}$ values is typical of carbonates that have not been affected by fluids during metamorphism (Engel *et al.*, 1958). The $\delta^{13}\text{C}$ values of the samples that my analyses focus on are depicted in Figure 46.

The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values are determined from the $\delta^{13}\text{C}$ values of the calcite and graphite. These values are located in Table 4. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values of all the samples in this study range from 3.12‰ to 6.11‰. Protomylonite $\Delta^{13}\text{C}_{\text{cal-gr}}$ values range from 4.80‰ to 3.12‰ across all of the outcrops. GM14-2 and WF14-1 are the only two localities that contain either mylonite or ultramylonite samples. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values at GM14-2 are 4.0‰ for the protomylonite, range from 3.65‰ to 4.44‰ for the mylonites, and range from 3.71‰ to 5.07‰ for the ultramylonites. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values at WF14-1 range from 3.12‰ to 4.48‰ for the protomylonites and from 4.98‰ to 6.11‰ for the mylonites.

We analyzed both calcite and graphite standards in order to determine the amount of uncertainty in our isotope values. Of the eight MHC calcite standards we analyzed, seven of the analyses were successful. These analyses yield a mean $\delta^{13}\text{C}$ of 3.14‰ and a standard deviation of 0.17‰ (Table 5). The long running $\delta^{13}\text{C}$ average for the MHC calcite standard is 3.21‰. We adjusted the values of replicates five through seven relative to the accepted value of the MHC calcite standard. We also analyzed fourteen MHC graphite standards. These standards yield a mean $\delta^{13}\text{C}$ of -6.60 and a standard deviation of 0.12‰ (Table 6). The long

running $\delta^{13}\text{C}$ average for the MHC graphite standard is -6.60‰ and so coincides with the mean of our analyses. The combined $\delta^{13}\text{C}$ standard deviation from the calcite and graphite standard analyses yields a total $\Delta^{13}\text{C}$ uncertainty of 0.29‰.

DISCUSSION

The localities sampled in this study are located along the Bancroft Shear Zone between the 600°C and 700°C isotherms, with all but one of the localities (BT14-1) located between the Cardiff, Cheddar, and Anstruther domes and the 700°C isotherm, including that of our classic BSZ locality, GM14-2 (Figure 12). Therefore the protoliths of the marbles in our study probably experienced peak regional metamorphic temperatures between 600°C and 700°C, with most experiencing peak temperatures between approximately 650 and 700°C (van der Pluijm and Carlson, 1989). This is the temperature range we expect the samples to exhibit if the calcite-graphite thermometer was not reset during shearing. However, temperature estimates slightly outside this range could be due to the uncertainty in the $\delta^{13}\text{C}$ values rather than from resetting. The combined uncertainty in the $\delta^{13}\text{C}$ values from the calcite and graphite results in a $\Delta^{13}\text{C}_{\text{cal-gr}}$ uncertainty of 0.29‰. I used the Kitchen and Valley (1995) thermometer calibration to determine the temperature uncertainty at multiple temperatures throughout the range of sample temperatures (Table 7). Due to the shape of the temperature calibration curve, the uncertainty in the temperature increases as the temperature increases, from $\pm 20^\circ\text{C}$ at 500°C to $\pm 54^\circ\text{C}$ at 800°C. Therefore sample temperatures with slightly higher or lower temperatures than the regional peak

metamorphic temperatures may still agree with protolith temperature estimates if their estimate falls within this range of uncertainty.

Since we know the protolith experienced peak metamorphic temperatures between 600°C and 700°C, we expect the protomylonite values to reflect similar temperatures regardless of whether the thermometer is reset during shearing because protomylonites experienced the least shearing. Protomylonite $\Delta^{13}\text{C}_{\text{cal-gr}}$ values range from 4.80‰ to 3.12‰, which correspond to a range in temperature of 588°C to 794°C (Figure 47). The mean protomylonite temperatures at all of the localities except GM14-6 fall within the 600°C to 700°C range predicted by the regional isotherms in Figure 12. This range in protomylonite temperatures also agrees with the peak regional metamorphic isograds determined by Rathmell *et al.* (1999) since the localities are located to the northwest of their 600°C and 650°C isotherms (Figure 11). Locality BT14-1 has the lowest mean protomylonite temperature (608°C) of all the localities. This lower temperature is supported by the sample location on the regional isotherm map (Figure 12) because this is the locality adjacent to the 600°C isotherm, while the rest of the samples are located adjacent to the estimated 700°C isotherm. Therefore the calculated temperatures of the protomylonites in this study agree well with the regional peak metamorphic temperatures of the surrounding area, providing support for the accuracy of the dataset.

While the mean protomylonite temperatures agree well with the regional peak metamorphic temperatures, a few of the protomylonite samples indicate

temperatures outside the expected range. These temperature estimates fall closer to the expected range if the 0.29‰ uncertainty in the $\Delta^{13}\text{C}_{\text{cal-gr}}$ values is considered. This uncertainty does not greatly affect the temperature estimates of samples with lower temperatures, but does have a greater influence on samples that indicate higher temperatures ($>750^\circ\text{C}$). Three of the protomylonite samples indicate unreasonably high temperatures ($>780^\circ\text{C}$). However, if you consider the uncertainty at this temperature, their estimates are brought down to more reasonable values according to the regional isotherms. One of these high temperature samples is a protomylonite from WF14-1 (794°C), and its inclusion raises the mean protomylonite temperature at this locality. If the 54°C uncertainty at this temperature is considered, the temperature estimate of this sample becomes a more reasonable estimate of 740°C . Additionally, GM14-6 has a slightly higher protomylonite mean of 721°C because three of the samples indicate temperatures above 700°C , with two samples at almost 800°C . However, if we consider our approximately 50°C uncertainty at this temperature, the temperature estimates of these samples are lowered to more reasonable values that agree better with the regional isotherms. For example, sample GM14-6-1A yields an estimate of 793°C , but when the uncertainty is considered this sample yields a more reasonable temperature estimate of approximately 739°C .

After determining the temperature estimates of the protomylonites from all the localities agree with the regional peak metamorphic temperatures, I focus my analyses on the two localities that contain mylonite and ultramylonite samples to

determine how the temperature estimates of the samples that experienced a greater extent of mylonitization compare to the regional isotherms. GM14-2 is the only sample locality that yields calcite-graphite isotope data for all three levels of mylonitization. The one protomylonite sample from this locality, GM14-2-9, has a $\Delta^{13}\text{C}_{\text{cal-gr}}$ value of 4.00‰, which corresponds to a temperature of 670°C. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values of the mylonites at this locality range from 3.65‰ to 4.44‰, which correspond to a temperature range from 623°C to 714°C. The ultramylonite $\Delta^{13}\text{C}_{\text{cal-gr}}$ values range from 3.71‰ to 5.07‰ which correspond to a range in temperature from 565°C to 707°C. Most of the temperatures calculated at this locality fall within close range of the temperatures predicted by the isotherms depicted in Figure 12. The mylonites have a mean temperature of 668°C, and the ultramylonites have a mean temperature of 642°C (Figure 48), both of which agree with the temperature of regional peak metamorphism in the study area.

I also compare protomylonite and mylonite temperatures at locality WF14-1 to help determine how increased mylonitization affects the temperature estimates that the isotope values indicate. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values of the protomylonites at this locality range from 3.12‰ to 4.48‰, which correspond to a range in temperature of 619°C to 794°C. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values of the mylonites range from 4.98‰ to 6.11‰, which correspond to a temperature range of 490°C to 572°C. One sample, WF14-1A, has an unreasonably high temperature estimate based on the isotherms in Figure 12. The protomylonites at WF14-1 have a mean temperature of 691°C while the mylonites have a lower mean temperature of

531°C. (Figure 48). Unfortunately, we have less data from this locality than from GM14-2, and we do not have ultramylonite data that could help us determine whether this temperature difference is real or not.

I first investigate whether there is a difference in temperature between the two localities in order to determine whether the samples from these two localities can be analyzed together, or if the locality also needs to be considered in the analysis. GM14-2 has a mean temperature of 652°C (n=8), while WF14-1 has a mean temperature of 627°C (n=5). The difference in temperature between these two localities is not significant ($p = 0.598$). The results of the one-way ANOVA for this analysis are located in Table 8. This lack of a significant difference in temperature between the two localities makes sense because they are both located an approximately equal distance from the 700°C isograd. Therefore I combine all the data from these two sample localities to analyze whether there is a difference in temperature due to the extent of mylonitization.

I determine whether mylonites and ultramylonites exhibit the lower shearing temperatures that occurred during the development of the Bancroft Shear Zone by combining the samples from the two localities that contain multiple mylonite stages. Protomylonite samples from GM14-2 and WF14-1 have $\Delta^{13}\text{C}_{\text{cal-gr}}$ values that range from 3.12‰ to 4.48‰, which correspond to a temperature range from 619°C to 794°C, yielding a mean temperature of 686°C (n=4). Mylonite $\Delta^{13}\text{C}_{\text{cal-gr}}$ values range from 6.11‰ to 3.65‰ which correspond to a temperature range of 490°C to 714°C and a mean of 600°C (n=4). Ultramylonite $\Delta^{13}\text{C}_{\text{cal-gr}}$

values range from 5.07‰ to 3.71‰ which correspond to temperatures of 565°C to 707°C and a mean temperature of 642°C ($n=5$) (Figure 49). The difference in temperature due to the extent of mylonitization is not significant ($p = 0.326$). The results of the one-way ANOVA are located in Table 9. Analysis of the residual values versus the predicted values shows that the standard deviations of the residuals are the same across both localities and across all stages of mylonitization, therefore meeting the ANOVA assumptions.

Although the isotopic values of my samples indicate high temperatures, the mylonites and ultramylonites in my study are fine grained, and so we know that shearing must have occurred at low enough temperatures that annealing of the calcite could not occur. Van der Pluijm (1991) states that carbonates anneal rapidly above 500°C, and so shearing must have occurred well below these temperatures to maintain the extremely fine grained textures seen in the ultramylonite samples. The twin styles that occur in the protomylonites indicate low temperature deformation, from less than 200°C to over 250°C, and so shearing would have occurred under these temperature conditions at least at the end of deformation and possibly throughout a greater duration of the shearing process. Therefore the temperatures indicated by my samples are higher than the shearing temperatures and mainly within the range of temperature indicated by the isotherms of the regional metamorphism produced by the Ottawa orogeny.

The literature is inconclusive about what conditions reset the calcite-graphite thermometer. Van der Pluijm and Carlson (1989) report data indicating

the calcite-graphite thermometer was reset to a temperature of approximately 450°C during extensional shearing within the Bancroft Shear Zone. The van der Pluijm and Carlson (1989) $\Delta^{13}\text{C}_{\text{cal-gr}}$ values range from 9.5‰ to 4.7‰, which correspond to shearing temperatures from 339°C to 597°C using the Kitchen and Valley (1995) calibration. Van der Pluijm (1991) found that ultramylonites in the shear zone have $\Delta^{13}\text{C}_{\text{cal-gr}}$ values between 9.5‰ and 6.2‰, which correspond to a temperature range of 450°C to 540°C. Using this data, van der Pluijm and Carlson (1989) conclude that the calcite-graphite thermometer was reset during shearing to shearing temperatures of around 450°C and that the mylonites that indicate higher temperatures than this never reached equilibrium. They suggest that the small grain size of the graphite within the ultramylonites enabled the graphite to experience isotopic exchange with the calcite due to its larger surface area to volume ratio (van der Pluijm and Carlson, 1989).

However, Dunn and Valley (1992) believe that in order for the calcite-graphite thermometer to be reset, graphite recrystallization must occur, due to the extremely slow diffusion rate of carbon out of crystalline graphite. If graphite recrystallization had occurred, textural evidence including rough grain surfaces, zoning, or overgrowths would be present in the thin section (Dunn and Valley, 1992). Dunn and Valley (1992) report data indicating that the calcite-graphite thermometer was not reset within the contact aureole around the Tutor gabbro to the peak temperature of subsequent regional metamorphism during the Ottawa Orogeny. The Tudor gabbro intruded approximately 1250 Ma and so predates the

the regional metamorphism that occurred during the Ottawa orogeny (Rathmell *et al.*, 1999). Calcite-graphite thermometry conducted on samples near the gabbro indicate temperatures from 700°C to 750°C, while temperatures decrease proceeding away from the gabbro (Dunn and Valley, 1992). Meanwhile calcite-dolomite thermometry around the gabbro indicated temperatures around 500°C, which Dunn and Valley (1992) interpreted as the temperature of regional metamorphism from the Ottawa orogeny. This data therefore implies that the calcite-graphite thermometer was not reset at regional metamorphic temperatures of 500°C, while the calcite-dolomite thermometer was reset (Dunn and Valley, 1992).

The data from my study do not support the conclusions of van der Pluijm and Carlson (1989) because I did not find a significant difference in temperature as the mylonitization increased. Van der Pluijm (1991) cites mylonite temperatures as low as 330°C, but the lowest temperature indicated by my samples is 490°C from a mylonite, and most are well above this temperature, including the temperatures from ultramylonite samples. My data therefore indicate that the $\Delta^{13}\text{C}_{\text{cal-gr}}$ values in the mylonites and ultramylonites have not been reset to record the lower shearing temperatures. However, this is only a tentative conclusion since the number of samples is too low to have strong statistical power, and the graphite textures have not been analyzed to determine whether the graphite recrystallized during shearing.

If the van der Pluijm and Carlson (1989) data are correct, there are two explanations for the differences between our results. One possible explanation is that when shearing occurs, the graphite and calcite become displaced relative to the graphite and calcite that they equilibrated near. This would cause the isotope values to not reflect any real temperature values, but rather would represent meaningless scatter. If this process were occurring, we could expect the temperatures to show a lot of variability, with both unusually high and low temperatures. While my data have a few values that are a little higher or lower than the majority of the values, all of the ultramylonites have very reasonable temperature estimates, especially after considering the $\delta^{13}\text{C}$ uncertainty. Since the ultramylonites experienced the greatest amount of shearing, one would expect the calcite and graphite to be the most displaced in these samples if this process were occurring. However, the ultramylonite values are all relatively reasonable, making this explanation less likely. Unreasonably high temperatures could also be due to the presence of a nearby igneous intrusion. However, this can probably be ruled out because a large portion of the outcrop would likely exhibit an elevated temperature due to an intrusion since the $\delta^{18}\text{O}$ values were not low enough for the samples to have experienced localized metamorphic fluid intrusion. The few temperatures that seem unreasonably high ($>750^\circ\text{C}$) are likely just due to the uncertainty in our calcite $\delta^{13}\text{C}$ values, since we had some difficulty reliably measuring these values on the mass spectrometer.

The other explanation for the disagreement of my results with those of van der Pluijm and Carlson (1989) is that the graphite could be partially recrystallizing during shearing, allowing for partial isotope exchange. This partial recrystallization and exchange would result in an isotopic disequilibrium between the graphite and calcite (van der Pluijm and Carlson, 1989), causing some samples to yield the same temperatures as the protomylonites, while other samples that experienced more graphite recrystallization and isotope exchange would yield lower temperatures closer to the estimated shearing temperature. Skeletal overgrowths of graphite on well-crystallized graphite are evidence of graphite recrystallization. The presence of skeletal graphite would indicate that some of the graphite recrystallized after peak metamorphism, yielding lower temperature estimates (Valley and O'Neil, 1981). SEM analyses and petrographic observations could be used to determine whether the graphite grains in my samples have skeletal overgrowth or rims (Valley and O'Neil, 1981).

A few of the mylonite and ultramylonite samples from my dataset indicate temperatures between 565°C and 600°C, and one mylonite sample indicates a temperature of 490°C. These lower temperatures could be due to partial resetting of the thermometer enabled by partial graphite recrystallization. The presence or lack of graphite recrystallization could be confirmed through thin section work examining graphite grains for textural evidence of skeletal graphite. However, the mean mylonite and ultramylonite temperatures are not significantly different from those of the protomylonites. While this lack of significance could be due the small

sample size of my data, the lower temperatures of these samples could also be due to the uncertainty in my $\delta^{13}\text{C}$ values, rather than due to graphite recrystallization and partial resetting of the thermometer. Additionally, while my dataset contains a few lower temperature samples, none of my samples indicate temperatures as low ($>400^\circ\text{C}$) as some of the mylonite samples analyzed by van der Pluijm and Carlson (1989). Therefore my data indicates that the calcite-graphite thermometer has not been reset by mylonitization in the mylonite and ultramylonite samples analyzed in this study.

CONCLUSIONS

Shearing during orogenic collapse produced marble mylonites within the Bancroft Shear Zone. In van der Pluijm and Carlson (1989), calcite-graphite thermometry was conducted on samples from this shear zone that exhibit various degrees of mylonitization. Previous studies by van der Pluijm and Carlson (1989) and by Dunn and Valley (1992) provide differing conclusions about the conditions that reset the calcite-graphite thermometer. My data indicate that protomylonite samples have a mean temperature of 686°C (n=4), mylonite samples have a mean temperature of 600°C (n=4), and ultramylonite samples have a mean temperature of 642°C (n=5). These results indicate that there is no significant difference in temperature due to the extent of mylonitization ($p = 0.326$). We therefore conclude that mylonites within the Bancroft Shear Zone probably retain the isotopic signature from the previous episode of regional peak metamorphism, rather than from the subsequent shearing event, and that graphite recrystallization may require higher temperatures than those that formed the mylonites. Therefore calcite-graphite thermometry may still provide accurate estimates of previous regional peak metamorphic temperatures even within highly sheared marbles.

FIGURE APPENDIX

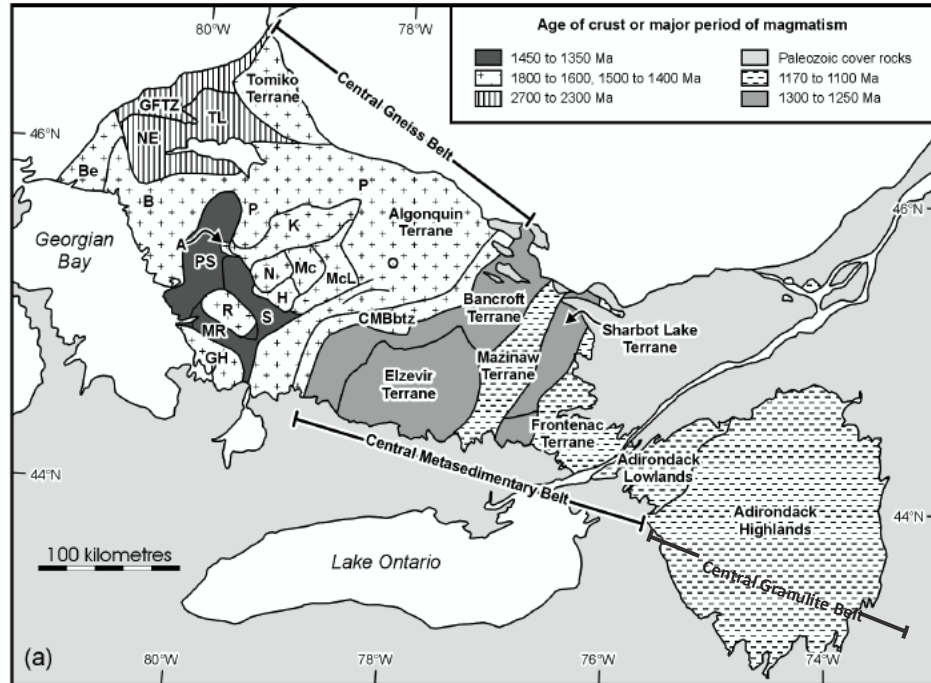


Figure 1. The locations and ages of the terranes within the Grenville Province. The Central Gneiss Belt, Central Metasedimentary Belt, and Central Granulite Belt occur from west to east. The Bancroft Shear Zone is located in the Central Metasedimentary Belt. Modified from Carr *et al.* (2000).

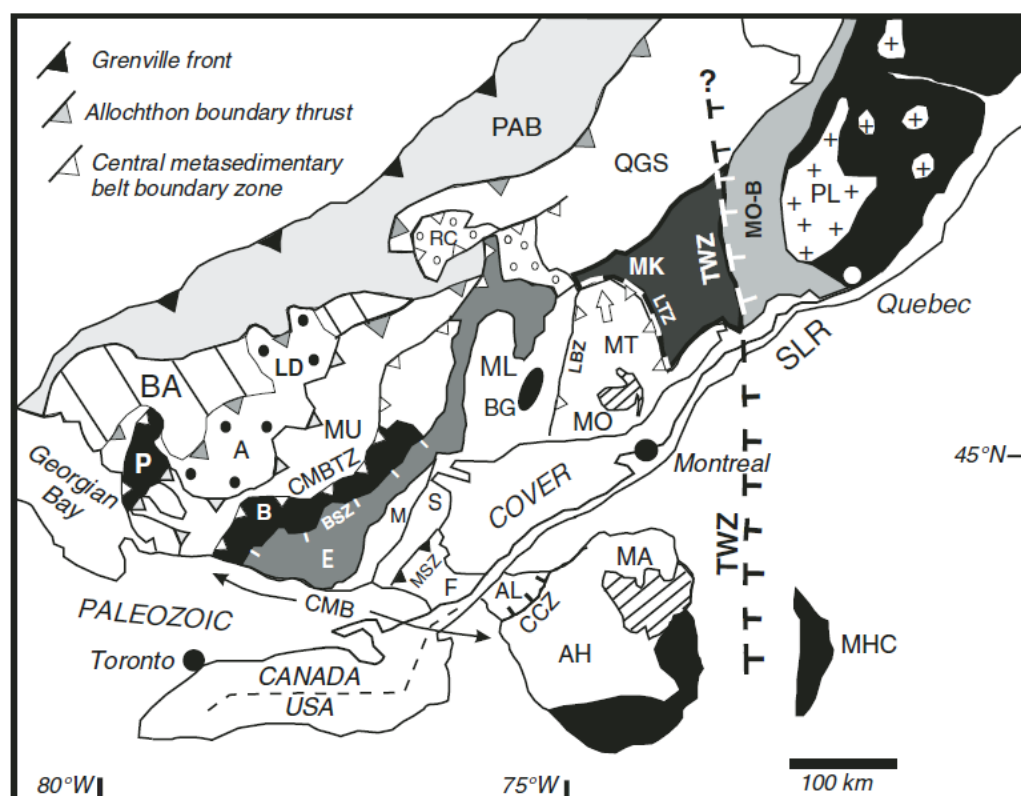


Figure 2. Generalized geologic map of the southern region of the Grenville Province. The southernmost portion of this map is of interest in this study. BSZ – Bancroft shear zone; B – Bancroft terrane; E – Elzevir terrane; CMB – Central Metasedimentary Belt; CMBTZ – Central Metasedimentary Belt thrust zone. The Bancroft shear zone occurs between the Bancroft and Elzevir terranes within the Central Metasedimentary Belt. Taken from McLelland *et al.* (2010).

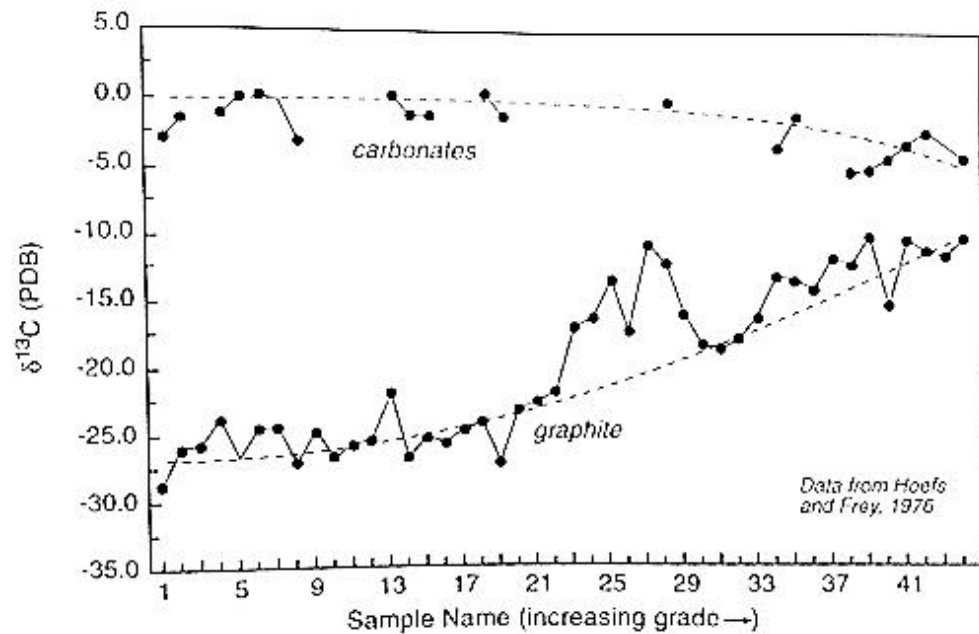


Figure 3. Relationship between $\delta^{13}\text{C}$ and metamorphic grade. Unmetamorphosed carbonates have $\delta^{13}\text{C}$ values around 0‰ while the organic sediments that form graphite start with $\delta^{13}\text{C}$ values around -30.0‰. As the temperature increases, isotopic exchange occurs causing the $\Delta^{13}\text{C}_{\text{cal-gr}}$ value to become smaller. Taken from Valley (2001).

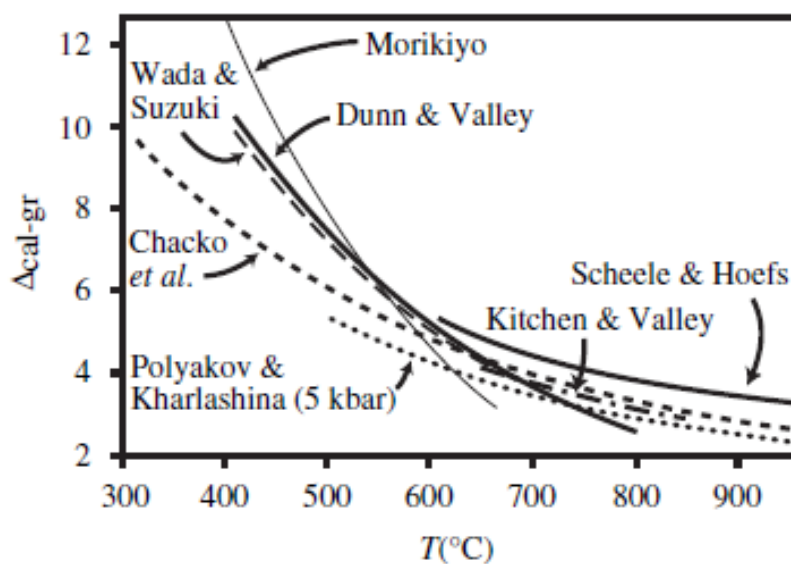


Figure 4. Calibration curves of the calcite-graphite isotope thermometer. The Kitchen & Valley (1995) calibration of the calcite-graphite thermometer was used in this study due to its accuracy at higher temperatures. Many other studies have worked to calibrate the calcite-graphite thermometer. Taken from Dunn (2005).

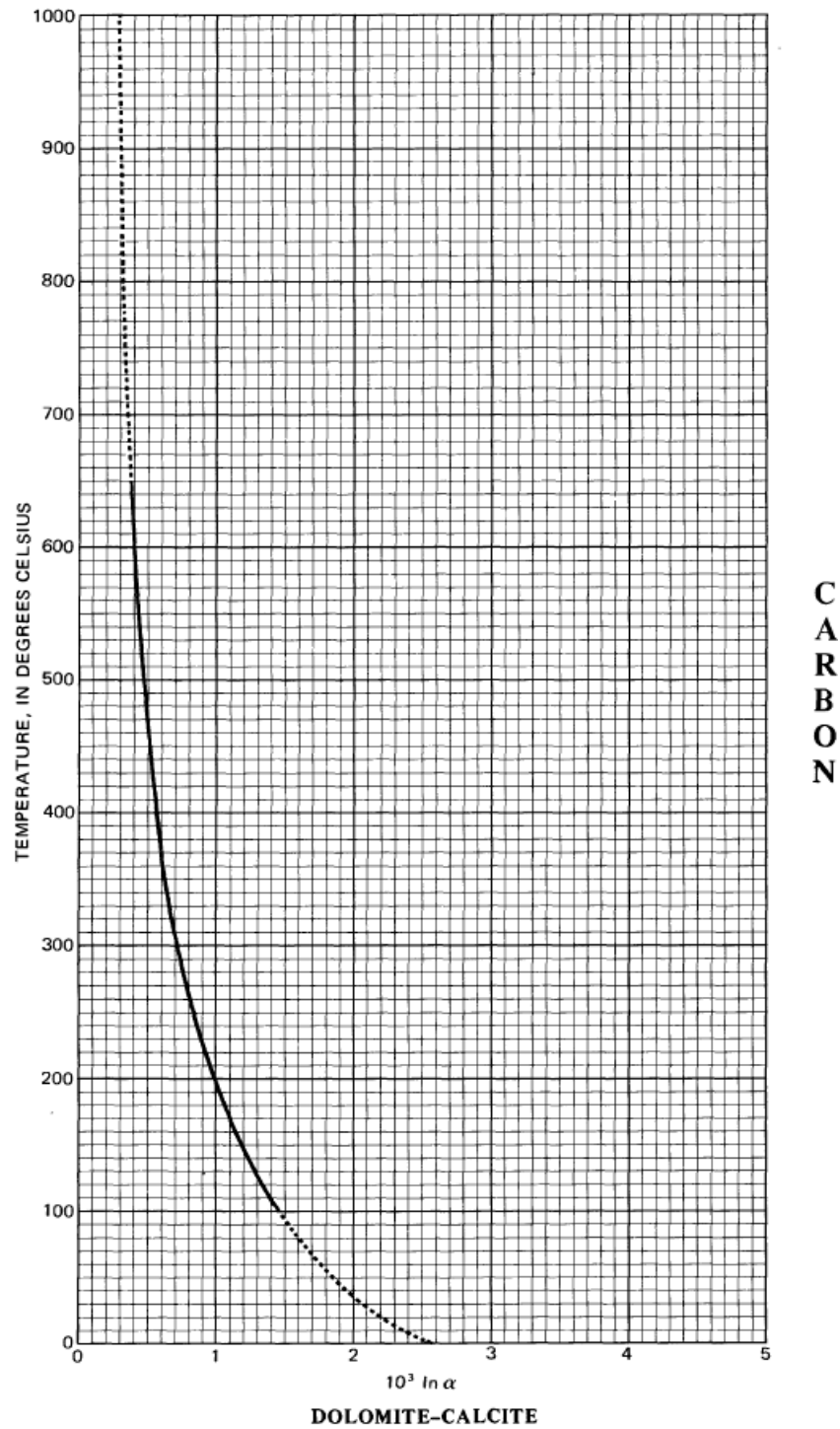


Figure 5. Fractionation between coexisting dolomite and calcite within marbles from 100°C to 650°C; $10^3 \ln \alpha = 0.18(10^6 T^{-2}) + 0.17$. When dolomite is present, it preferentially takes the carbon-13, resulting in lower temperature interpretations. Taken from Sheppard & Schwarcz (1970).

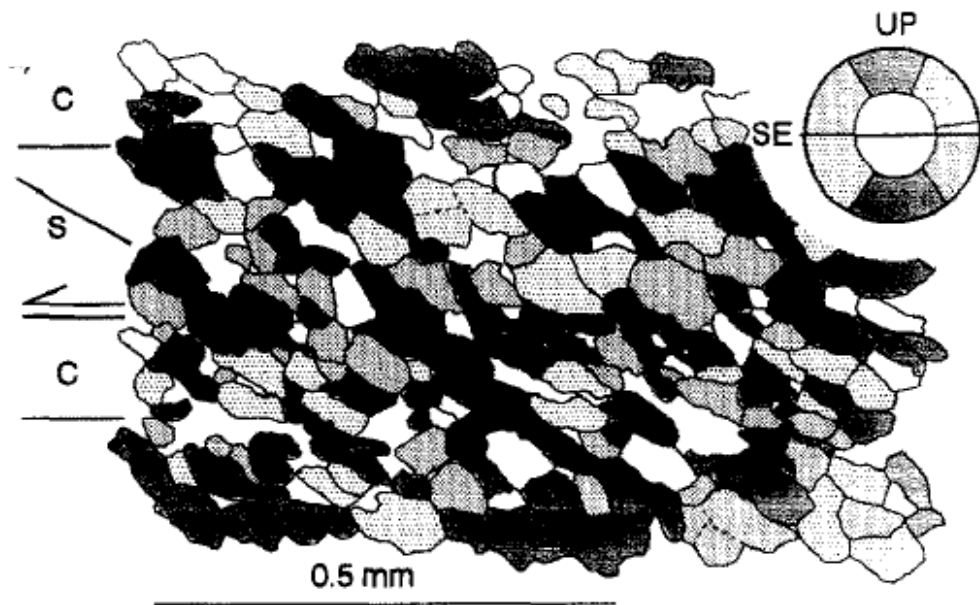


Figure 6. The appearance of an S-C texture in a mylonite. The long axes of the calcite grains occur at an angle to the shear plane. This texture is indicative of the continued shearing and recovery characteristic of dynamic recrystallization. Taken from Busch and van der Pluijm (1995).

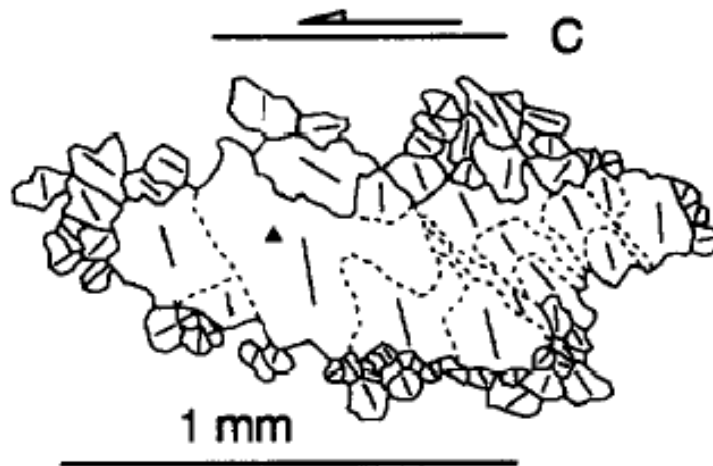


Figure 7. Sub-grain formation within a porphyroblast of calcite during deformation. Newly formed grains surround the porphyroblast. Taken from Busch and van der Pluijm (1995).

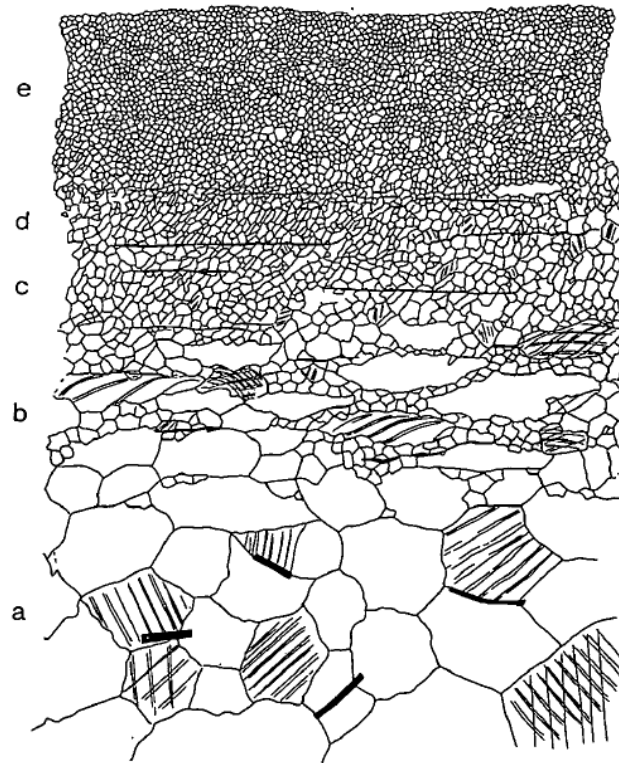


Figure 8. Composite sketch of the range of marble textures found within the Bancroft Shear Zone. (a) Protoliths, (b) protomylonites, (c) coarse mylonites, (d) fine mylonites, and (e) finally ultramylonites are all progressively finer grained. Taken from van der Pluijm (1991).

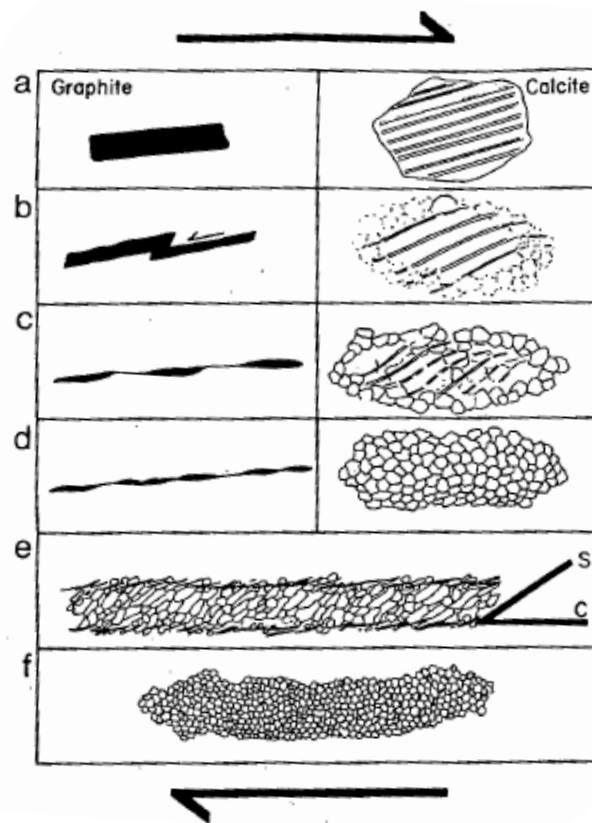


Figure 9. Calcite and graphite microstructures. (a) Protoliths consist of twinned calcite grains and large flakes of graphite. (b) Protomylonites contain calcite sub-grains and larger grains with bent twins or (c) distinct core and mantle structures. (d) Coarse mylonites have equant and uniform grains. (e) S-C mylonites (fine mylonites) exhibit grain elongation. (f) Ultramylonites consist of very fine, equi-dimensional grains. Taken from van der Pluijm (1991).

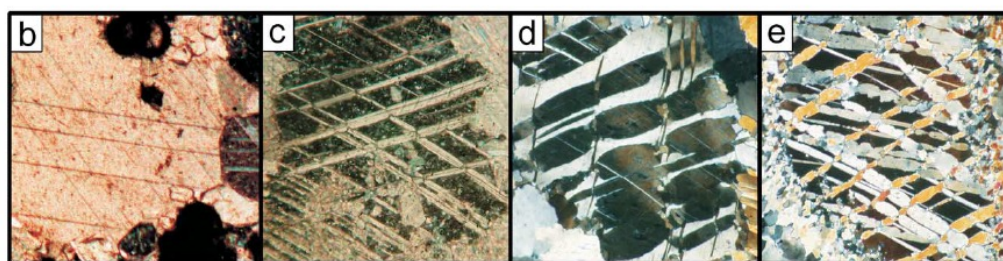
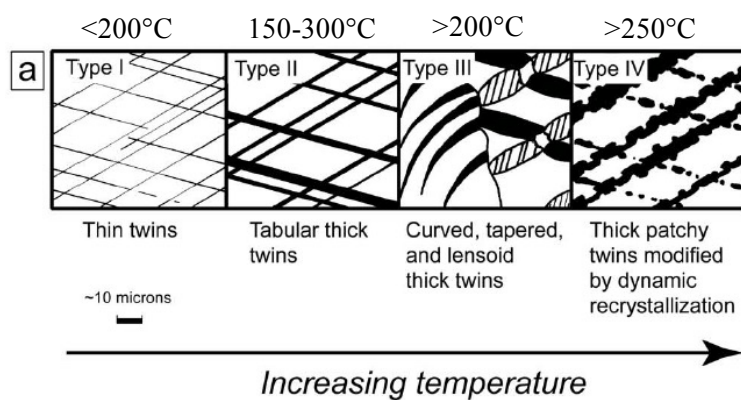


Figure 10. Deformation twinning in calcite crystals at various temperatures. Taken from Ferrill *et al.* (2004). Modified with temperatures from Passchier and Trouw (1996).

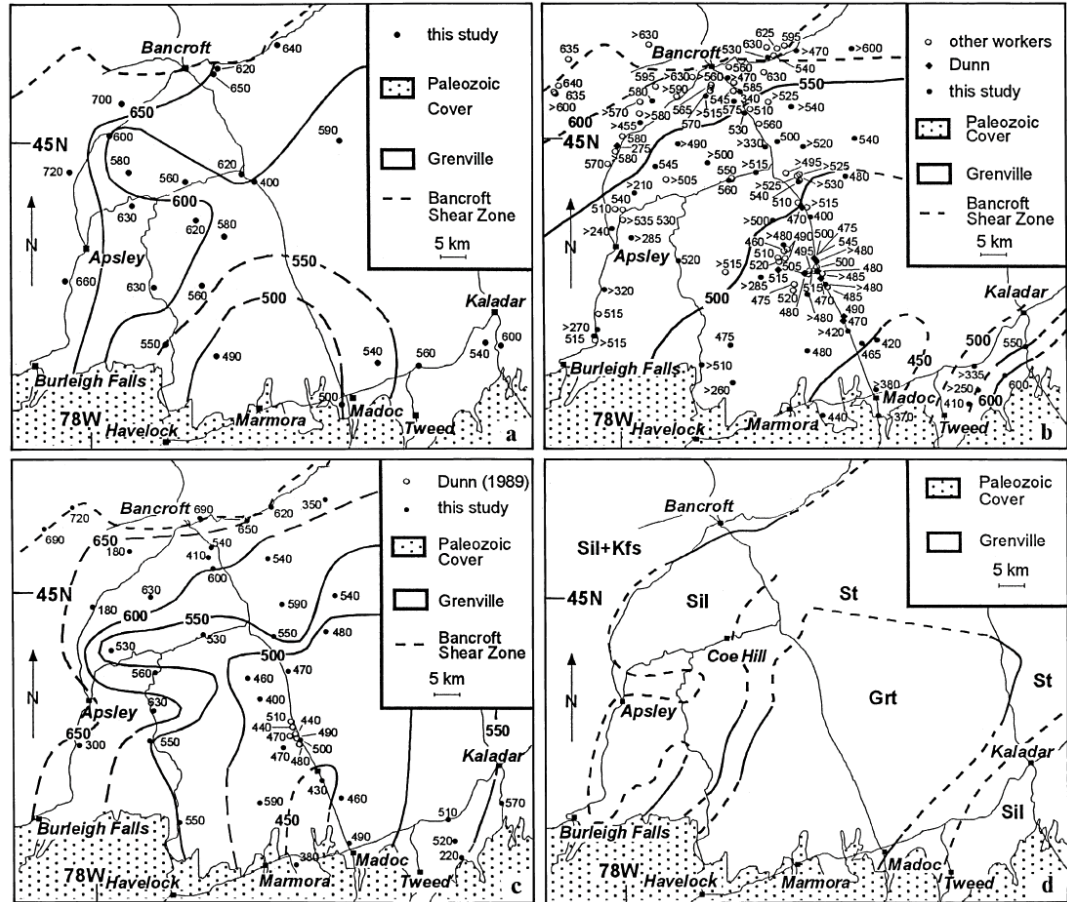


Figure 11. Regional metamorphic temperatures based on (a) garnet-biotite thermometry, (b) calcite-dolomite thermometry, (c) calcite-graphite thermometry, and (d) pelitic isograds. The dashed lines represent locations where the isotherms are inferred. Taken from Rathmell *et al.* (1999).

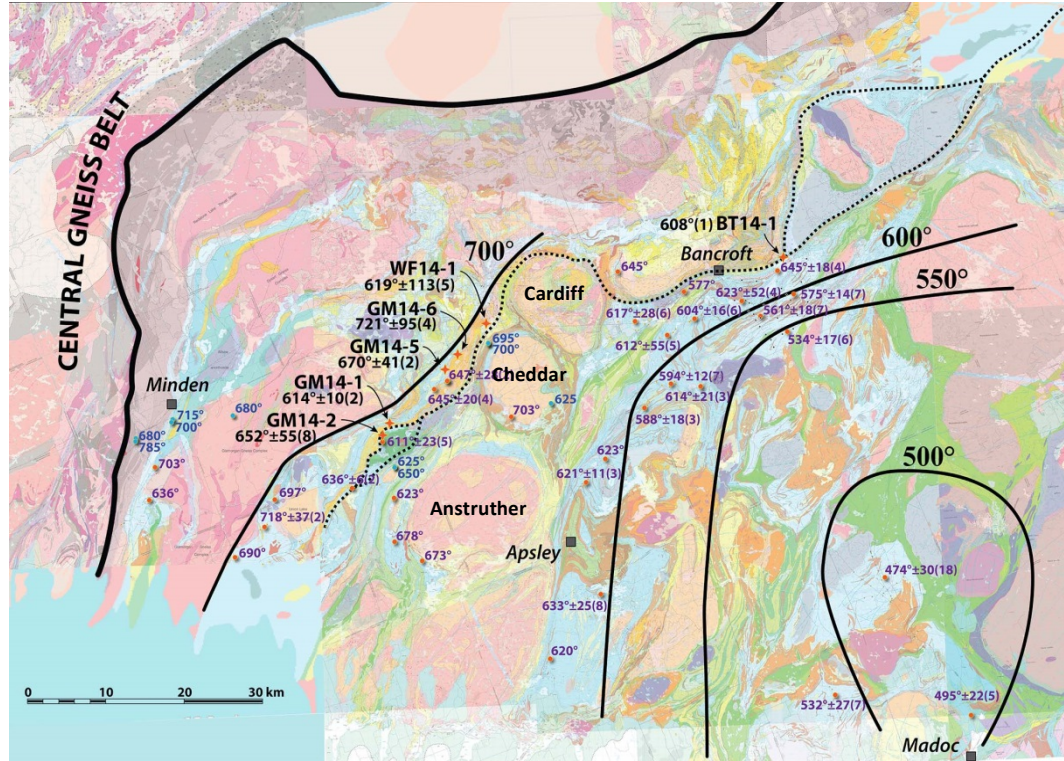


Figure 12. Grenville geology of southern Ontario. The light blue regions represent marble lithologies. The teal blue regions around the scale bar are Ordovician sedimentary rocks. Temperatures depicted in blue were determined by Fowler-Gerace (2012) using garnet-biotite thermometry and Thermocalc. The pressure used for this thermometry was 7kbar. The red-orange symbols with purple temperatures were determined using calcite-graphite thermometry and are from Dunn and Valley (1992), Dunn (2005), and unpublished data. These temperatures are either single samples or are given as an average and standard deviation with the number of samples in parentheses. The Bancroft shear zone is delineated by the dashed line and is approximated from that presented in van der Pluijm (1991). The placement of the regional isotherms was influenced by Rathmell *et al.* (1999) in the east and by regional structure in the west. The heavy line in the west indicates the approximate boundary between the Central Gneiss Belt and the Central Metasedimentary Belt boundary thrust zone. The classic BSZ locality, GM14-2, is located in the Elzevir terrane. The six localities sampled in this study are written in bold, and their positions are indicated by red-orange crosses (Figure created by Dunn, 2015).



Figure 13. Field image of locality GM14-1 (a) This locality consists of anastomosing layers of dark gray marble caused by fine-grained graphite between the calcite grains. These layers dip to the East. Dark bands range in thickness from 1 to 5 cm. Dolomite is present throughout much of the outcrop. (b) The marble at this outcrop contains abundant serpentine. Phlogopite is also present in the marble.

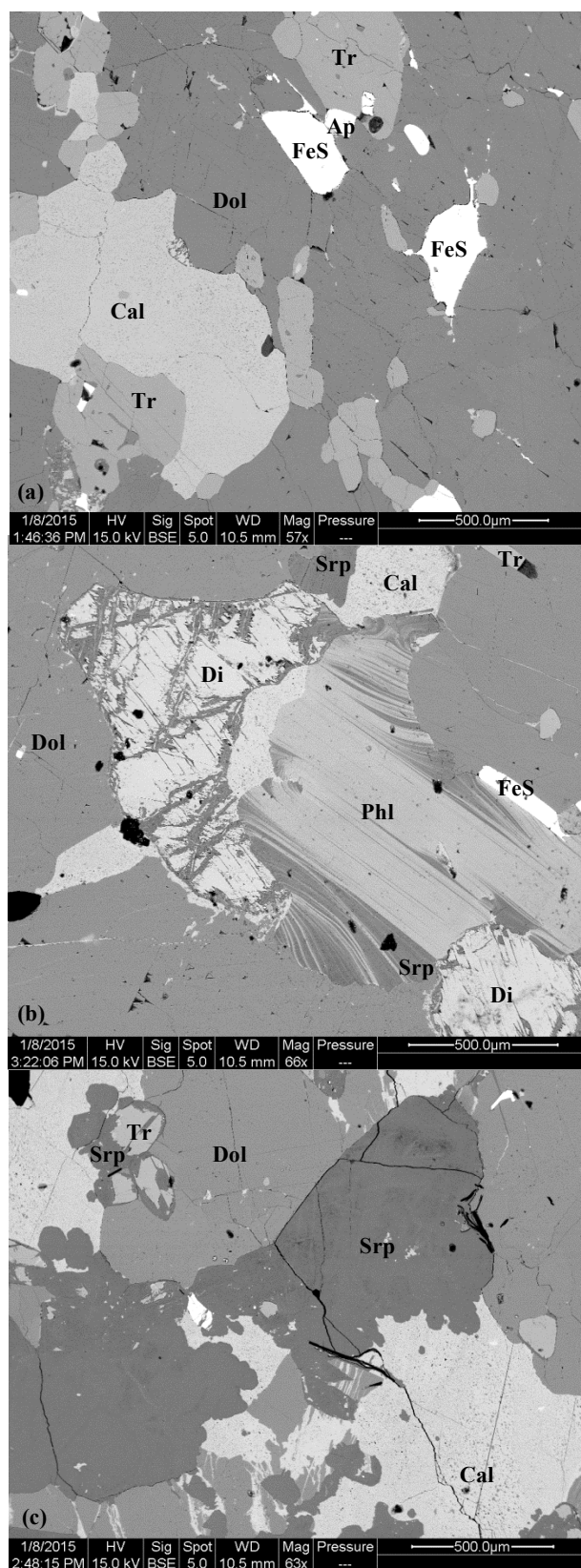


Figure 14. SEM backscattered electron image of GM14-1-1. This sample is a dolomitic marble. (a) Calcite, tremolite, and iron sulfides occur within the marble. (b) Serpentine is intergrown with the phlogopite and diopside grains. (c) Serpentine rims some of the tremolite grains in the upper left corner.

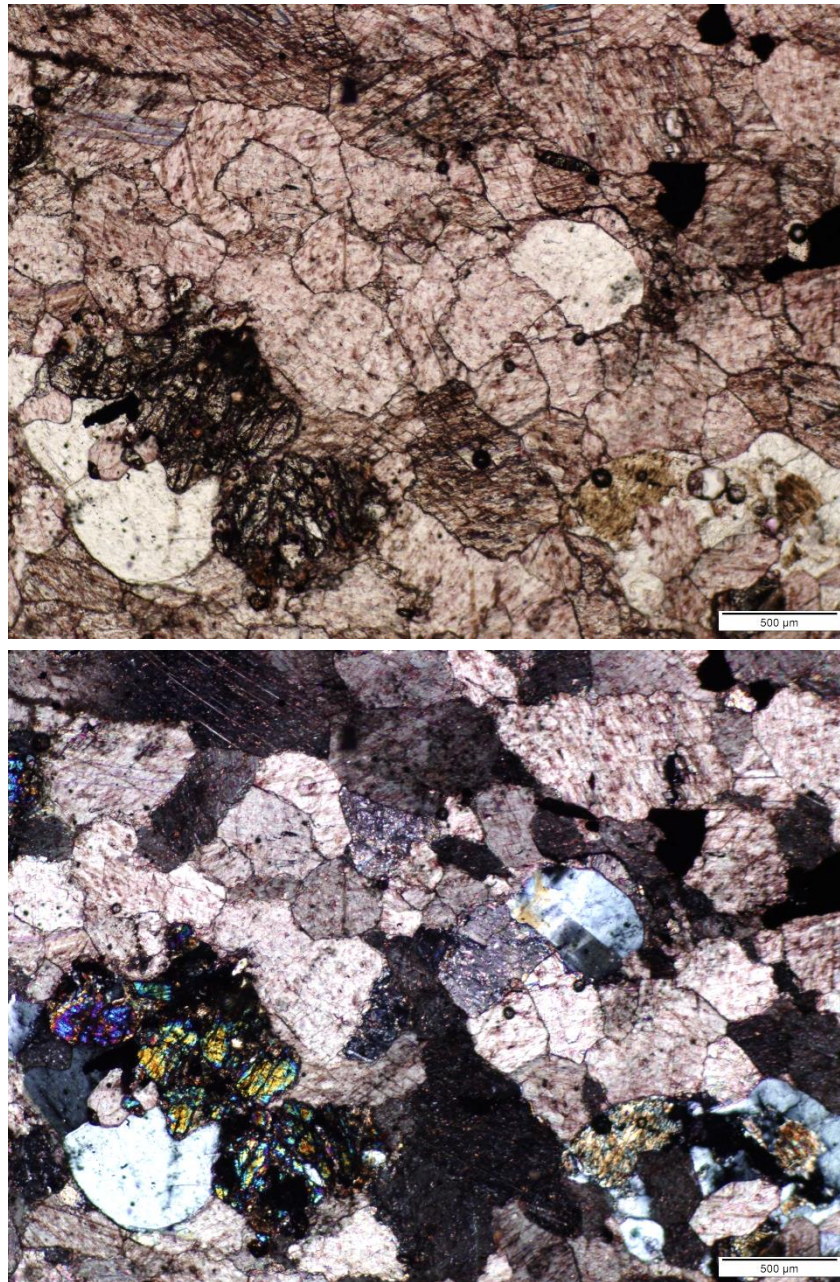


Figure 15. Unpolished thin section of sample GM14-1-4 under (a) plane polarized light and (b) cross polarized light. The calcite grains are stained pink. The calcite grains have variable sizes ranging from 100 μm to 1200 μm . Twinning is not very distinct in many of the calcite grains and the twins are straight where they are present. Other minerals in the sample include alkali feldspar and diopside. The wisps of sheared graphite and other opaques define the foliation. This sample is a protomylonite.

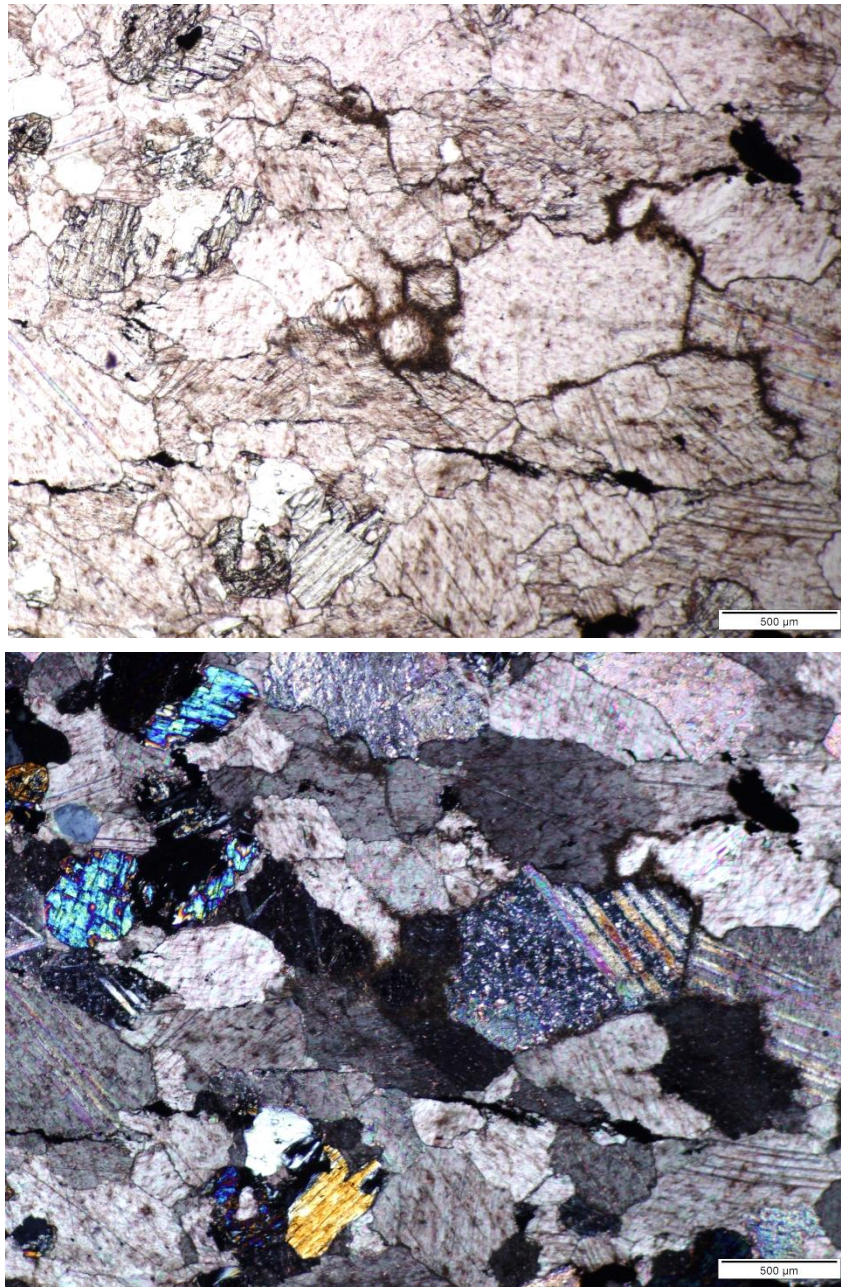


Figure 16. Unpolished thin section of sample GM14-1-5B under (a) plane polarized light and (b) cross polarized light. The calcite is stained pink. Calcite grain sizes range from 200 μm to 1600 μm with some smaller sub-grains around other minerals. The preferred orientation of sheared graphite and other opaques between the calcite grains strongly defines the foliation at the scale of the thin section. Other minerals in the sample include alkali feldspar and diopside. This sample is a protomylonite.

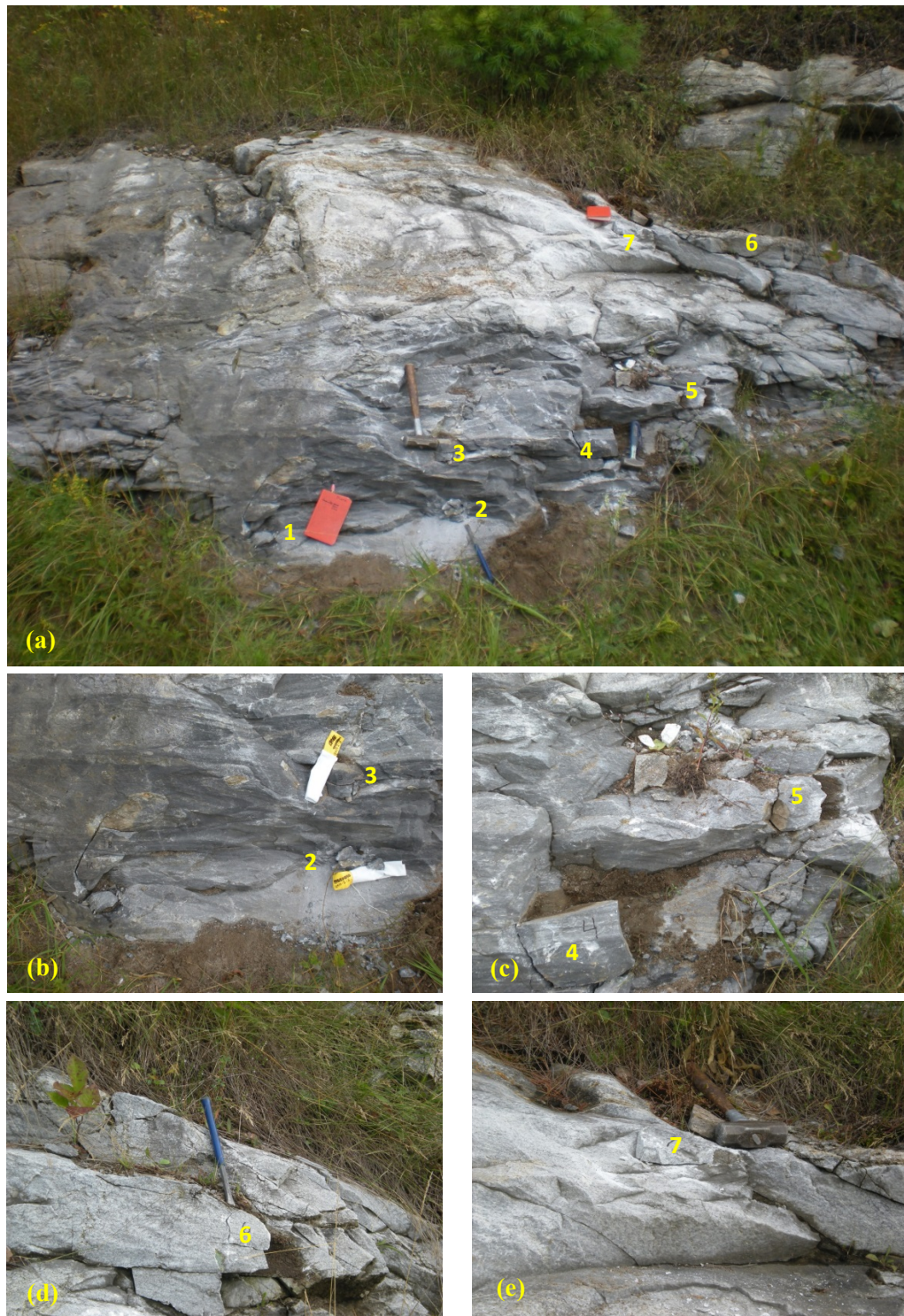


Figure 17. Field image of locality GM14-2. (a) This locality contains marble that ranges from protomylonites to ultramylonites. The numbers indicate the positions of samples 1 through 7. The hammers and notebooks are for scale. (b) Samples 2 and 3 are in the ultramylonite region of the outcrop. (c) Sample 4 is located in the ultramylonite region of the outcrop while sample 5 is located in the mylonite region. (d) Sample 6 and (e) 7 are mylonites.

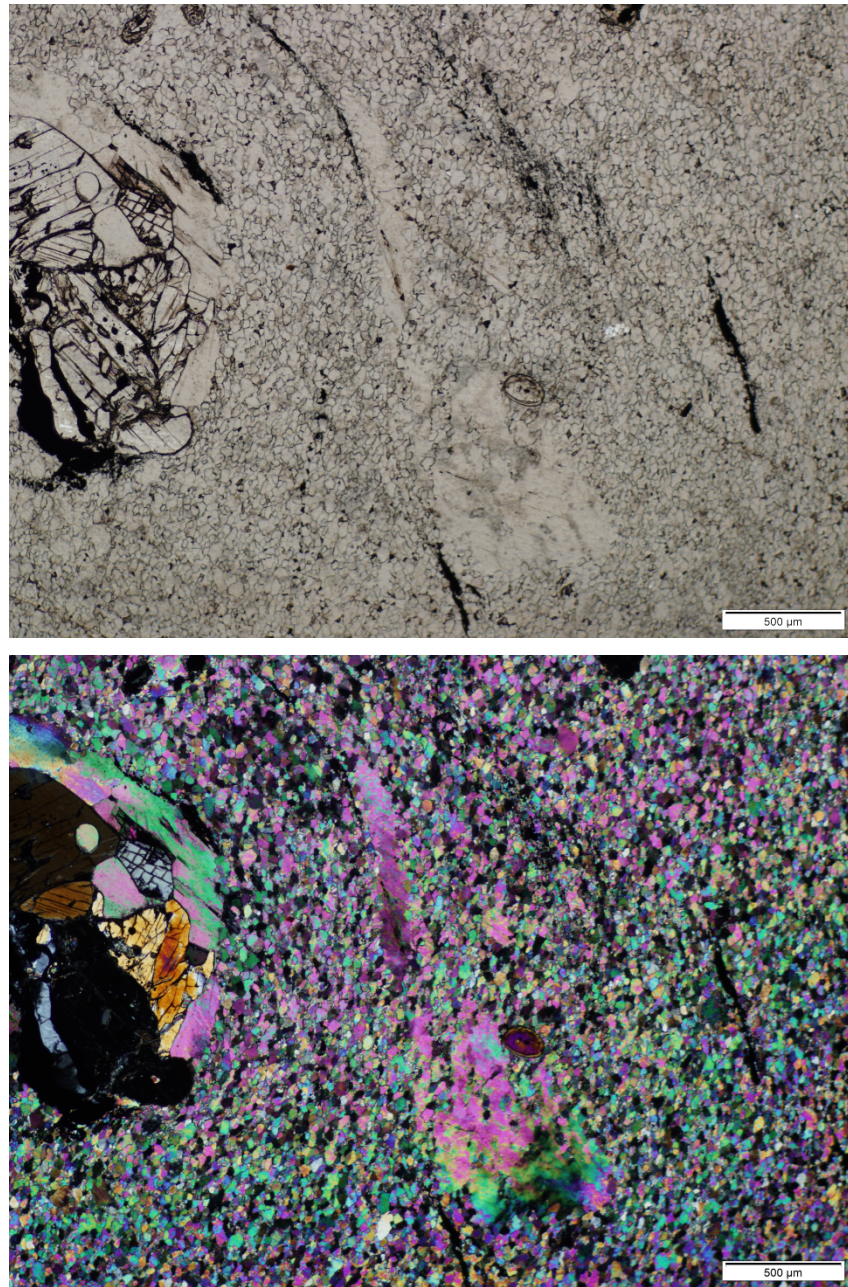


Figure 18. Polished thin section of sample GM14-2-1A under (a) plane polarized light and (b) cross polarized light. Most calcite grains range from 10 μm to 70 μm in length. The calcite grains do not exhibit twinning. The preferred orientation of sheared graphite and other opaques strongly defines the foliation at the scale of the thin section. Graphite grains are as long as 150 μm and many grains are smaller than 10 μm . Diopside grains also occur within this field of view. This sample is an ultramylonite.

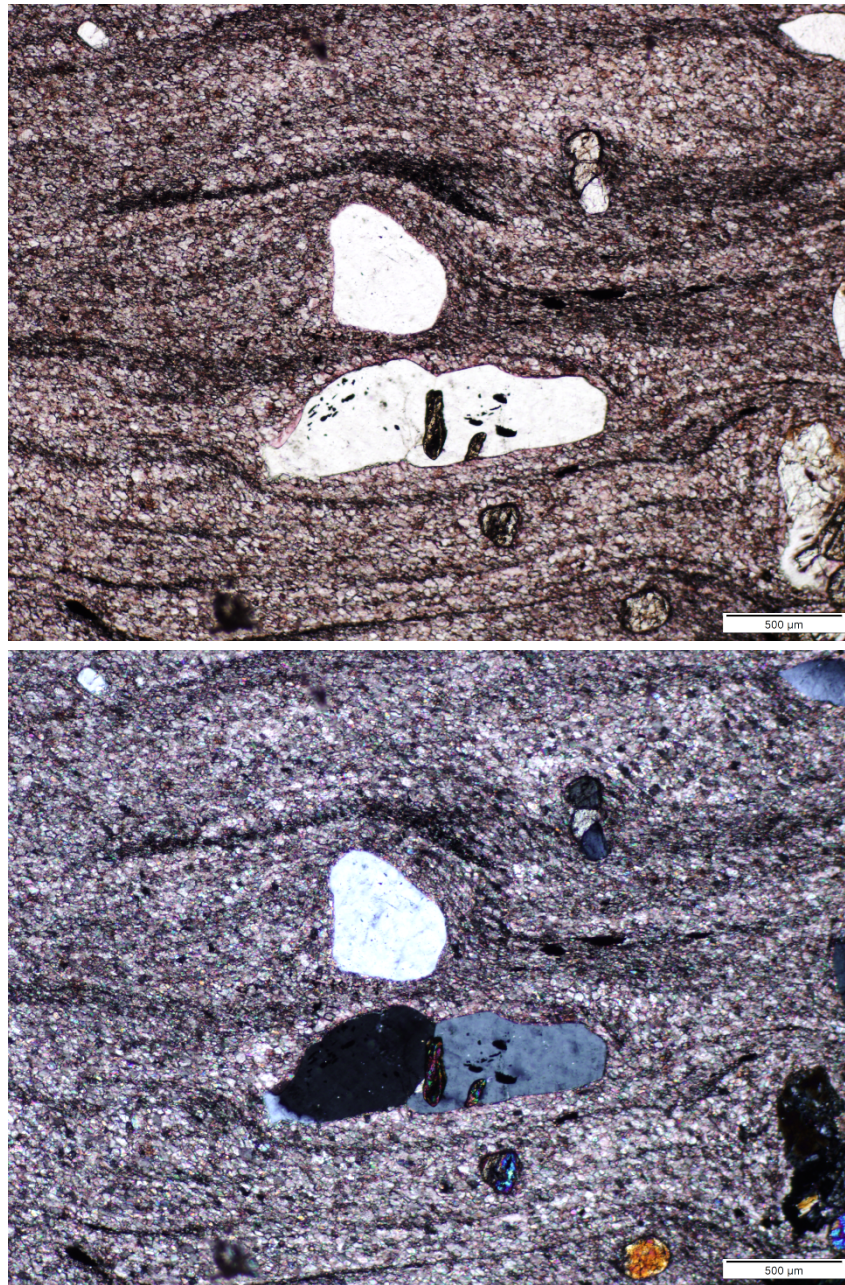


Figure 19. Unpolished thin section of sample GM14-2-2 under (a) plane polarized light and (b) cross polarized light. The calcite is stained pink. Most calcite grains range from 5 μm to 40 μm . The wisps of sheared graphite and other opaques strongly define the foliation at the scale of the thin section. Alkali feldspar and diopside also occur in this field of view. This sample is an ultramylonite.

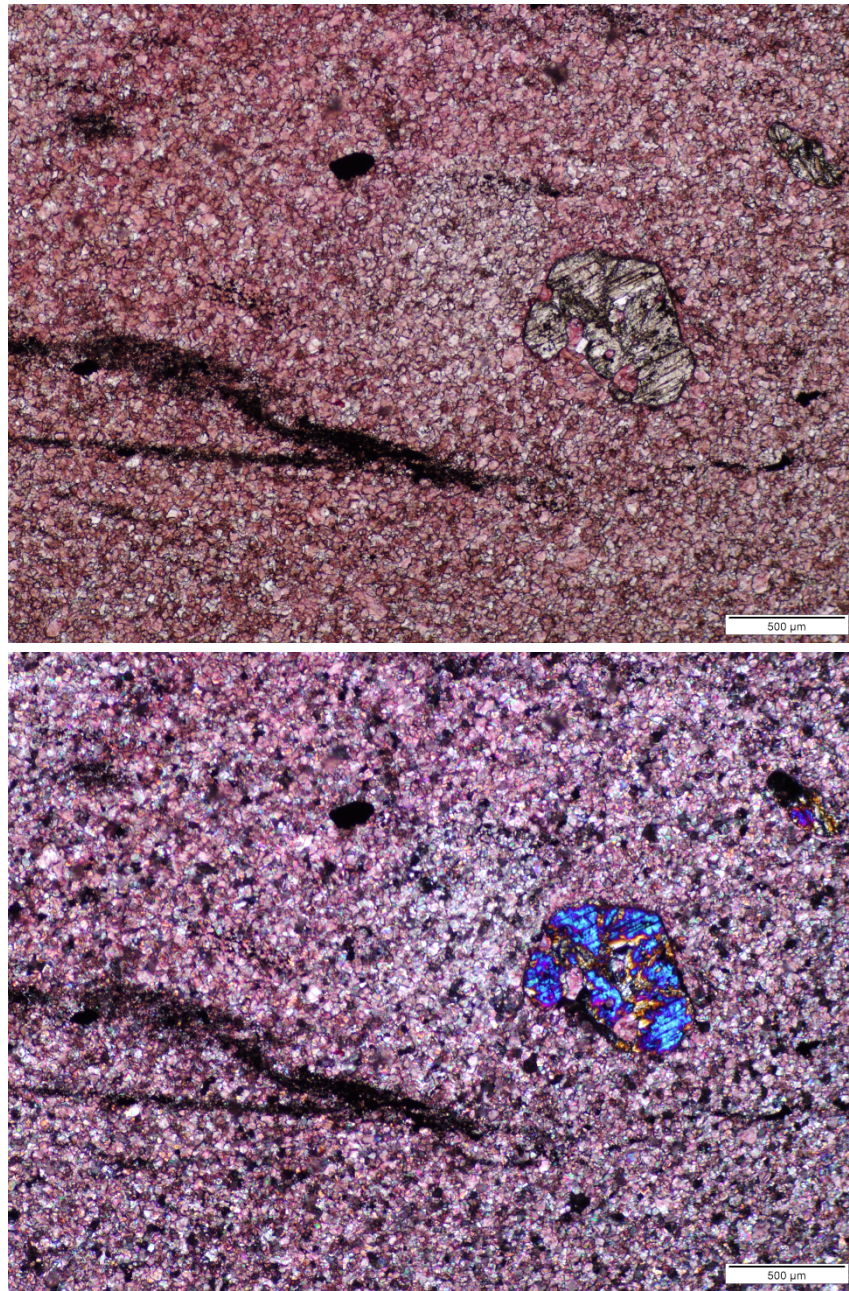


Figure 20. Unpolished thin section of sample GM14-2-3B under (a) plane polarized light and (b) cross polarized light. The calcite is stained pink. The calcite is fine grained, ranging from 5 μm to 60 μm . The wisps of fine-grained graphite and other opaques strongly define the foliation at the scale of the thin section. This sample is an ultramylonite.

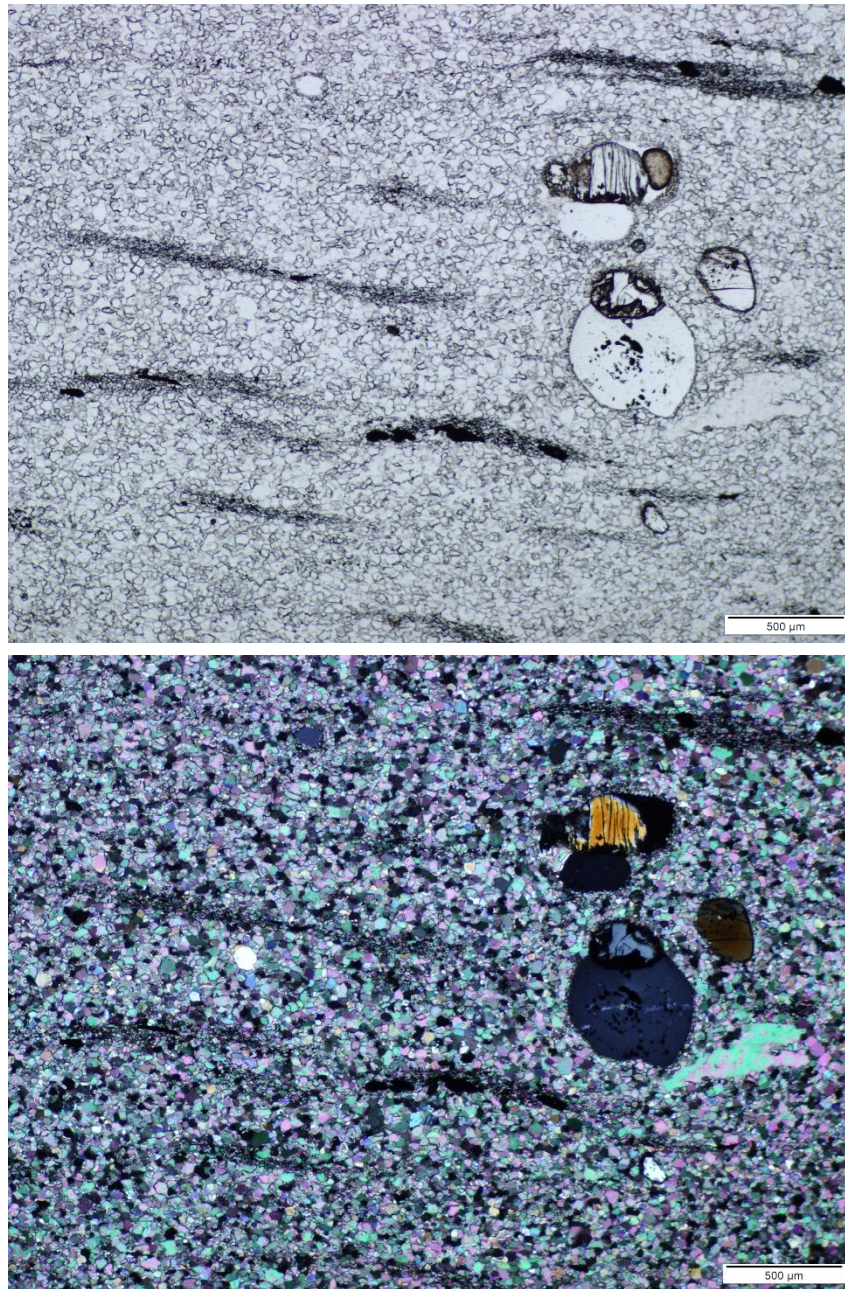


Figure 21. Polished thin section of sample GM14-2-4 under (a) plane polarized light and (b) cross polarized light. The majority of the calcite grains range from 10 μm to 50 μm . The preferred orientation of fine-grained wisps of graphite and other opaques strongly define the foliation at the scale of the thin section. This sample is an ultramylonite.

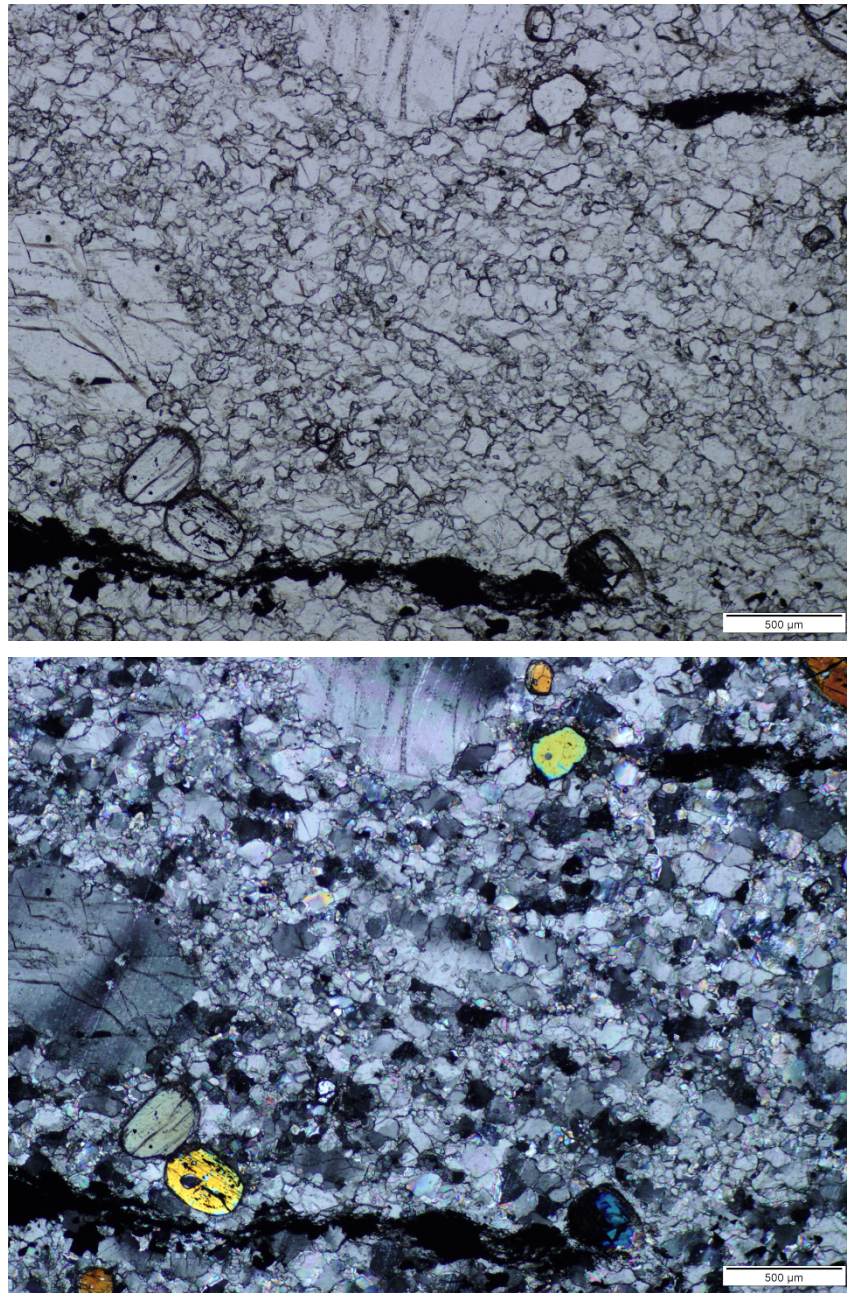


Figure 22. Polished thin section of sample GM14-2-6 under (a) plane polarized light and (b) cross polarized light. The size of calcite grains ranges from 20 μm to 1160 μm . The graphite is located between the calcite grains and ranges from 20 μm to less than 5 μm in length. Diopside also occurs in this field of view. This sample is a mylonite.

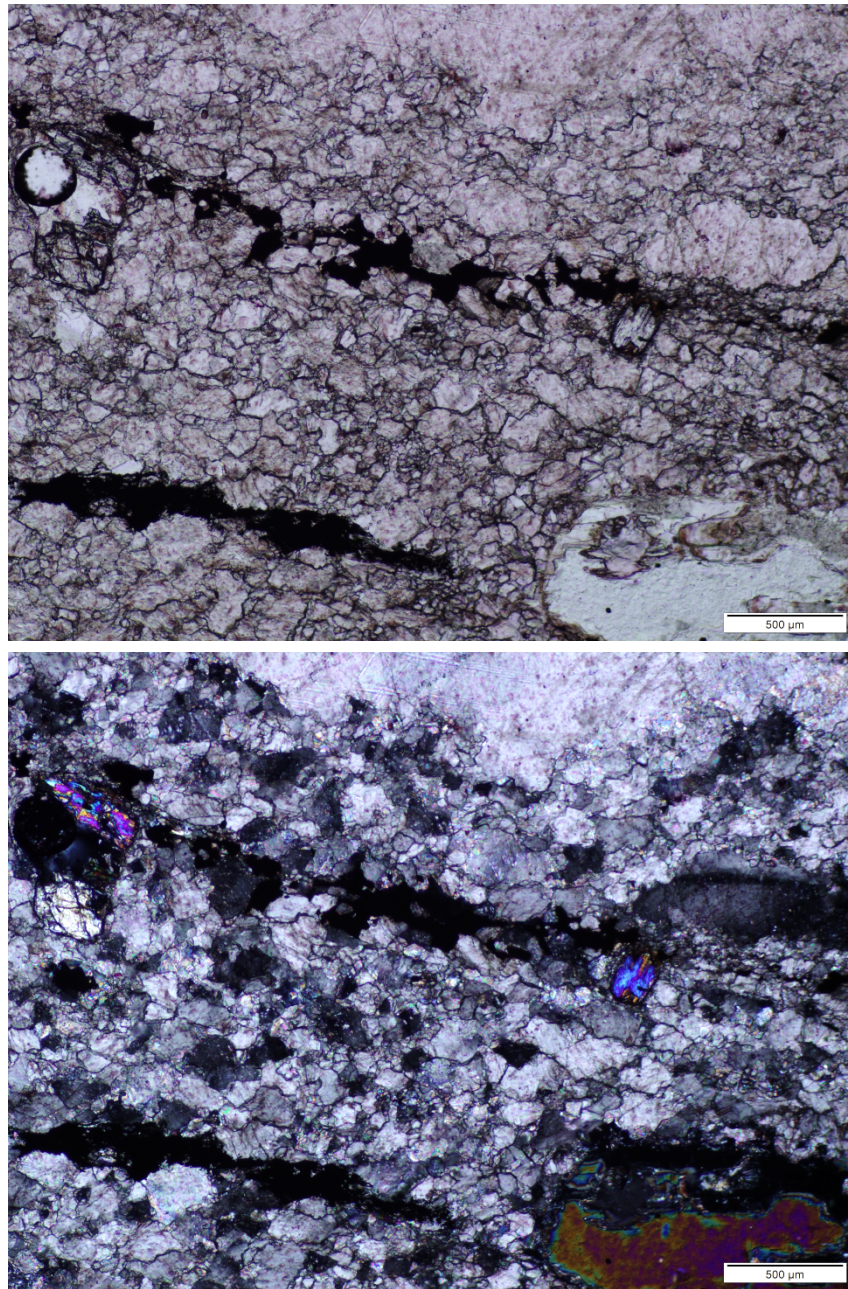


Figure 23. Unpolished thin section of sample GM14-2-7 under (a) plane polarized light and (b) cross polarized light. The calcite grains vary in size with grains ranging from 20 μm to 2800 μm in length. The preferred orientation of sheared graphite and other opaques defines the foliation at the scale of the thin section. Other minerals within the sample include feldspars, tremolite, and diopside. This sample is a mylonite.

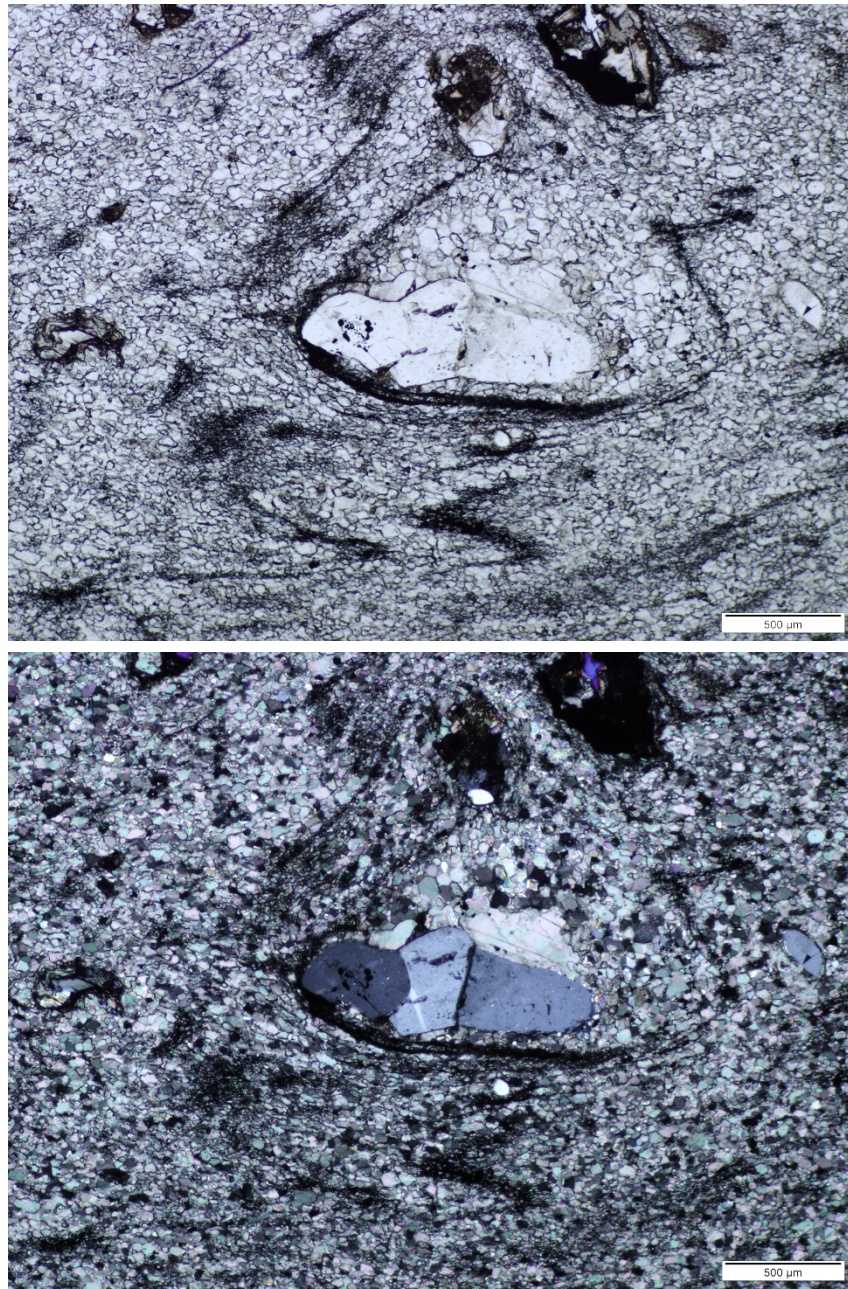


Figure 24. Polished thin section of sample GM14-2-8 under (a) plane polarized light and (b) cross polarized light. The majority of the calcite grains range from 10 μm to 60 μm . Some graphite grains are as long as 100 μm but many grains are 20 μm or smaller. The preferred orientation of sheared graphite and other opaques weakly defines the foliation at the scale of the thin section. Alkali feldspar also occurs in the center of this field of view. This sample is an ultramylonite.

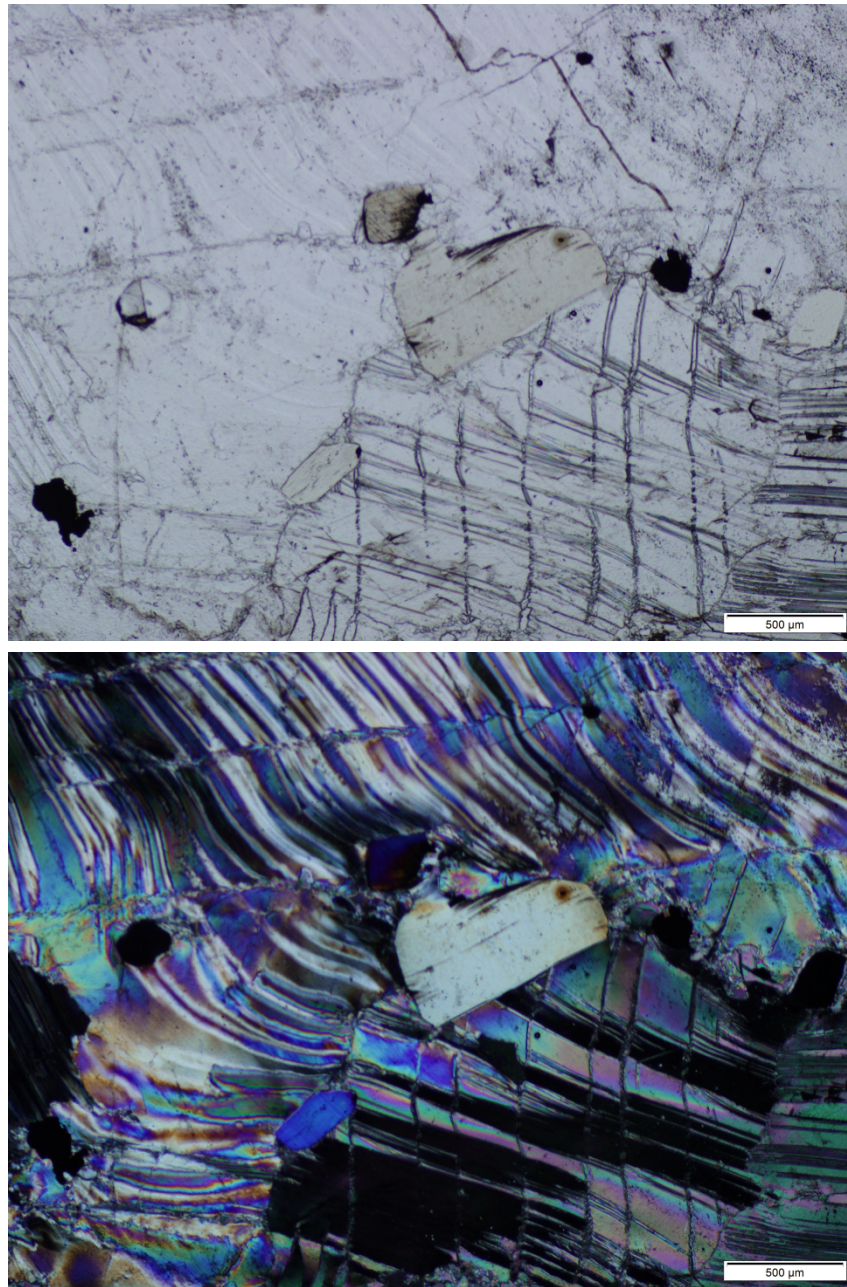


Figure 25. Polished thin section of sample GM14-2-9 under (a) plane polarized light and (b) cross polarized light. Calcite grain sizes range from 560 μm to 5000 μm . Elongate grains of graphite range from 70 μm to 350 μm in length. The calcite in this sample exhibits thick, bent and tapered twins that represent type III twins. I classify this sample as a protomylonite.



Figure 26. Field image of locality GM14-5. Thin mylonite bands within coarse-grained marble, with a quarter for scale, are present at locality GM14-5.

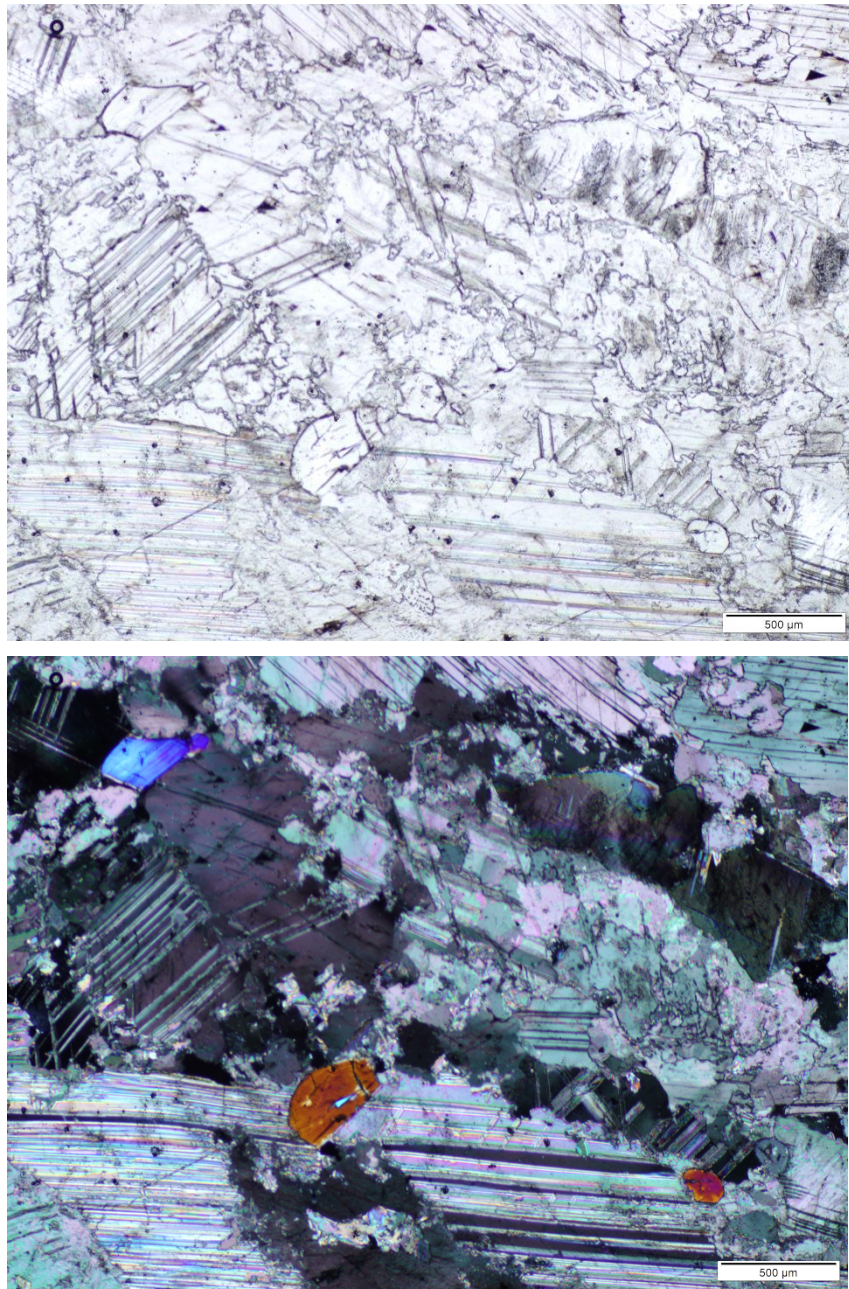


Figure 27. Polished thin section of sample GM14-5-1 under (a) plane polarized light and (b) cross polarized light. Calcite grain sizes range from 300 μm to 3000 μm . Elongate grains of graphite range from 70 μm to 880 μm in length. This sample is classified as a protomylonite.

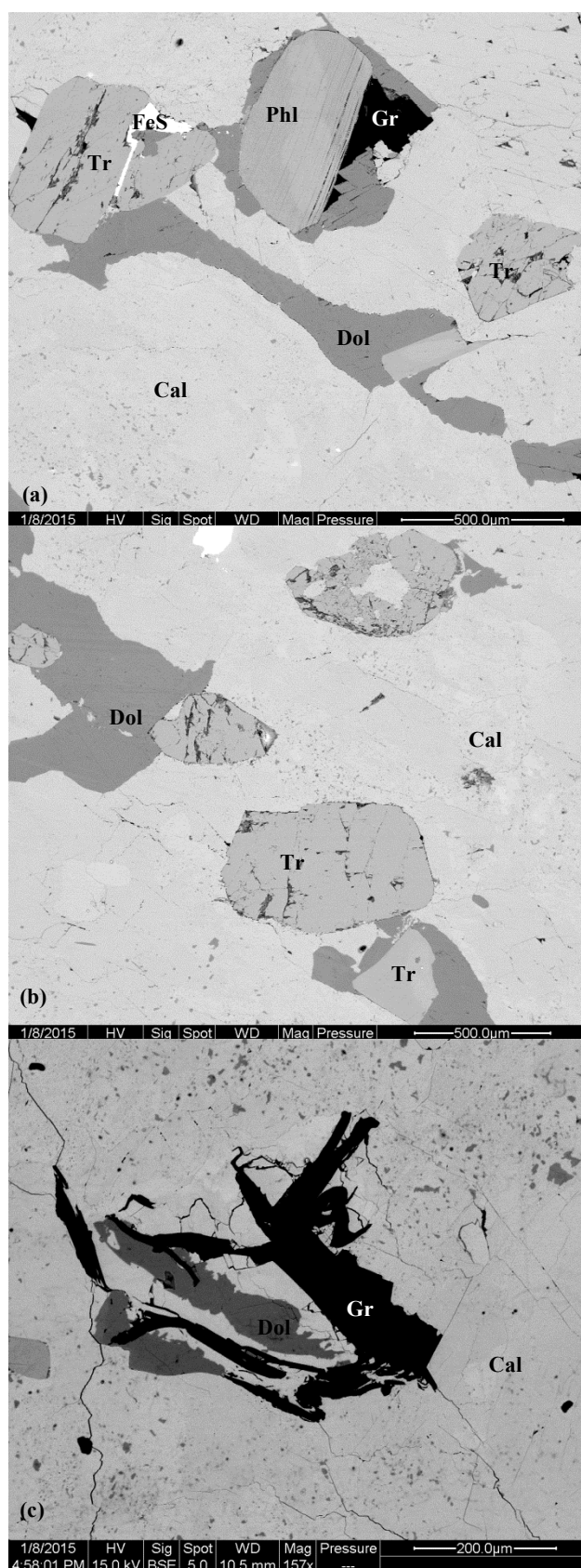


Figure 28. SEM backscattered electron image of GM14-5-1. This protomylonite sample is a predominantly calcite marble. (a) Dolomite rims some of the phlogopite and tremolite grains. An iron sulfide grain (white) is also in this field of view. (b) Dolomite surrounds some of the tremolite. (c) A large graphite grain is bent around a grain of dolomite. Dolomite exsolution blebs are visible within the calcite.

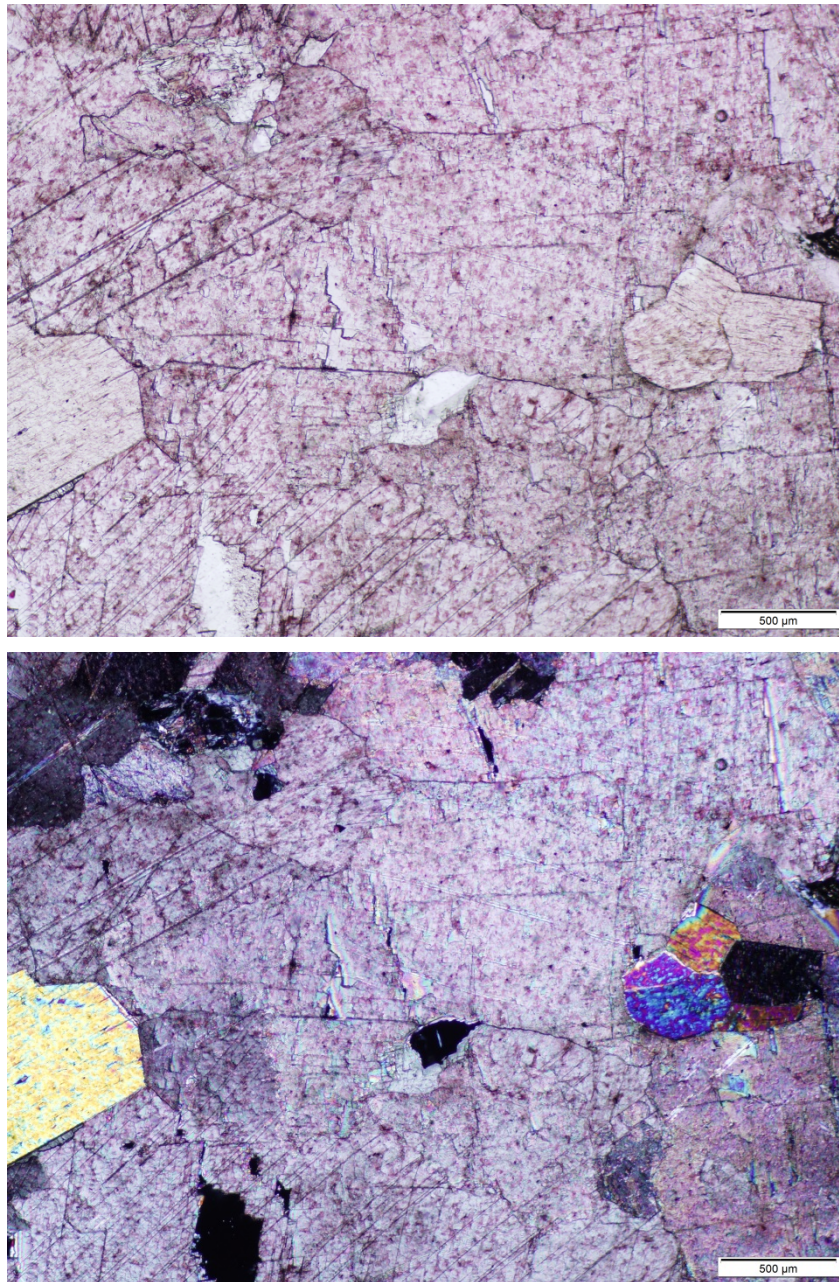


Figure 29. Unpolished thin section of sample GM14-5-4 under (a) plane polarized light and (b) cross polarized light. The calcite is stained pink. Calcite grain sizes range from 260 μm to 6400 μm . Elongate grains of graphite range from 70 μm to 880 μm in length. Other minerals present in the sample include tremolite, phlogopite, titanite, and small amounts of dolomite. This sample is classified as a protomylonite.



Figure 30. Field image of locality GM14-6. A white, coarse-grained marble with dark, anastomosing zones of shearing as thin as 2-4 mm occurs at this locality. A lineation is apparent in some of these shear zones.

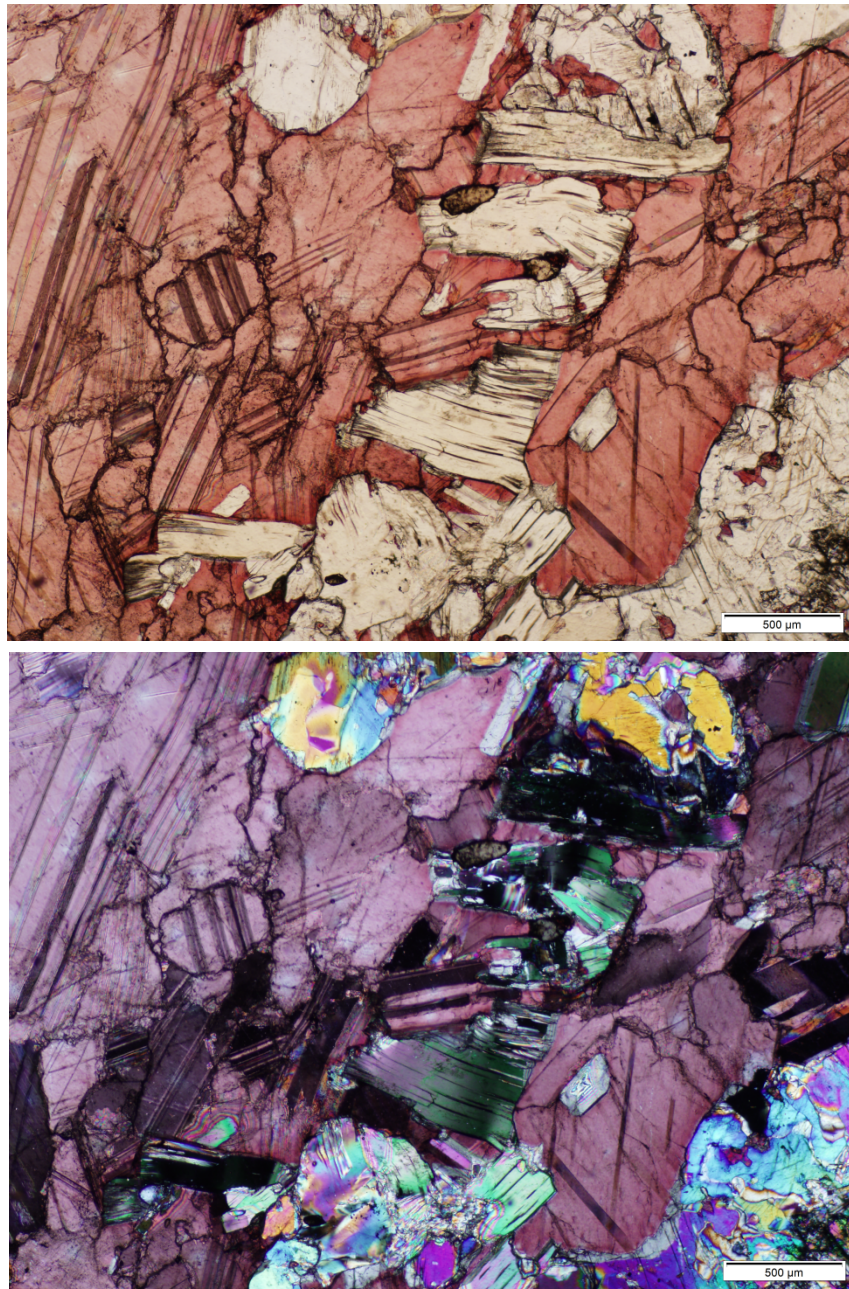


Figure 31. Unpolished thin section of sample GM14-6-1A under (a) plane polarized light and (b) cross polarized light. The calcite is stained pink. Calcite grain sizes range from 30 μm to 2600 μm . Other minerals present in the sample include tremolite, phlogopite, and diopside. This sample is classified as a protomylonite.

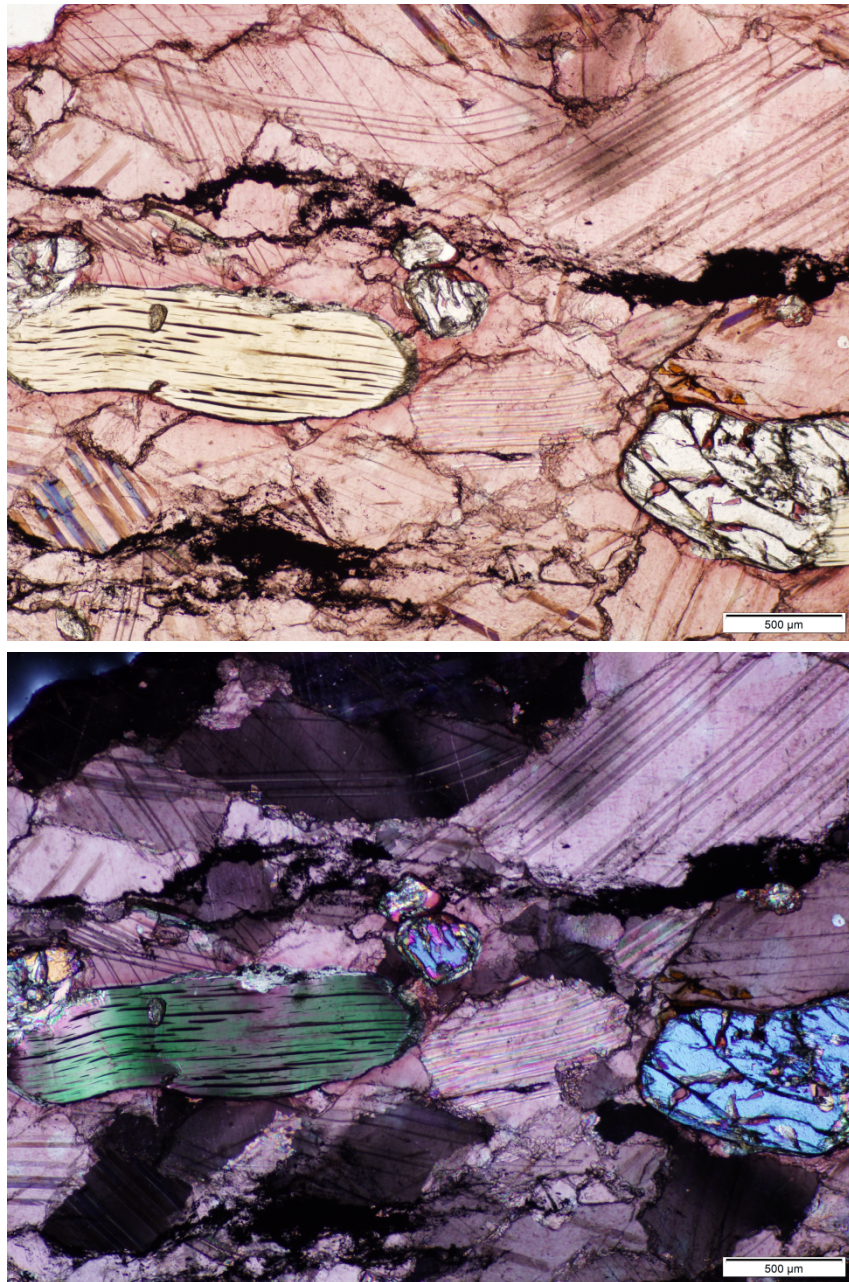


Figure 32. Unpolished thin section of sample GM14-6-1B under (a) plane polarized light and (b) cross polarized light. Calcite grain sizes range from 100 μm to 1200 μm . The preferred orientation of sheared graphite and other opaques strongly defines the foliation at the scale of the thin section. The phlogopite grains in this field of view are oriented parallel to this foliation. This sample is a protomylonite.

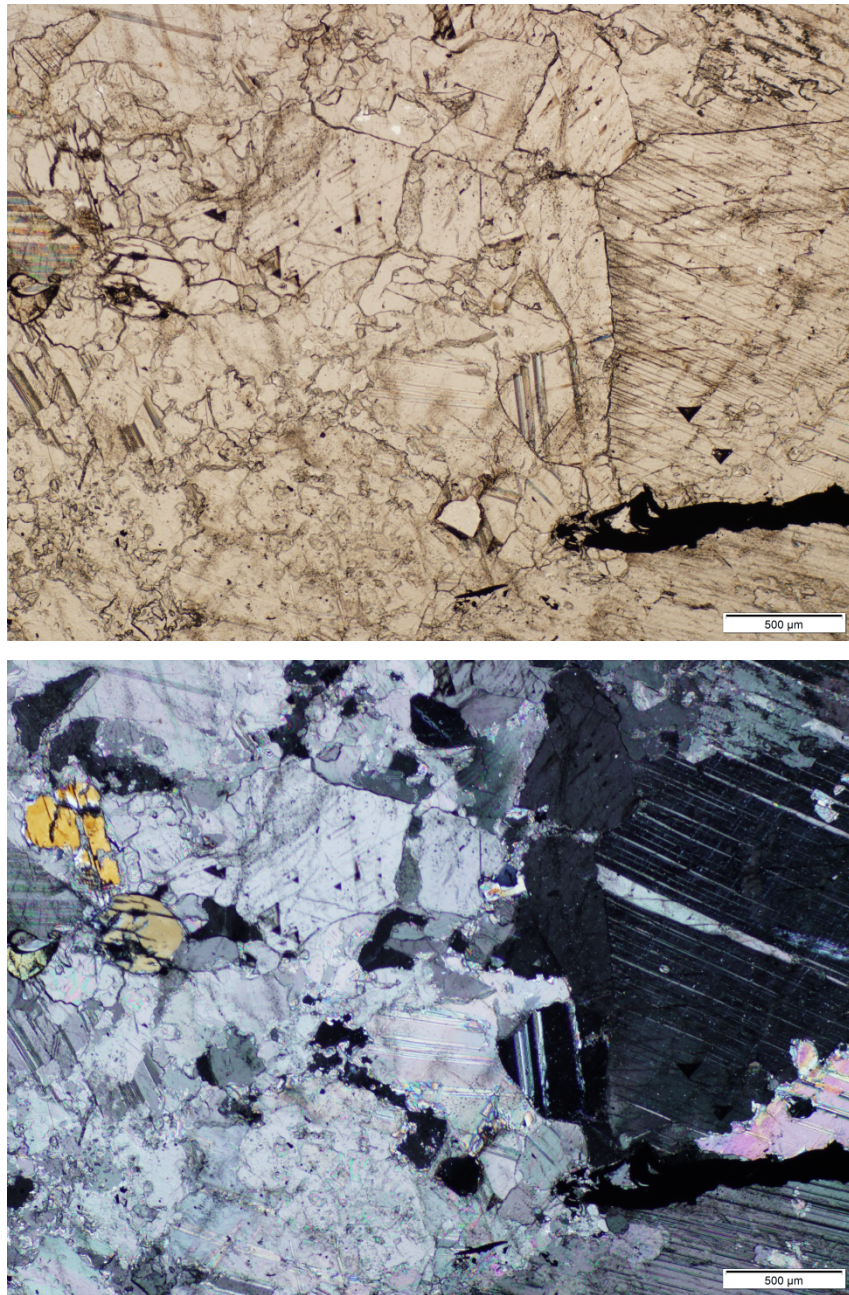


Figure 33. Polished thin section of sample GM14-6-2 under (a) plane polarized light and (b) cross polarized light. Calcite grains range from 60 μm to 4800 μm in length. Elongate grains of graphite range from 100 μm to 400 μm in length. Other minerals present in the sample include tremolite and phlogopite. This sample is classified as a protomylonite.

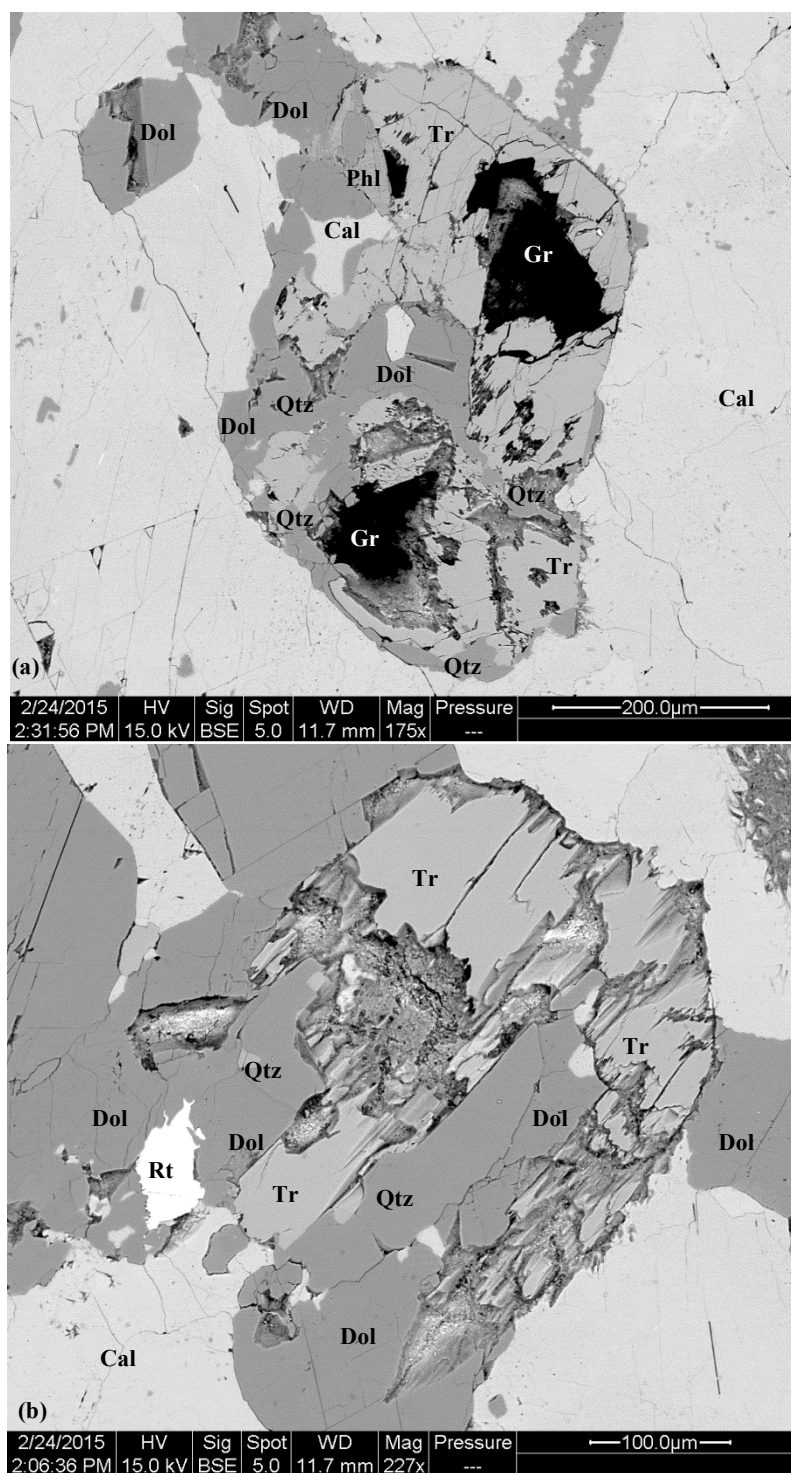


Figure 34. SEM backscattered electron image of GM14-6-2. This sample is a calcite marble. (a) Dolomite and quartz rim and are intergrown with tremolite and graphite. (b) Dolomite is intergrown with quartz and tremolite. A rutile grain is also in this field of view. This mineral assemblage could indicate the reactions $Rt + Cal + Qtz = Ttn$ or $Dol + Qtz = Tr + Cal$. It is unclear whether these assemblages represent equilibrium conditions or overprinting.

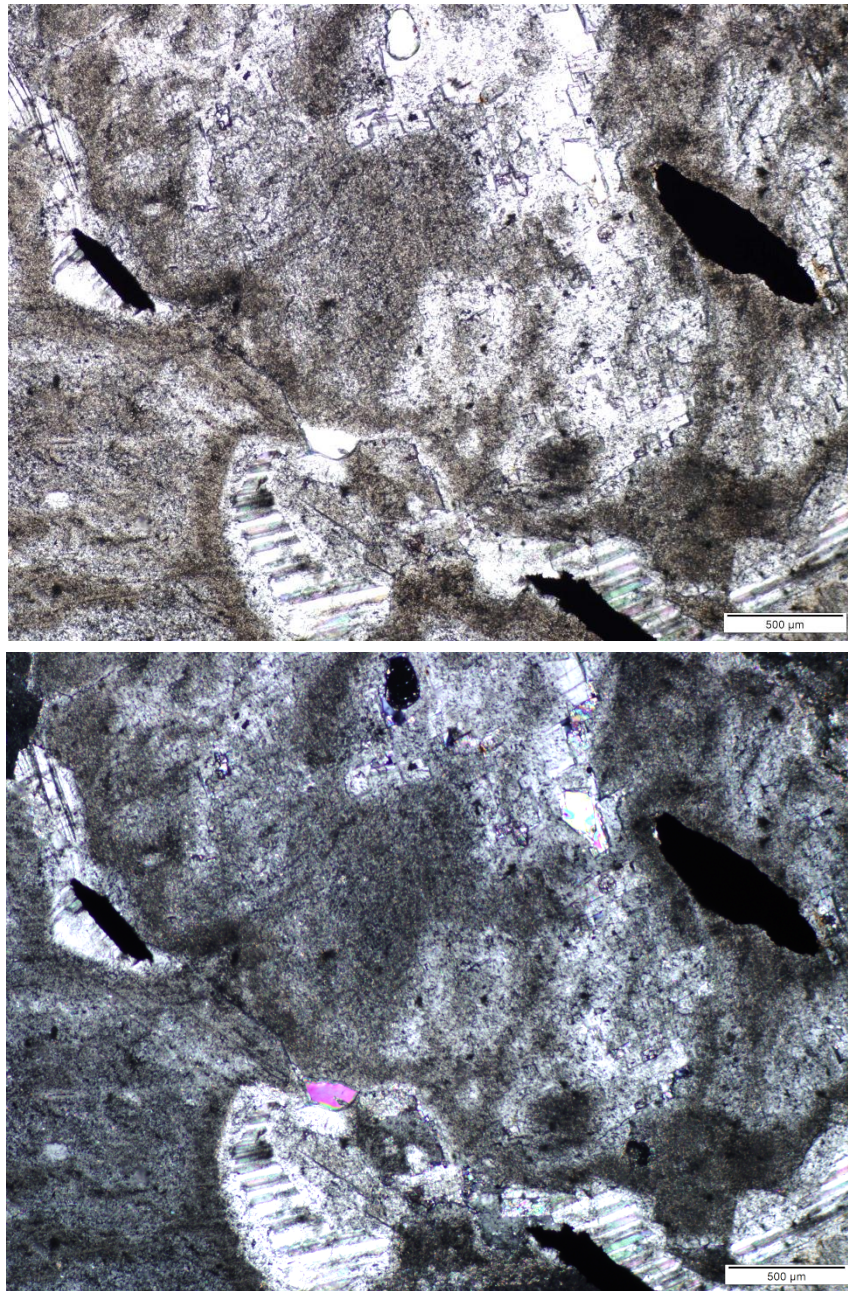


Figure 35. Unpolished thin section of sample GM14-6-3 under (a) plane polarized light and (b) cross polarized light. The lack of pink staining indicates that this sample is a dolomitic marble. The dolomite grains range from 400 μm to over 4000 μm in length with sub-grains beginning to form in some porphyroclasts. The graphite grains range from 200 μm to 900 μm in length. This sample is a protomylonite.



Figure 36. Field image of locality BT14-1. This outcrop contains mylonite layers that dip to the southeast. A thick dark mylonite is visible at my head.

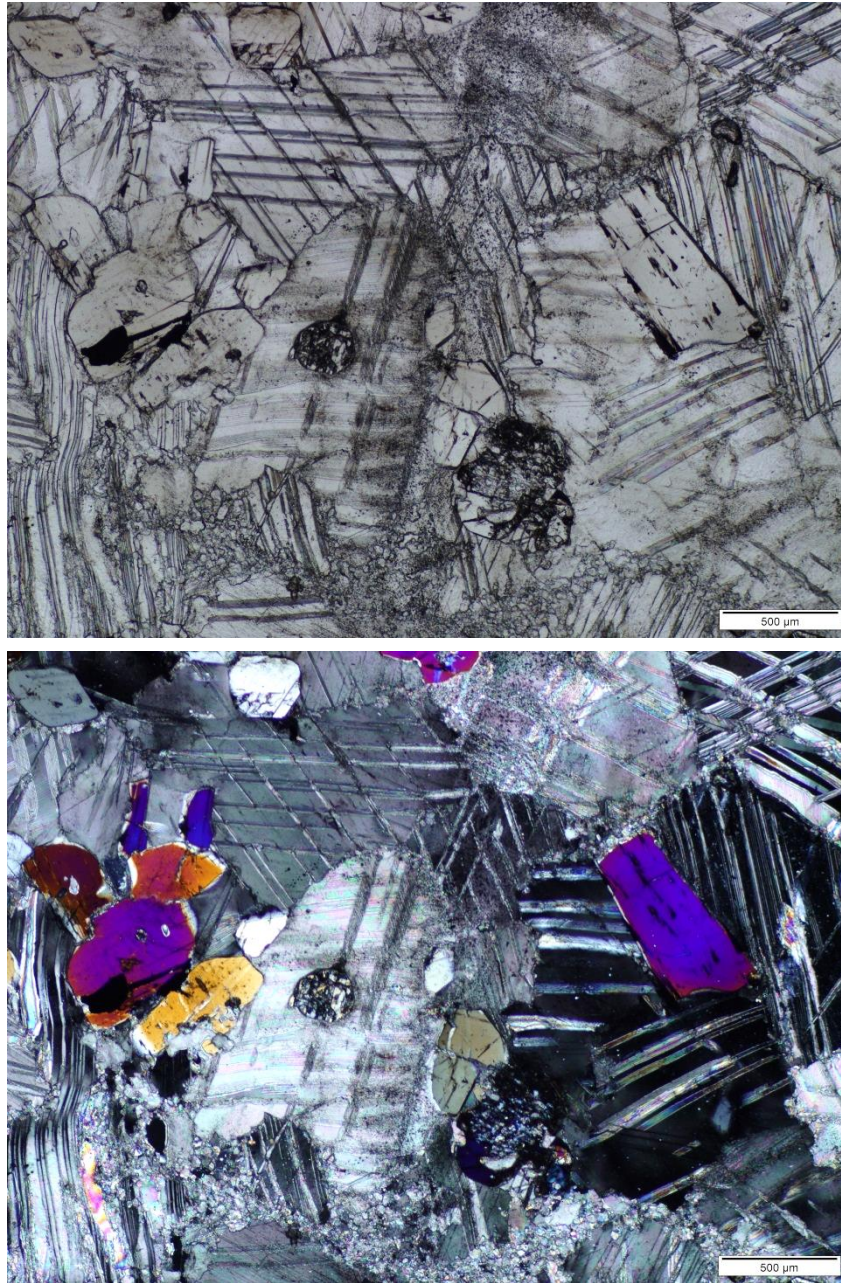


Figure 37. Polished thin section of sample BT14-1-2 under (a) plane polarized light and (b) cross polarized light. The sample consists mainly of coarse-grained calcite with grains sizes ranging from 200 μm up to 2200 μm . The graphite grains range from 100 μm to 440 μm in length. The calcite grains have thick and bent twins resembling type II and type III twinning. This sample is a protomylonite.

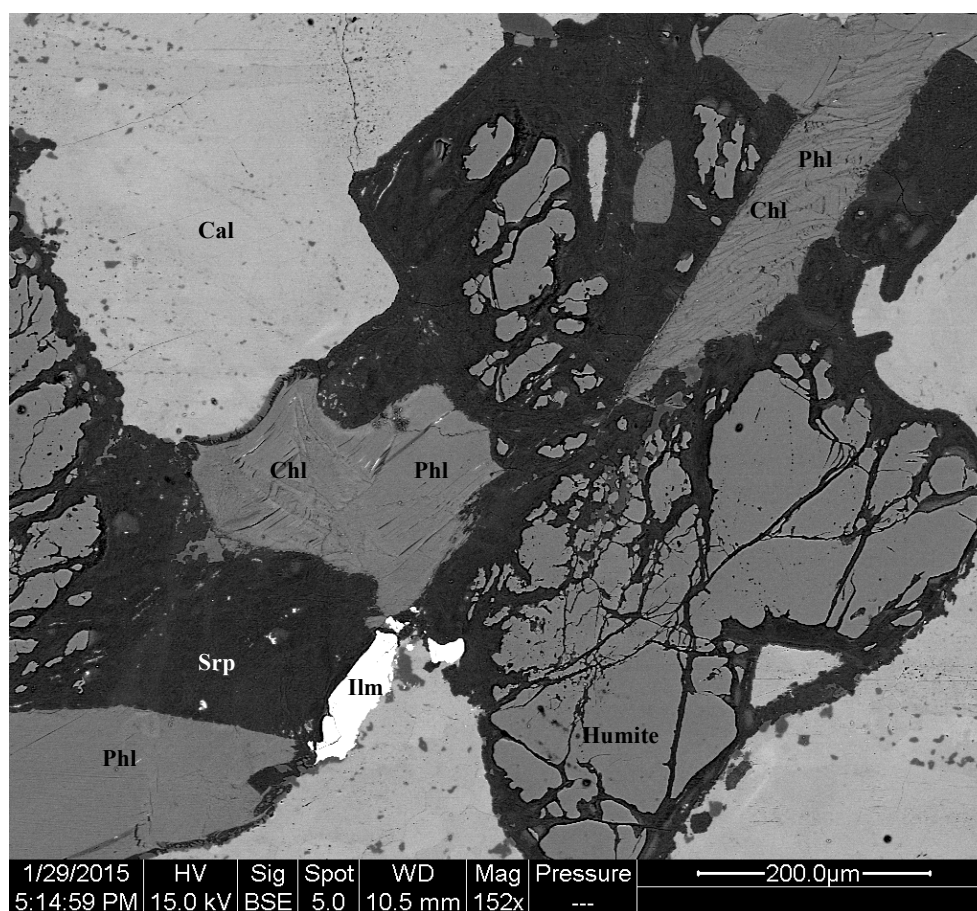


Figure 38. SEM backscattered electron image of BT14-1-3. This sample is a calcite marble. Serpentine forms rims around phlogopite, chlorite and humite group mineral grains in this sample. The phlogopite and chlorite are intergrown in some areas.



Figure 39. Field image of locality WF14-1. This outcrop contains thick mylonite layers. (a) Samples 2 through 4 are located within and adjacent to a mylonite layer. (b) Sample 5 is located in the mylonite layer while sample 6 is located in the protomylonite region of the outcrop.

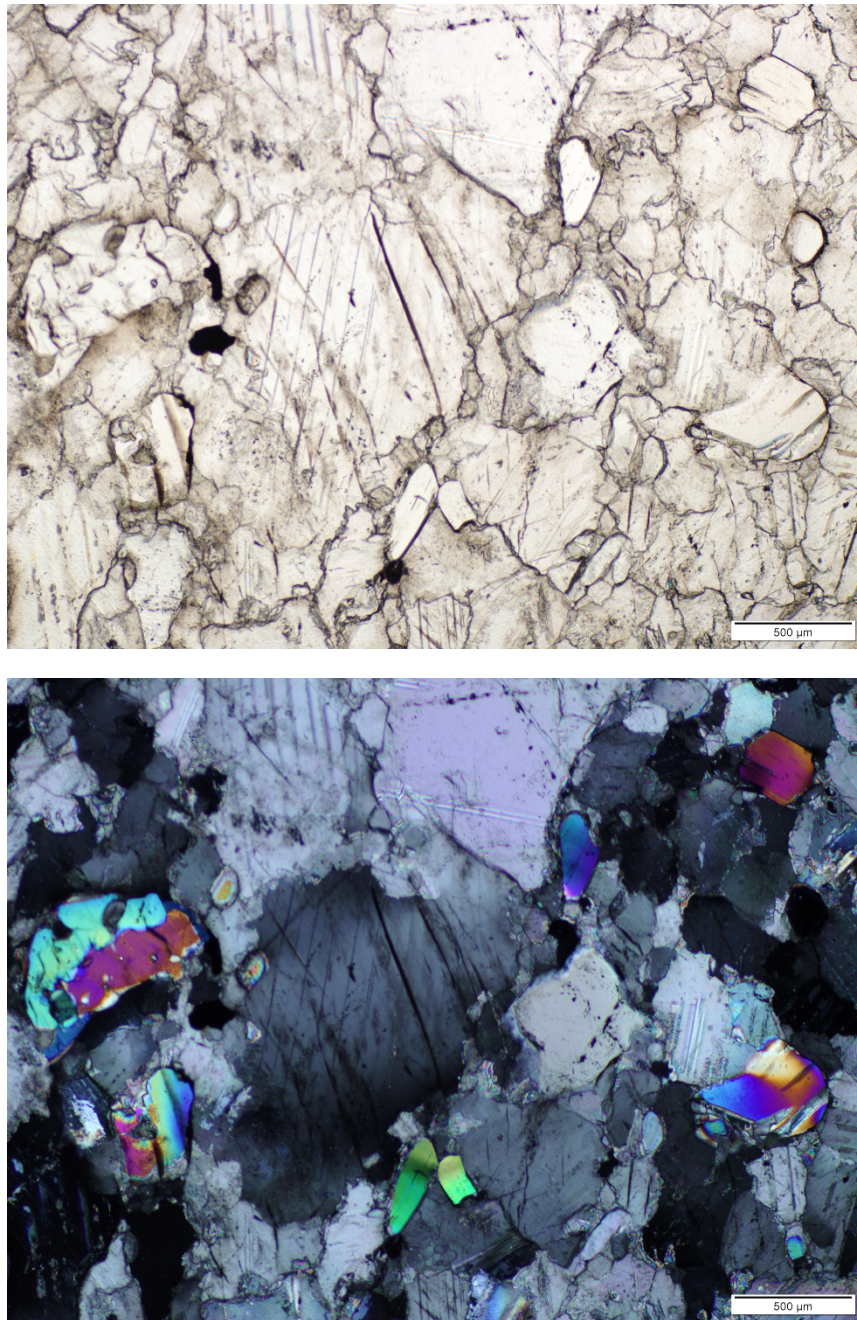


Figure 40. Polished thin section of sample WF14-1-1A under (a) plane polarized light and (b) cross polarized light. This sample is a mylonite. The calcite grains range from 10 μm to 2400 μm in length. Grains and wisps of sheared out graphite occur with a similar orientation as the phlogopite grains, defining the foliation at the thin section scale. The grains of graphite are up to 700 μm in length and can be less than 10 μm . Iron sulfides occur within and around some calcite grains, as shown in the above field of view.

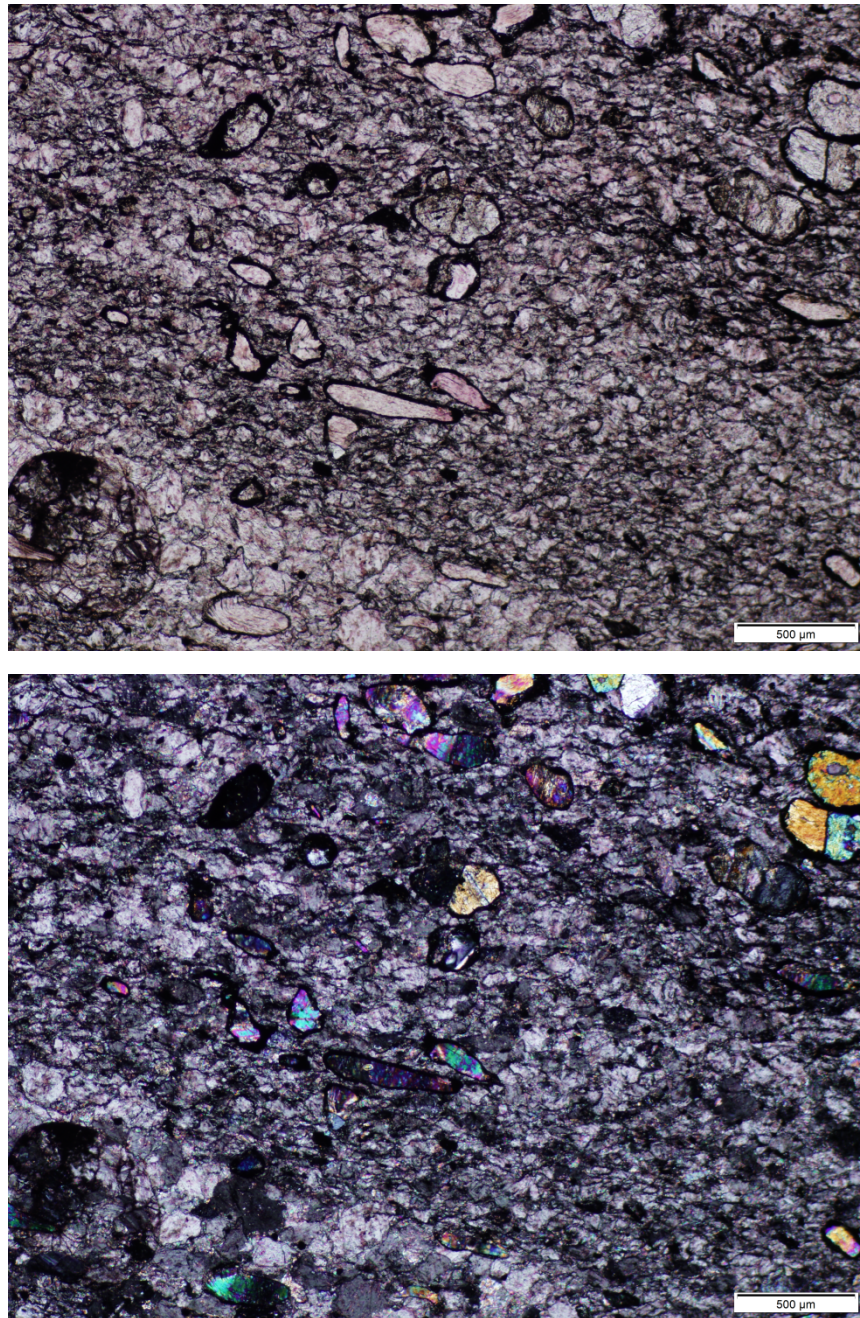


Figure 41. Unpolished thin section of sample WF14-1-3A under (a) plane polarized light and (b) cross polarized light. The calcite is stained pink. The calcite grains range from 10 μm to 300 μm in length. The opaques are very fine grained ($>20\ \mu\text{m}$), and dispersed fairly evenly between the calcite grains. This sample is a mylonite.

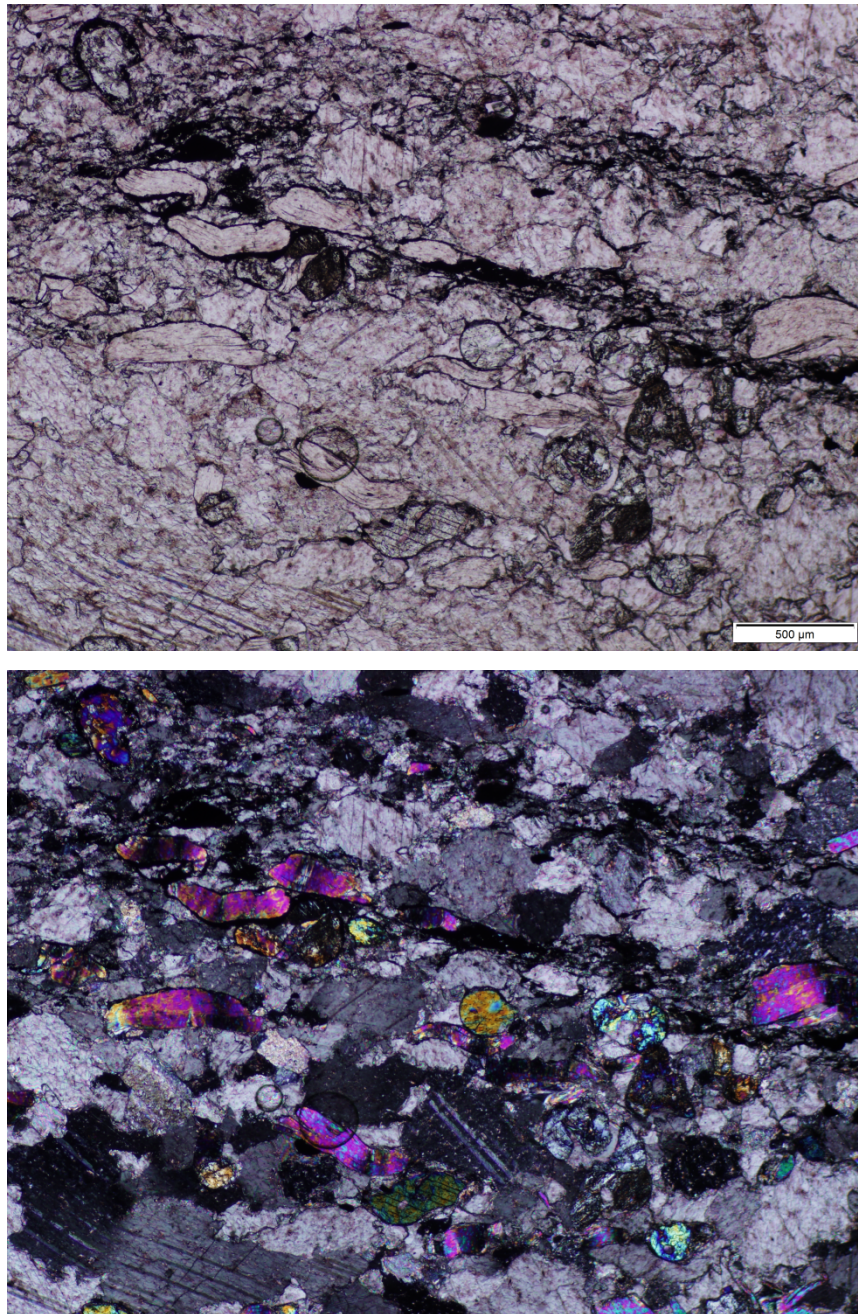


Figure 42. Unpolished thin section of sample WF14-1-3B under (a) plane polarized light and (b) cross polarized light. The calcite is stained pink. Calcite grains range from 100 μm to 1800 μm in length. Strands and wisps of fine-grained opaques define a foliation at the thin section scale. The phlogopite grains in this field of view show a similar preferred orientation to the wisps of opaques. This sample is a protomylonite.

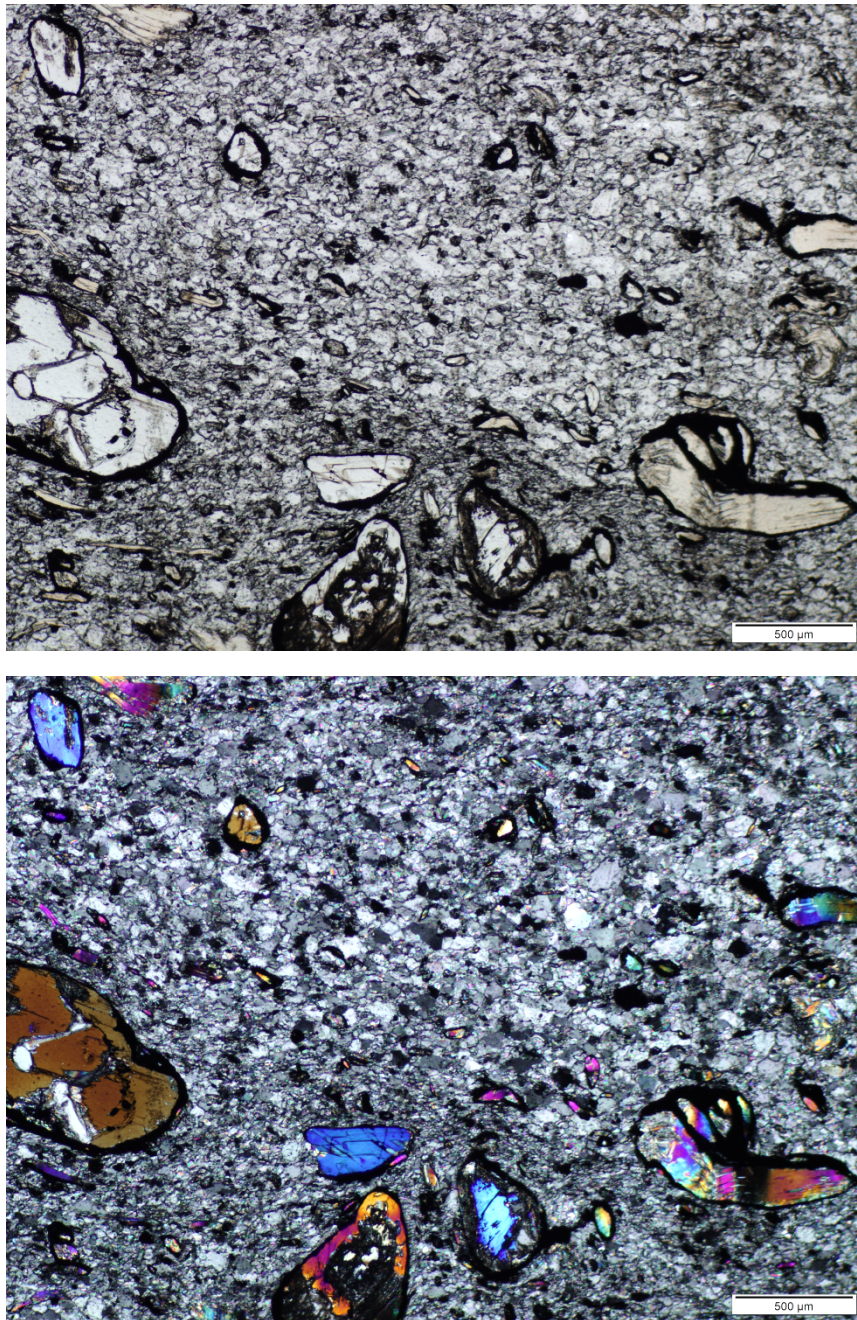


Figure 43. Polished thin section sample WF14-1-5B under (a) plane polarized light and (b) cross polarized light. The calcite grains range from 10 μm to 130 μm . Fine-grained iron sulfides and graphite are found both in sheared out wisps between calcite grains, defining the foliation at the scale of the thin section. On the left edge of this field of view, relic diopside occurs as an inclusion within tremolite. This sample is a mylonite.

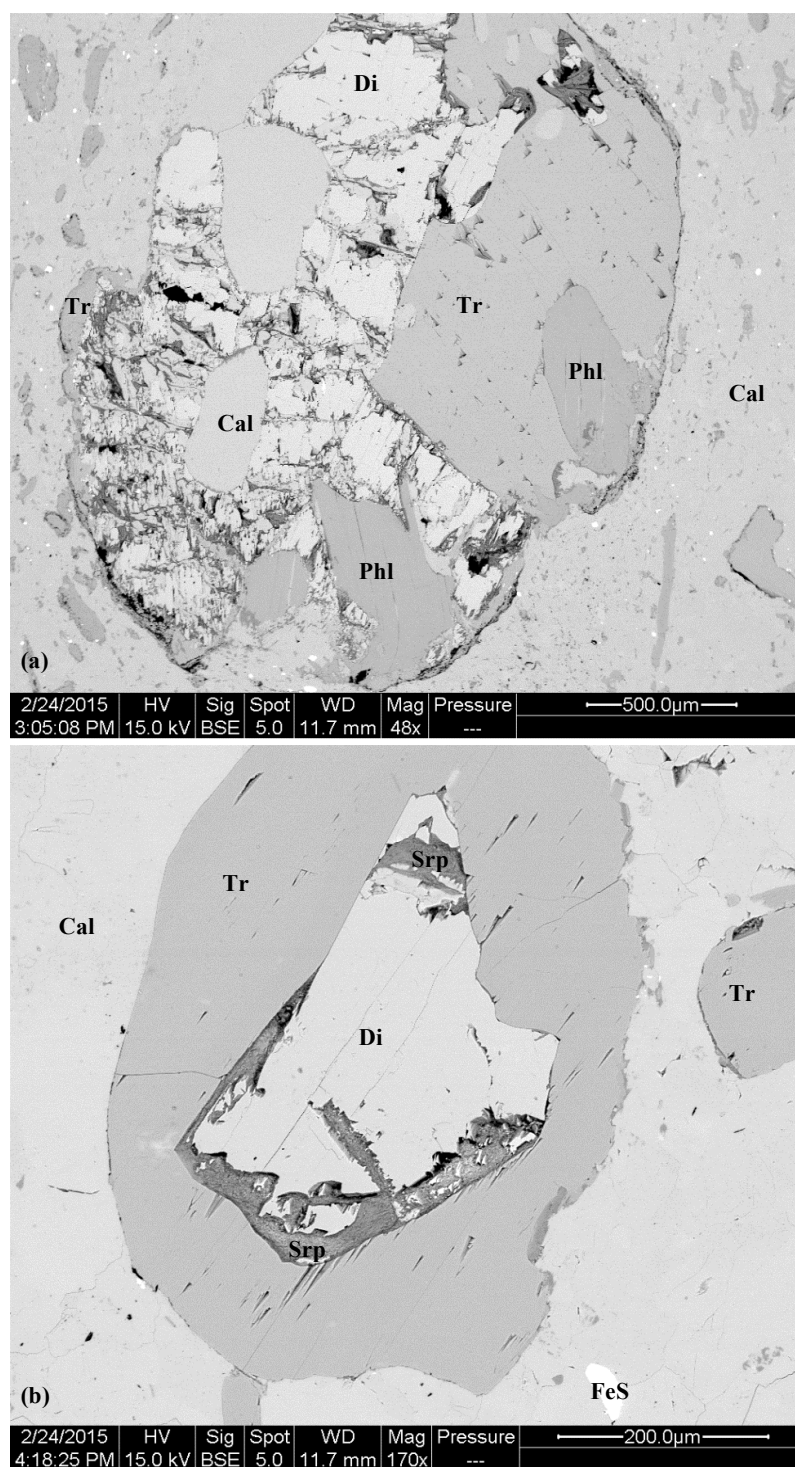


Figure 44. SEM backscattered electron image of WF14-1-5B. This sample is a calcite marble. (a) Tremolite, phlogopite, and diopside are all intergrown, with tremolite forming a thin rim around the diopside. (b) Tremolite has formed a thick rim around this diopside grain. Serpentine also rims this diopside grain within this tremolite rim.

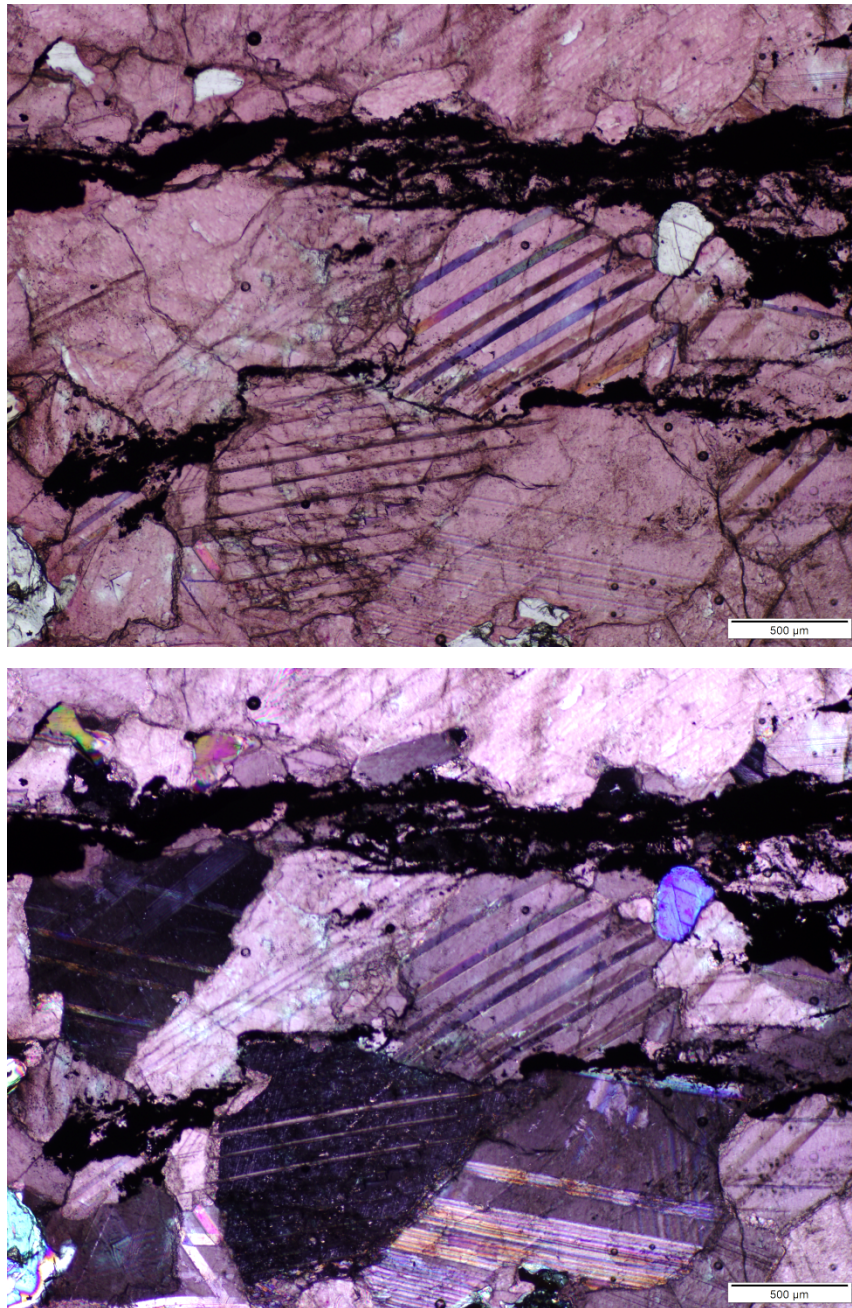


Figure 45. Unpolished thin section of sample WF14-1-6 under (a) plane polarized light and (b) cross polarized light. The calcite is stained pink. The calcite grains range from 160 μm to 2400 μm . The calcite grains exhibit type I and type II twinning. The grains of graphite can be as long as 2000 μm all the way down to very fine grains. This sample is a protomylonite.

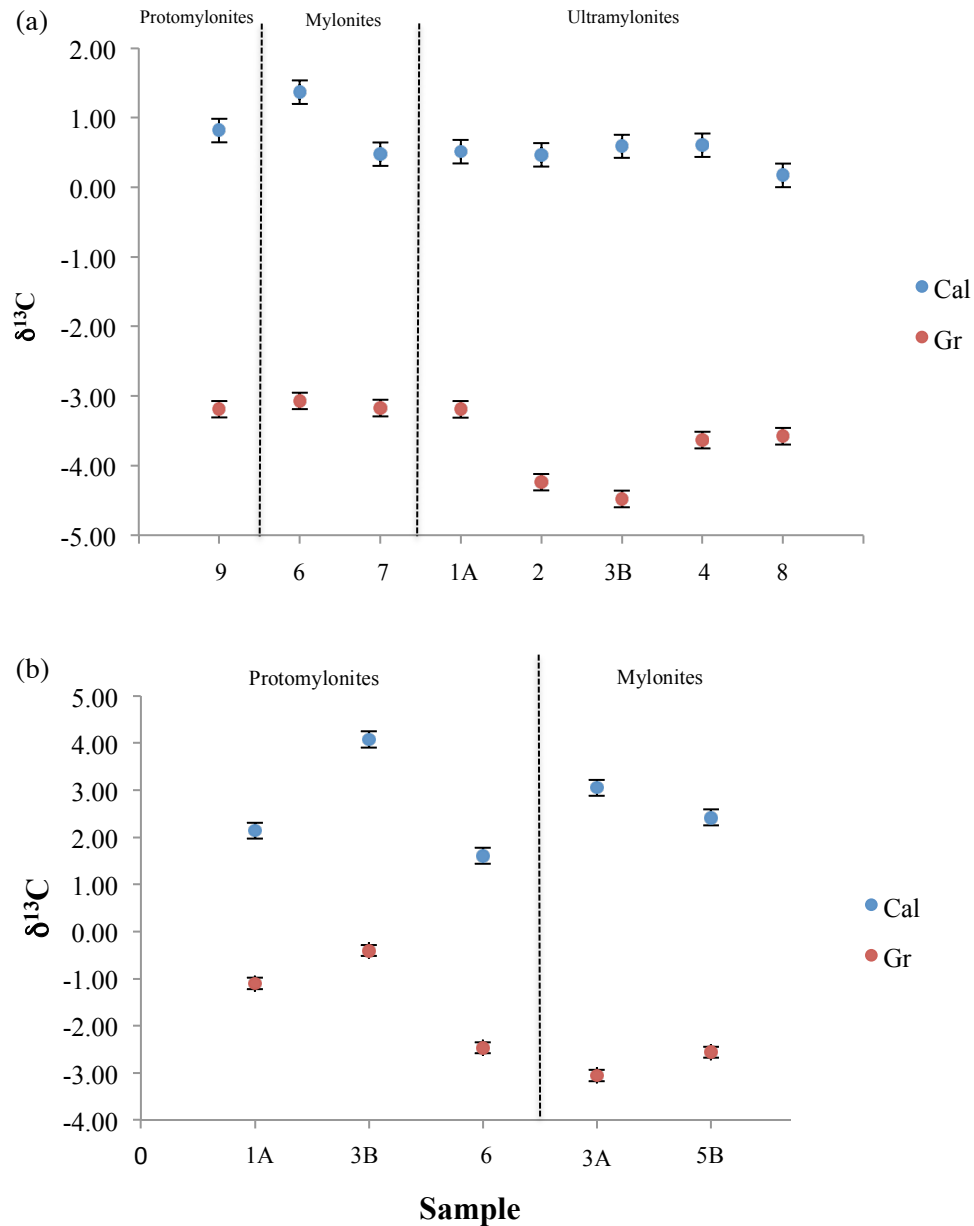


Figure 46. $\delta^{13}\text{C}$ values for calcite and graphite from protomylonites, mylonites, and ultramylonites at (a) GM14-2 and (b) WF14-1. (a) Graphite values from locality GM14-2 range from -4.48‰ to -3.07‰. Calcite values range from 0.17‰ to 1.37‰. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values range from 3.65‰ to 5.07‰. (b) Graphite values from WF14-1 range from -3.06‰ to -0.40‰. Calcite values range from 1.61‰ to 4.07‰. The $\Delta^{13}\text{C}_{\text{cal-gr}}$ values range from 3.12‰ to 6.11‰. Error bars are the estimated uncertainty of the standards (0.17‰ for graphite and 0.12‰ for calcite).

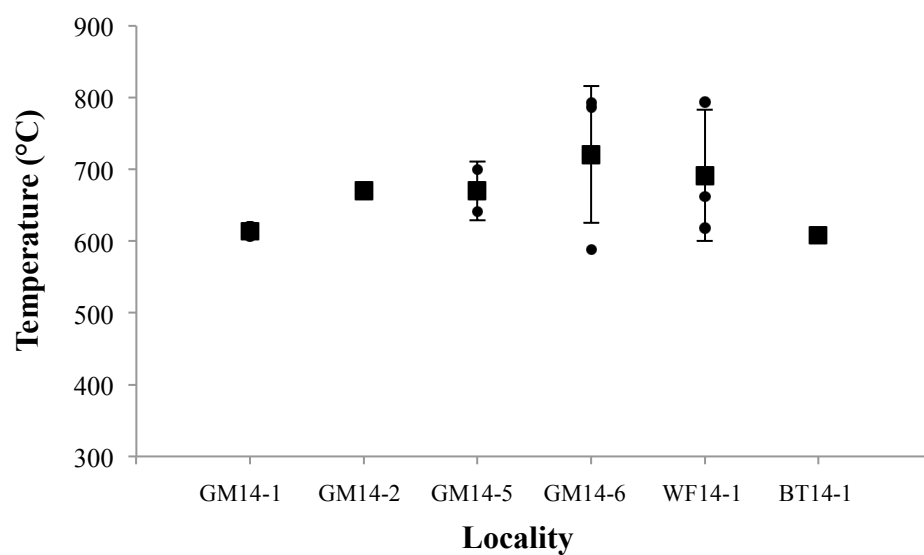


Figure 47. Temperature variation of the protomylonites from the sample locations. The black dots are the temperatures calculated from each protomylonite sample. The black squares indicate the mean temperature of the protomylonites at that locality. The error bars represent the standard deviation.

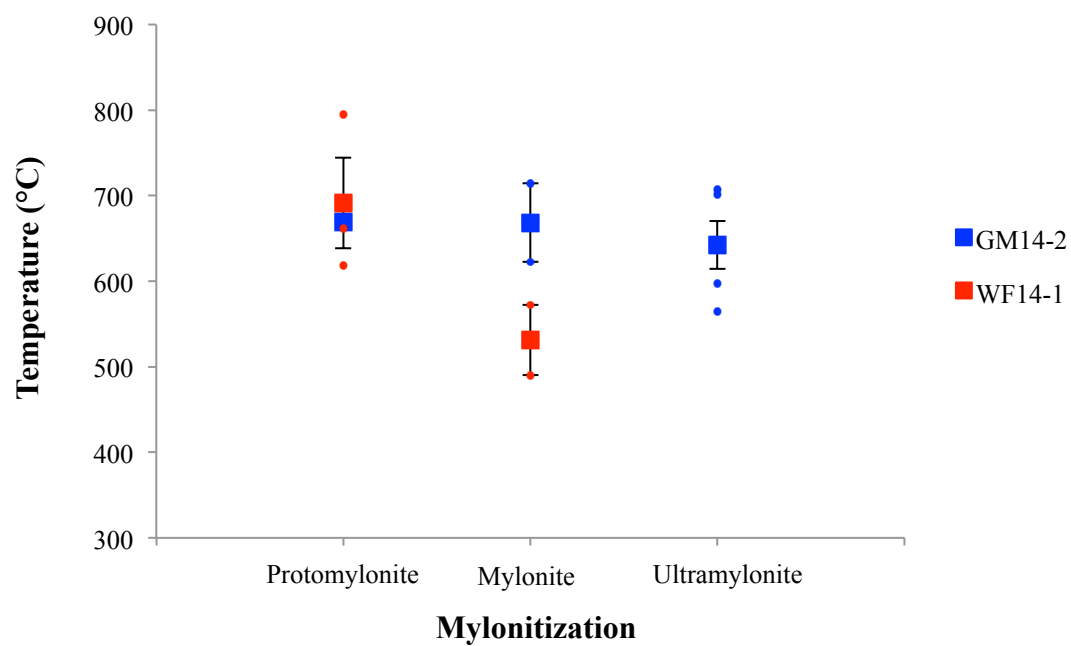


Figure 48. Temperature verses mylonitization at GM14-2 and WF14-1. The dots represent the temperature data. The squares represent the mean temperature. The error bars represent standard error. The temperatures of the samples do not have a significant difference due to their locality ($p = 0.598$).

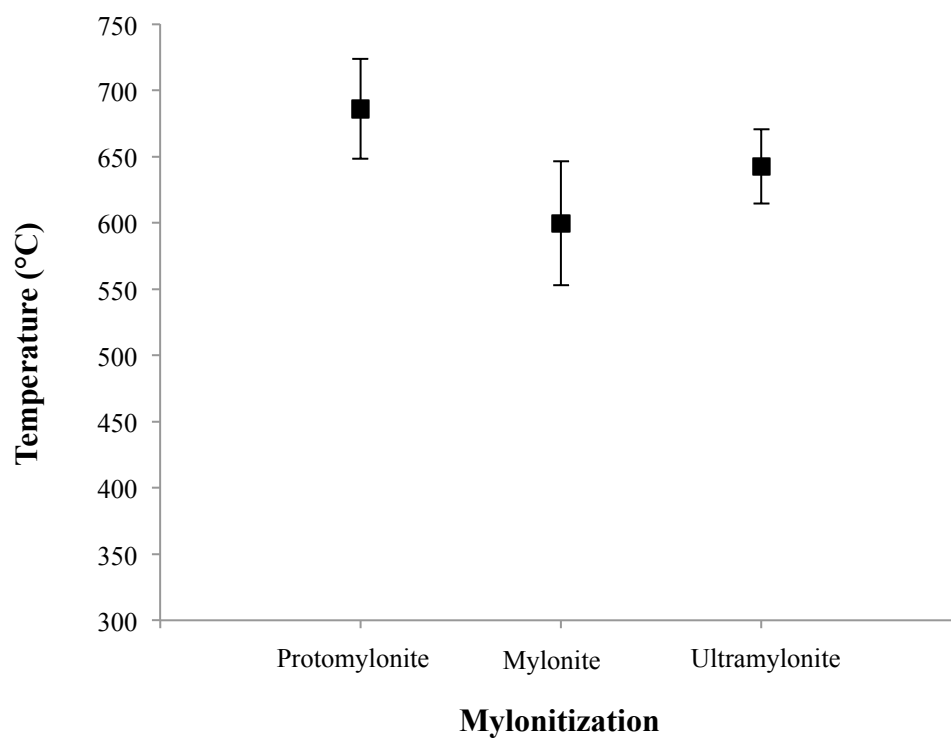


Figure 49. Average temperature versus mylonitization. The squares represent the mean temperature. The error bars represent standard error. There is not a significant difference in temperature due to the extent of mylonitization ($p = 0.326$).

TABLE APPENDIX

Table 1. GPS coordinates of sample localities

Sample Locality	Date	N lat deg	lat min	lat sec	W long deg	long min	long sec	Field Notes
GM14-1	8/21/14	44	54	4.04	78	22	53.19	rte 507 0.3 miles south of gooderham- big marble outcrop/roadcut
GM14-2	8/21/14	44	52	53.32	78	23	37.15	rte 507 2.2 miles south of gooderham (classic bancroft locality)
GM14-3	8/21/14	44	52	29.66	78	23	34.2	rte 507 2.7 miles south of gooderham (classic bancroft locality)
GM14-4	8/21/14	44	52	37.66	78	23	37.17	just north around the corner from GM14-3
BT14-1	8/22/14	45	4	4.26	77	43	50.84	rte 28 about 10 miles east of Bancroft (classic York River locality)
WF14-1	8/23/14	45	0	18.51	78	13	8.9	rte 648 1.6 miles north of T w/rte 118
GM14-5	8/23/14	44	57	34.12	78	17	12.08	rte 503 1.20 miles W of Tory Hill
GM14-6	8/23/14	44	58	26.15	78	16	10.35	0.3 m E of Tory Hill on rte 118

Table 2. Sample petrography

Sample ID	Cal	Dol	Tr	Di	Pl	Chl	Kfs	Pl	Ttn	Chn	Srp	Ilm	Ap	Qtz	Rt	Opaques	SEM	$\Delta^{13}\text{C}$
GM14-1-1	10	65	5	5	2						3		>1			10% Gr, 9% Fe sulfides	Yes	n.a.
GM14-1-2	40	35			2						20					No Gr, 3% Fe sulfides	No	n.a.
GM14-1-4	80			5			10									5%	No	4.46
GM14-1-5A	80			8			7	>1								5%	No	n.a.
GM14-1-5B	75		5	5			10	>1								5%	No	4.60
GM14-2-1A	80			5			10	>1								5%	No	3.71
GM14-2-1B	60		8	5			6	6			5					1%	No	n.a.
GM14-2-2	65			5	3		10		2							15%	No	4.70
GM14-2-3A	75		5				10	3	2							5%	No	n.a.
GM14-2-3B	70			5	5		10	>1								10%	No	5.07
GM14-2-4	75		5	5			5									7% Gr, 3% Fe sulfides	No	4.24
GM14-2-5	75			5	5		5									7% Gr, 3% Fe sulfides	No	n.a.
GM14-2-6	60		5	10	5		10	>1								6% Gr, 4% Fe sulfides	No	4.44
GM14-2-7	65		5	10	>5		10		1							5%	No	3.65
GM14-2-8	65		5	5			10									1% Gr, 5% Fe sulfides	No	3.75
GM14-2-9	70			10	15			>1								3% Gr, 2% Fe sulfides	No	4.00
GM14-5-1	70	8	5		10				2							2% Gr, 3% Fe sulfides	Yes	4.26
GM14-5-2	60	10		6	12		2									No Gr, 10% Fe sulfides	No	n.a.
GM14-5-4	80		2		10		3									5%	No	3.77
GM14-6-1A	60		6	6	10		5		3							10%	No	3.13
GM14-6-1B	60		6	6	10		5		3							10%	No	4.80
GM14-6-2	65	10	10		5	>1								>1	>1	7%	Yes	3.64
GM14-6-3		80			7		8									5%	No	3.17
WF14-1-1A	50	30		5	10											5%	No	3.12
WF14-1-3A	55			10	15		10									10%	No	6.11
WF14-1-3B	60			10	20											10%	No	4.48
WF14-1-4A	70			10	5		10									5%	No	n.a.
WF14-1-4B	70			10	5		10		2							3%	No	n.a.
WF14-1-5A	60		10	5	15											10%	No	n.a.
WF14-1-5B	60		5	5	15											15% Gr and Fe sulfides	Yes	4.98
WF14-1-6	75			5	15			>1								5%	No	4.08
BT14-1-1A	50	5	5	3	5		5	5			7					15%	No	n.a.
BT14-1-1B	20	40		5	10			>1			15					10%	No	n.a.
BT14-1-2	70			20	5											5%	No	4.59
BT14-1-3	60	1		5	8	7				3	12	1				3% Gr and Fe sulfides	Yes	n.a.

Table 3. Range of calcite grain sizes

Sample ID	Cal Grain Size (μm)	Category
GM14-1-4	100 - 1200	Protomylonite
GM14-1-5B	150-1200	Protomylonite
GM14-2-1A	10 - 70	Ultramylonite
GM14-2-2	5 - 40	Ultramylonite
GM14-2-3B	5 - 60	Ultramylonite
GM14-2-4	10 - 50	Ultramylonite
GM14-2-6	20 - 1160	Mylonite
GM14-2-7	20 -2800	Mylonite
GM14-2-8	10 - 60	Ultramylonite
GM14-2-9	560 - 5000	Protomylonite
GM14-5-1	300 - 3000	Protomylonite
GM14-5-4	260 - 6400	Protomylonite
GM14-6-1A	30 - 2600	Protomylonite
GM14-6-1B	100 - 1200	Protomylonite
GM14-6-2	60 - 4800	Protomylonite
GM14-6-3	400 - 4000	Protomylonite
WF14-1-1A	10 - 2400	Protomylonite
WF14-1-3A	10 - 300	Mylonite
WF14-1-3B	100 - 1800	Protomylonite
WF14-1-5B	10 - 130	Mylonite
WF14-1-6	160 -2400	Protomylonite
BT14-1-2	200 - 2200	Protomylonite

Table 4. Isotope data and temperature estimates

Sample	Sample ID	$\delta^{13}\text{C}$ graphite	$\delta^{13}\text{C}$ calcite	$\delta^{18}\text{O}$ -SMOW calcite	Mean $\delta^{13}\text{C}$ graphite	$\Delta^{13}\text{C}$ (cal-gr)	T(°C) K&V	Texture
GM14-1-4	G2-7-11	-2.61	1.82	27.48	-2.63	4.46	621	Protomylonite
GM14-1-4	G2-7-12	-2.65						
GM14-1-5B	G2-10-7	-3.14	1.53	27.57	-3.07	4.60	606	Protomylonite
GM14-1-5B	G2-10-8	-3.00						
GM14-2-1A	G2-3-3	-3.09	0.51	25.04	-3.19	3.71	707	Ultramylonite
GM14-2-1A	G2-3-4	-3.30						
GM14-2-2	G2-7-9	-4.24	0.47	25.70	-4.24	4.70	597	Ultramylonite
GM14-2-3B	G2-8-8	-4.48	0.59	24.29	-4.48	5.07	565	Ultramylonite
GM14-2-4	G2-7-5	-3.65	0.61	24.92	-3.64	4.24	643	Ultramylonite
GM14-2-4	G2-7-6	-3.62						
GM14-2-6	G2-4-9	-3.03	1.37	25.03	-3.07	4.44	623	Mylonite
GM14-2-6	G2-4-10	-3.10						
GM14-2-7	G2-4-11	-3.12	0.48	24.24	-3.17	3.65	714	Mylonite
GM14-2-7	G2-4-12	-3.23						
GM14-2-8	G2-7-1	-3.45	0.17	25.61	-3.58	3.75	701	Ultramylonite
GM14-2-8	G2-7-1	-3.72						
GM14-2-9	G2-3-5	-3.17	0.82	21.34	-3.19	4.00	670	Protomylonite
GM14-2-9	G2-3-6	-3.21						
GM14-5-1	G2-4-7	-1.17	3.10	27.38	-1.16	4.26	641	Protomylonite
GM14-5-1	G2-4-8	-1.14						
GM14-5-4	G2-3-9	-1.58	2.19	26.53	-1.58	3.77	699	Protomylonite
GM14-6-1A	G2-9-7	-0.19	2.89	24.68	-0.24	3.13	793	Protomylonite
GM14-6-1A	G2-9-8	-0.30						
GM14-6-1B	G2-9-9	-1.31	3.12	26.47	-1.69	4.80	588	Protomylonite
GM14-6-1B	G2-9-10	-2.07						
GM14-6-2	G2-3-11	-1.22	2.49	27.21	-1.15	3.72	716	Protomylonite
GM14-6-2	G2-3-12	-1.08						
GM14-6-3	G2-4-3	-1.34	1.84	27.29	-1.33	3.17	787	Protomylonite
GM14-6-3	G2-4-4	-1.33						
WF14-1-1A	G2-8-1	-1.15	2.02	22.06	-1.10	3.12	794	Protomylonite
WF14-1-1A	G2-8-2	-1.05						
WF14-1-3A	G2-9-5	-3.06	3.05	25.19	-3.06	6.11	490	Mylonite
WF14-1-3B	G2-9-3	-0.67	4.07	25.15	-0.40	4.48	619	Protomylonite
WF14-1-3B	G2-9-4	-0.14						
WF14-1-5B	G2-9-11	-2.32	2.42	21.38	-2.56	4.98	572	Mylonite
WF14-1-5B	G2-9-12	-2.80						
WF14-1-6	G2-8-3	-2.44	1.61	19.30	-2.47	4.08	662	Protomylonite
WF14-1-6	G2-8-4	-2.50						
BT14-1-2	G2-10-5	-1.86	2.74	25.20	-1.85	4.59	608	Protomylonite
BT14-1-2	G2-10-6	-1.84						

Table 5. $\delta^{13}\text{C}$ values of the calcite standard

MHC Calcite Standards	$\delta^{13}\text{C}$
1	3.19
2	3.18
3	3.19
4	2.76
5	3.13
6	3.22
7	3.30
Average	3.14
Standard Deviation	0.17
Longterm Accepted Value	3.21

Table 6. $\delta^{13}\text{C}$ values for the MHC graphite standards

MHC Graphite Standard ID	$\delta^{13}\text{C}$
G2-3-1	-6.53
G2-3-2	-6.43
G2-4-5	-6.85
G2-4-6	-6.61
G2-7-3	-6.58
G2-7-4	-6.52
G2-7-7	-6.37
G2-7-8	-6.62
G2-8-5	-6.72
G2-8-6	-6.62
G2-9-1	-6.68
G2-9-2	-6.58
G2-10-1	-6.63
G2-10-2	-6.62
Average	-6.60
Standard Deviation	0.12
Longterm Accepted Value	-6.60

Table 7. Uncertainty in temperature for $\pm 0.29\text{‰}$ uncertainty in $\Delta^{13}\text{C}_{\text{cal-gr}}$

T (°C)	Uncertainty (°C)
500	20
600	28
700	40
800	54

Table 8. One-way ANOVA table for temperature versus locality (for localities GM14-2 and WF14-1)

Tests of Between-Subjects Effects

Dependent Variable: Temp

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1932.406 ^a	1	1932.406	.295	.598
Intercept	5038686.015	1	5038686.015	768.859	.000
Locality	1932.406	1	1932.406	.295	.598
Error	72088.044	11	6553.459		
Total	5444345.395	13			
Corrected Total	74020.450	12			

a. R Squared = .026 (Adjusted R Squared = -.062)

Table 9. One-way ANOVA table for temperature versus mylonitization**Tests of Between-Subjects Effects**

Dependent Variable: Temp

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	14861.196 ^a	2	7430.598	1.256	.326
Intercept	5311700.357	1	5311700.357	897.865	.000
Texture	14861.196	2	7430.598	1.256	.326
Error	59159.255	10	5915.925		
Total	5444345.395	13			
Corrected Total	74020.450	12			

a. R Squared = .201 (Adjusted R Squared = .041)

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