KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FIFTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2012
Amherst College, Amherst, MA

Dr. Robert J. Varga, Editor
Director, Keck Geology Consortium
Pomona College

Dr. Tekla Harms
Symposium Convenor
Amherst College

Carol Morgan
Keck Geology Consortium Administrative Assistant

Diane Kadyk
Symposium Proceedings Layout & Design
Department of Earth & Environment
Franklin & Marshall College

Keck Geology Consortium
Geology Department, Pomona College
185 E. 6th St., Claremont, CA 91711
(909) 607-0651, keckgeology@pomona.edu, keckgeology.org

ISSN# 1528-7491

The Consortium Colleges The National Science Foundation ExxonMobil Corporation

KECK GEOLOGY CONSORTIUM
PROCEEDINGS OF THE TWENTY-FIFTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

ISSN# 1528-7491

April 2012

Robert J. Varga
Editor and Keck Director
Pomona College

Keck Geology Consortium
Pomona College
185 E 6th St., Claremont, CA 91711

Diane Kadyk
Proceedings Layout & Design
Franklin & Marshall College

Keck Geology Consortium Member Institutions:
Amherst College, Beloit College, Carleton College, Colgate University, The College of Wooster, The Colorado College, Franklin & Marshall College, Macalester College, Mt Holyoke College, Oberlin College, Pomona College, Smith College, Trinity University, Union College, Washington & Lee University, Wesleyan University, Whitman College, Williams College

2011-2012 PROJECTS

TECTONIC EVOLUTION OF THE CHUGACH-PRINCE WILLIAM TERRANE, SOUTH-CENTRAL ALASKA
Faculty: *JOHN GARVER*, Union College, *Cameron Davidson*, Carleton College
Students: *EMILY JOHNSON*, Whitman College, *BENJAMIN CARLSON*, Union College, *LUCY MINER*, Macalester College, *STEVEN ESPINOSA*, University of Texas-El Paso, *HANNAH HILBERT-WOLF*, Carleton College, *SARAH OLIVAS*, University of Texas-El Paso.

ORIGINS OF SINUOUS AND BRAIDED CHANNELS ON ASCRAEUS MONS, MARS
Faculty: *ANDREW DE WET*, Franklin & Marshall College, *JAKE BLEACHER*, NASA-GSFC, *BRENT GARRY*, Smithsonian
Students: *JULIA SIGNORELLA*, Franklin & Marshall College, *ANDREW COLLINS*, The College of Wooster, *ZACHARY SCHIERL*, Whitman College.

TROPICAL HOLOCENE CLIMATIC INSIGHTS FROM RECORDS OF VARIABILITY IN ANDEAN PALEOGLACIERS
Faculty: *DONALD RODBELL*, Union College, *NATHAN STANSELL*, Byrd Polar Research Center
Students: *CHRISTOPHER SEDLAK*, Ohio State University, *SASHA ROTHENBERG*, Union College, *EMMA CORONADO*, St. Lawrence University, *JESSICA TREANTON*, Colorado College.

EOCENE TECTONIC EVOLUTION OF THE TETON-ABSAROKA RANGES, WYOMING
Faculty: *JOHN CRADDOCK*. Macalester College, *DAVE MALONE*. Illinois State University
Students: *ANDREW KELLY*, Amherst College, *KATHRYN SCHROEDER*, Illinois State University, *MAREN MATHISEN*, Augustana College, *ALISON MACNAMEE*, Colgate University, *STUART KENDERES*, Western Kentucky University, *BEN KRASUSHAAR*

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
Faculty: *DAVID DETHIER*, Williams College
Students: JAMES WINKLER, University of Connecticut, SARAH *BEGANSKAS*, Amherst College, *ALEXANDRA HORNE*, Mt. Holyoke College

DEPTH-RELATED PATTERNS OF BIOEROSION: ST. JOHN, U.S. VIRGIN ISLANDS
Faculty: *DENNY HUBBARD* and *KARLA PARSONS-HUBBARD*, Oberlin College
Students: *ELIZABETH WHITCHER*, Oberlin College, *JOHNATHAN ROGERS*, University of Wisconsin-Oshkosh, *WILLIAM BENSON*, Washington & Lee University, *CONOR NEAL*, Franklin & Marshall College, *CORNELIA CLARK*, Pomona College, *CLAIRE McELROY*, Otterbein College.

THE HRAFNFJORDUR CENTRAL VOLCANO, NORTHWESTERN ICELAND
Faculty: *BRENNAN JORDAN*, University of South Dakota, *MEAGEN POLLOCK*, The College of Wooster
Students: *KATHRYN KUMAMOTO*, Williams College, *EMILY CARBONE*, Smith College, *ERICA WINELAND-THOMSON*, Colorado College, *THAD STODDARD*, University of South Dakota, *NINA WHITNEY*, Carleton College, *KATHARINE, SCHLEICH*, The College of Wooster.

SEDIMENT DYNAMICS OF THE LOWER CONNECTICUT RIVER
Faculty: *SUZANNE O'CONNELL* and *PETER PATTON*, Wesleyan University
Students: *MICHAEL CUTTLER*, Boston College, *ELIZABETH GEORGE*, Washington & Lee University, *JONATHON SCHNEYER*, University of Massachusetts-Amherst, *TIRZAH ABBOTT*, Beloit College, *DANIELLE MARTIN*, Wesleyan University, *HANNAH BLATCHFORD*, Beloit College.

ANATOMY OF A MID-CRUSTAL SUTURE: PETROLOGY OF THE CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE, GRENVILLE PROVINCE, ONTARIO
Faculty: *WILLIAM PECK,* Colgate University, *STEVE DUNN,* Mount Holyoke College, *MICHELLE MARKLEY*, Mount Holyoke College
Students: *KENJO AGUSTSSON*, California Polytechnic State University, *BO MONTANYE*, Colgate University, *NAOMI BARSHI*, Smith College, *CALLIE SENDEK*, Pomona College, *CALVIN MAKO*, University of Maine, Orono, *ABIGAIL MONREAL*, University of Texas-El Paso, *EDWARD MARSHALL*, Earlham College, *NEVA FOWLER-GERACE*, Oberlin College, *JACQUELYNE NESBIT*, Princeton University.

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1005122
ExxonMobil Corporation

Keck Geology Consortium: Projects 2011-2012
Short Contributions— Grenville Province, Ontario Project

PETROLOGY AND STRUCTURE OF THE CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE ITS HANGING WALL, GRENVILLE PROVINCE, ONTARIO
Project Faculty: WILIAM H. PECK, Colgate University, STEVEN R. DUNN, Mount Holyoke College
MICHELLE J. MARKLEY, Mount Holyoke College

GEOCHEMISTRY AND GEOCHRONOLOGY OF CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE THRUST SHEETS IN SOUTHERN ONTARIO, GRENVILLE PROVINCE
KENJO S. AGUSTSSON, California Polytechnic State University, San Luis Obispo
Research Advisor: Scott Johnston

CONFLICTING KINEMATICS OF THE SALERNO CREEK DEFORMATION ZONE, GRENVILLE PROVINCE, ONTARIO
NAOMI BARSHI, Smith College
Research Advisor: Jack Loveless

THERMOBAROMETRIC EVIDENCE FOR A COMMON CENTRAL METASEDIMENTARY BELT AFFINITY OF THE BANCROFT AND ELZEVIR TERRANES, ONTARIO, CANADA
NEVA FOWLER-GERACE, Oberlin College
Research Advisor: F. Zeb Page

HETEROGENEOUS DEFORMATION OF GABBROIC ROCKS
CALVIN MAKO, University of Maine
Research Advisor: Christopher Gerbi

PETROLOGY AND GEOCHEMISTRY OF THE ALLSAW ANORTHOSITE: A SCAPOLITIZED META-ANORTHOSITE IN GRENVILLE PROVINCE, ONTARIO
EDWARD W. MARSHALL, Earlham College
Research Advisor: Meg Streepey Smith

GARNET-BIOTITE GEOTHERMOBAROMETRY OF THE CENTRAL METASEDIMENTARY BELT BOUDARY THRUST ZONE OFTHE GRENVILLE PROVINCE, ONTARIO, CANADA
ABIGAIL MONREAL, University of Texas at El Paso
Research Advisor: Jasper G. Konter

CARBON ISOTOPE THERMOMETRY IN THE CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE
GRENVILLE PROVINCE, ONTARIO
BO MONTANYE, Colgate University
Research Advisor: William H. Peck

CALCITE-GRAPHITE THERMOMETRY IN THE SOUTHWESTERNMOST CENTRAL METASEDIMENTARY BELT, GRENVILLE PROVINCE, SOUTHERN ONTARIO
JACQUELYNE NESBIT, Princeton University
Research Advisor: Blair Schoene

USING STRUCTURAL ANALYSES TO ASSESS POSSIBLE FORMATION MECHANISMS OF THE CHEDDAR GNEISS DOME

CALIE SENDEK**,** Scripps College
Research Advisor: Linda Reinen

Keck Geology Consortium
Pomona College
185 E. 6th St., Claremont, CA 91711
Keckgeology.org

HETEROGENEOUS DEFORMATION OF GABBROIC ROCKS

CALVIN MAKO, University of Maine
Research Advisor: Christopher Gerbi

INTRODUCTION

Differential stresses are abundant within the crust and lithosphere and result from the tectonic forces that are pervasive within these regions. In the crust, deformation arising from these stresses is usually ductile in the middle to lower crust and brittle in the upper crust. In many cases this deformation is localized to discrete shear zones rather than being distributed throughout the crust. Localization results from existing and evolving strength heterogeneities which allow strain to be more easily accommodated in certain areas. Since strain localization in the form of faults and shear zones is abundant throughout the crust, it is important to understand how these zones initiate and evolve.

The purpose of this study is to examine an occurrence of shear zone localization and document the differences between strained and unstrained material there. From these data I will suggest mechanisms by which theses rocks have become weaker and strain has been localized. The rocks of interest are from an outcrop of the Salerno Creek deformation zone, a newly described mylonite zone in the upper part of the Central Metasedimentary Belt boundary thrust zone (CMBbtz), in the Grenville province of Southern Ontario (Easton and Kamo 2011). This region is an ancient exhumed orogen where mid-crustal, upper amphibolite facies rocks are exposed at the surface. The outcrop that is the focus of my research is a finger of an unnamed elongate gabbro body which occurs between the Trooper Lake Gabbro and the Anstruther gneiss complex (Easton and Kamo 2011). It is part of a string of gabbroic bodies that may define the base of the Central Metasedimentary Belt (Hanmer and McEachern 1992). Using electron backscatter diffraction (EBSD), wavelength dispersive spectroscopy (WDS) and optical microscopy, I have documented characteristics of low to high strain rocks that give clues to the mechanisms of strain localization.

GEOLOGIC SETTING AND METHODS

I have analyzed samples from a ~25m long outcrop of anorthositic gabbro, which is exposed as a road cut on route 507 near Gooderham, Ontario. The outcrop has many anastomosing meter-scale shear zones adjacent to rocks that show no visible strain (Fig. 1A). Though other outcrops of the Salerno Creek deformation zone are mylonitic this outcrop does not exhibit any mylonites. These rocks have a primarily plagioclase and hornblende mineralogy, with minor biotite (0-5%) and accessory pyrite, tourmaline, calcite and titanite.

I collected samples from various parts of the outcrop that exhibited high, moderate and low strain. Thin sections were cut parallel to lineation and perpendicular to foliation and prepared for optical microscopy (unpolished) as well as electron microscopy (polished). Using EBSD, I analyzed two to three small areas on each of six polished thin sections to characterize grain size, crystallographic preferred orientation (CPO) and shape preferred orientation (SPO). WDS measurements were taken on various hornblende and plagioclase grains throughout each polished section with attention to differences in texture and structure. A summary of the characteristics for each strain level is presented in Table 1.

RESULTS

Textures

On the hand sample scale, low strain samples exhibit igneous textures with no foliation or lineation. High strain samples show smaller grain sizes and strong gneissic foliation defined by compositional banding of alternating hornblende-rich and plagioclase-rich layers (Fig. 1A). At the optical microscope scale, the major difference between high and low strain rocks is the proportion of recrystallized and grain size reduced plagioclase and hornblende in the sample. The low

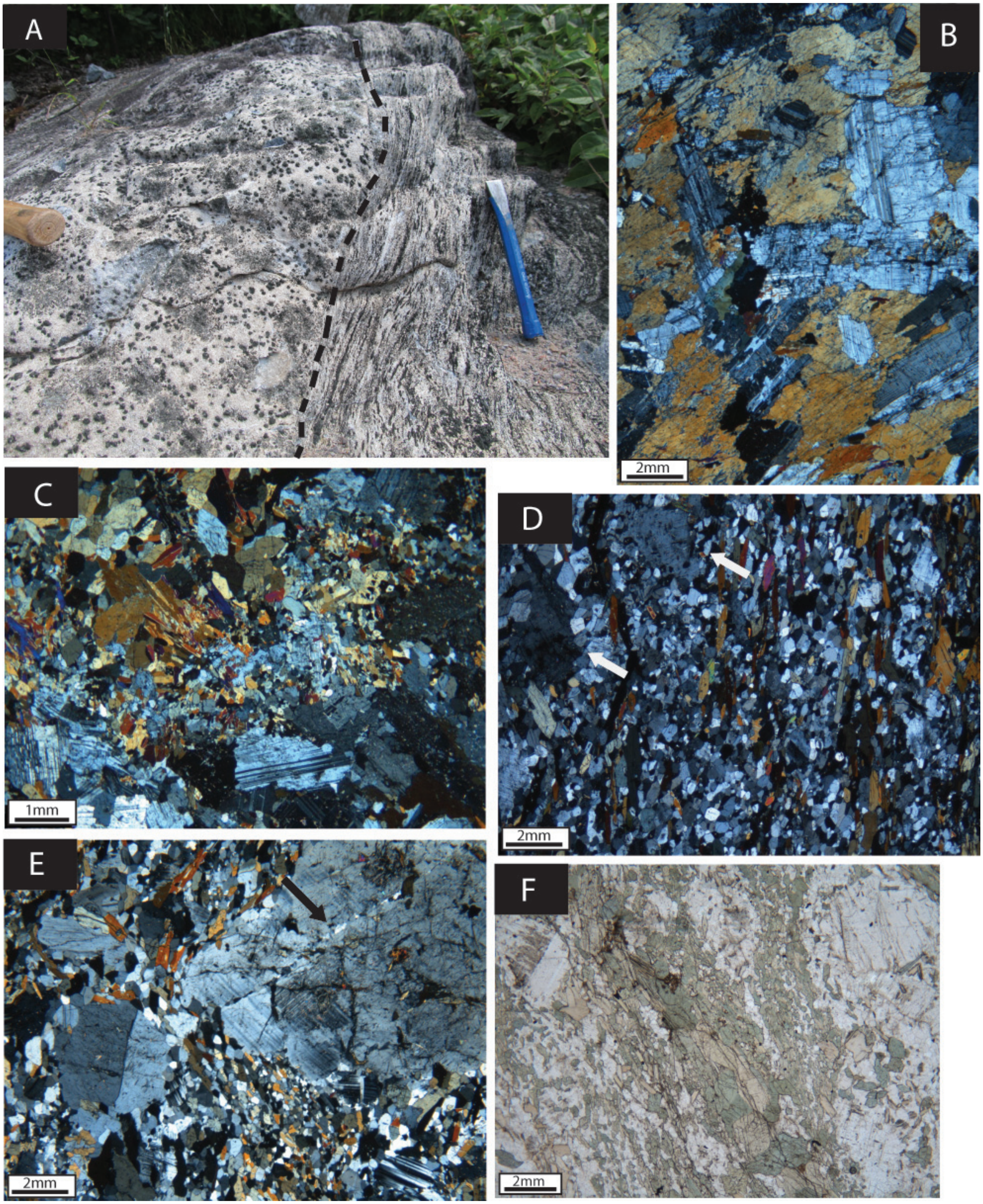

Figure 1. Textures of the analyzed rocks at outcrop and thin section scale. (A) An example of outcrop strain heterogeneity, with a dotted line dividing strained rock on right from rock showing no visible strain on the left. (B) Igneous texture from sample 025cy (low strain). (C) A small patch of fine grained recrystallized material in a high strain sample (025by). (D) Typical appearance of high strain samples with fine grained matrix and uncommon large plagioclase grains (white arrows). Crossed polarized light. (E) Typical appearance of moderately strained samples with more common large plagioclase grains and an example of plagioclase recrystallization following intergranular fractures (black arrow). (F) Apparent dismemberment of larger hornblende grains (plane polarized light) in moderately strained rocks.

strain rocks have mostly large grains with abundant deformation and albite twinning and little recrystallization or grains size reduction (Fig. 1B). Low strain samples exhibit minimal plagioclase recrystallization in small, disconnected patches (Fig. 1C).

The high strain samples contain plagioclase that is fine grained and almost completely recrystallized throughout the thin section (Fig. 1D). Large plagioclase grains are rare but present in the high strain rocks. In some locations the plagioclase has a core and mantle texture with small grains within and around the large grains, often in distinct lines that may mark intergranular fractures (Fig. 1E). The moderately strained samples are a combination of the two end-member strain types, having large grains as well as recrystallized plagioclase and dismembered hornblende (Fig. 1E).

In the recrystallized zones, hornblende generally has the appearance of being crushed and smeared out (Fig. 1F). Even in the low strain samples some hornblende grains appear broken but with little displacement. In high strain samples hornblende is finer grained and disseminated throughout the matrix. Hornblende grains are interconnected in some high and moderate strain samples, but in other high strain samples they are not. There does not seem to be any correlation between hornblende interconnectedness and strain.

At all strain levels, smaller recrystallized plagioclase grains are generally free of twins and have very clean grain interiors, which is in sharp contrast to the large grains. In the case of the fine grained plagioclase and the hornblende, grains often meet at triple junctions with 120˚ between boundaries. This is not always true and especially not when there are many fine grained plagioclase and hornblende crystals close together. In this latter case, crystals that are finer grained do not as commonly have 120˚ triple junctions.

Grain Size

Grain size varies greatly between these samples. In the low strain samples both plagioclase and hornblende have large grain size, the majority of the grains being >500μm in diameter. In the moderate and high strain samples the grain sizes of plagioclase and hornblende is reduced, with mean diameter around 100-200μm for both. The difference between these domains is that the moderate strain samples retain a large proportion of the original, larger grains, whereas the high strain rocks consist almost entirely of the small, recrystallized grains. In the high strain samples there are significantly fewer large plagioclase grains and the grain size of hornblende becomes somewhat larger but more irregular between samples.

Crystallographic Orientation

Plagioclase shows little to no CPO at all strain levels. In low strain rocks the number of plagioclase and hornblende grains analyzed is insufficient to have statistically significant results. In high strain samples c-axes of plagioclase are very weakly aligned parallel to foliation and b-axes are very weakly aligned in a plane perpendicular to foliation. Conversely, hornblende exhibits a strong CPO in high and moderate strain samples. C-axes are linearly aligned parallel to foliation in the high strain samples and in moderate strain samples c-axes are generally aligned in the plane of foliation. Hornblende a-axes are preferentially aligned perpendicular to foliation in high and moderate strain samples (more weakly in moderate strain) and b-axes have no common alignment.

Shape Preferred Orientation

SPO exists in the high, moderate and low strain samples for both hornblende and plagioclase. For hornblende in high strain samples the mode in major axis orientation is between 10° and 30° oblique to foliation. Moderate and low strain samples are similar to each other in that both distributions have the same general shape for hornblende and two apparent orientation modes, both symmetrically 30° to 50° oblique to foliation. Plagioclase SPO is generally the same across strain levels and major axes range from 30° to 50° symmetrically about foliation. In all of these, there are very few grains oriented parallel to foliation.

Mineral Chemistry

Plagioclase and hornblende have variable chemistry

		High Strain	Moderate Strain	Low Strain
Grain Size	Feldspar	Peak at 100-200µm	Peaks at 100-200µm and >500µm	>500µm
	Hbde	scattered distribution, most >200µm	ill-defined peak at 100-200µm	>500µm and minor peak at 100-200µm
CPO	Feldspar	Very weak c-axis alignment in plane of foliation	No preferred orientation	no preferred orientation
	Hbde	Strong c-axis lineation, b-axis perp. to foliation	Strong c-axis alignment in foliation plane, b-axis perp. to foliation	no preferred orientation
SPO	Feldspar	Two peaks 30-40˚ oblique to foliation, one stronger	Two peaks 30-40˚ oblique to foliation	Two peaks 30-40˚ oblique to foliation
	Hbde	Single peak 20-30˚ oblique to foliation	Two peaks 20-30˚ oblique to foliation	Two well defined peaks 20-30˚ oblique to foliation
Mineral Mode	Feldspar	80-85%	65-75%	60-75%
	Hbde	15-20%	25-35%	25-40%
	Biotite	~5% to absent	<5% to absent	Not present
Chemistry	Feldspar	An_{63} to An_{85}, widely spread bimodal distribution	An_{75} to An_{89}, bimodal distribution	An_{78} to An_{93}, unimodal distribution
	Hbde	Moderate silica and alkali content, wide distribution	High alkalis and low silica, concentrated distribution	Lowest silica and alkali, concentrated distribution
Texture	Feldspar	Almost entirely recrystallized, rare large grains	Large grains and recrystallized matrix	Almost completely large grains, small recrystallized patches
	Hbde	Defines gneissic banding	Dismembered and smeared out grains	Large, un-dismembered grains

Table 1. Summary of analyzed characteristics organized by strain state.

between the different degrees of strain. Plagioclase varies from An_{63} to An_{93}, and shows a trend towards more alkali composition with increasing strain. High strain samples have a broader range of An content than do low strain samples. Hornblende does not seem to exhibit a chemical trend or evolution relating to strain; the high strain samples have intermediate alkali and silica contents between moderate and high strain samples. The ranges in hornblende chemistry for the different strain levels have very little overlap. This is not true of plagioclase which shows significant overlap in composition between high, moderate and low strain samples.

Mineral Modes

The proportion of hornblende varies from ~17% to ~35% between the samples and that of plagioclase varies from 60% to 85%. The proportion of hornblende in the high strain rocks is generally lower, but this may not be representative of all high strain rocks (some unanalyzed high strain sections have a majority of hornblende). Biotite is present in the high and moderate strain samples it constitutes <5% in all cases and is absent in some high strain samples. Biotite doesn't appear to be significant in terms of rock strength.

MINERAL DEFORMATION MECHANISMS

We can make several inferences about microstructural processes from the above observations. First, it seems that these rocks have had time at depth to undergo static recrystallization and recovery. This is evident from the 120° triple junctions observed in small plagioclase grains and in many hornblende grains. Also we can infer from the general appearance of hornblende that it has deformed by brittle fracturing and grain boundary sliding. This is supported by previous research that shows that hornblende often deforms brittlely below temperatures of 650˚C (Berger and Stunitz 1996). The temperatures of metamorphism in this region are estimated at approximately 625°C (Fowler-Gerace, this volume).

Plagioclase has mostly deformed by dislocation creep which often seems to initiate along intergranular fractures in large plagioclase grains (Fig. 1E). Dislocation creep may have occurred through subgrain rotation and recrystallization. However, despite microstructural evidence, plagioclase does not exhibit the CPO associated with dislocation creep. It is possible that as grain size has been reduced, these rocks have experienced a switch from grain-size-insensitive dislocation creep, to grain-size-sensitive diffusion creep.

WEAKENING MECHANISMS

Various rock weakening mechanisms that can lead to shear localization have been proposed over the years (White et al. 1980, Kirby 1985), including texture related weakening, reaction softening, fluid related weakening, melt formation and thermal perturbation. Given the microstructural analysis that I have performed, melt formation can be ruled out from the lack of evidence in thin section and improper conditions for formation. Also, given the small size of these shear zones it is unlikely that there was enough of a temperature gradient across this space to cause localization, thus thermal perturbations are unlikely. Reaction related weakening, in the form of metasomatism or metamorphic phase changes, is not likely to have had an effect because the bulk mineralogy is fairly consistent across the strain gradient.

The changes that most probably led to weakening in these rocks are related to texture. It is possible, as noted above, that a switch from dislocation-dominated creep to diffusion-dominated creep may have occurred. At small grain sizes, diffusion creep can be faster than dislocation creep, meaning that if diffusive processes dominate the rocks would be weaker, allowing strain to localize. However, this conclusion is inconsistent with the work of De Bresser et al. (2001) who suggest that grain size reduction cannot cause a switch to diffusive processes because recovery will prevent it.

One fundamental question affecting this research is: which is weaker- hornblende or plagioclase? If hornblende is acting as the weak phase in these rocks whether or not the grains are linked up or isolated will affect the weakness of the rock. But hornblende interconnectedness seems unrelated to strain, implying that hornblende is not the weaker phase. Conversely, if grain size reduced areas of plagioclase are truly weaker, then whether or not these areas are interconnected could play a role in rock weakening. In fact, in high and moderate strain samples, zones of plagioclase are more interconnected and pervasive. These observations suggest that plagioclase is acting as the weaker phase and hornblende as the stronger one. If this is the case, hornblende could have experienced rigid body rotation to form the CPO that we observe in high strain samples.

In the Central Metasedimentary Belt and CMBbtz, fluids have likely been available (Grittins, 1961 and Marshall, this volume) so it is possible that hydrolytic weakening has played a role in strain localization. The presence of biotite in high and moderate strain samples is somewhat suggestive of the presence of water in these rocks because it is a hydrous phase. Since it appears that fracturing has played a role in recrystallization of plagioclase and hornblende, fractures may also have provided a route of entrance for fluids to interact with these rocks and weaken them.

CONCLUSION

This anorthositic gabbro body at the base of the Central Metasedimentary Belt has undergone meter-scale strain localization. Low strain rocks have a relict igneous texture; more highly strained samples exhibit grain size reduction of both hornblende and plagioclase. Plagioclase appears to have been the weaker phase during deformation. For plagioclase grains, dislocation creep may have initiated at grain fractures and ultimately yielded to diffusion creep. Hornblende has deformed by brittle fracture and appears to have been the stronger phase. A switch from grain-size-insensitive creep to grain-size-sensitive creep in combination with increased interconnection of the weak phase (plagioclase) may have caused these rocks to weaken locally. The introduction of fluids, possibly through fracturing, could also have resulted in rock weakening and shear zone development.

REFERENCES

Berger, A. and Stunitz, H., 1996, Deformation mechanisms and reactions of hornblende: examples from the Bergell tonalite (Central Alps), Tectonophysics, v. 257, p. 149-174.

De Bresser, J., Ter Heege, J., Spiers, C., 2001, Grain size reduction by dynamic recrystallization: can it result in major rheological weakening?, International Journal of Earth Sciences, v. 90, p. 28-45.

Easton, R. and Kamo, S., 2011, Harvey-Cardiff domain and its relationship to the Composite Arc Belt, Grenville Province: Insights from U-Pb geochronology and geochemistry, Canadian Journal of Earth Sciences, v. 48, p. 347-370.

Grittins, J., 1961, Nephelinization in the Haliburton-Bancroft District, Ontario, Canada, Journal of Geology, v. 61, p. 291-308.

Hanmer, S. and McEachern, S., 1992, Kinematic and rheological evolution of a crustal-scale ductile thrust zone, Central Metasedimentary Belt, Grenville orogen, Ontario, Canadian Journal of Earth Sciences, v. 29, p. 1779-1790.

Kirby, S., 1985, Rock mechanics pertinent to the rheology of the continental lithosphere and the localization of strain along shear zones, Tectonophysics, v. 119, p. 1-27.

White, S., Burrows, S., Carreras, J., Shaw, N., Humphreys, F., 1980, On mylonites in ductile shear zones, Journal of Structural Geology, v. 2, p. 175-187.