10-31-2013

Quantifying Syntectonic Weakening in Deep Orogenic Crust

Christopher Gerbi
Principal Investigator; University of Maine, Orono, christopher.gerbi@maine.edu

My Desktop
Prepare & Submit Proposals
Proposal Status
Proposal Functions
Awards & Reporting
Notifications & Requests
Project Reports
Submit Images/Videos
Award Functions
Manage Financials
Program Income Reporting
Federal Financial Report History
Financial Functions
Grantee Cash Management Section Contacts
Administration
User Management
Research Administration
Lookup NSF ID

Preview of Award 0837922 - Final Project Report

Cover |
Accomplishments |
Products |
Participants/Organizations |
Impacts |
Changes/Problems
| Special Requirements

Cover

Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	0837922
Project Title:	Quantifying Syntectonic Weakening in Deep Orogenic Crust
PD/PI Name:	Christopher C Gerbi, Principal Investigator
Recipient Organization:	University of Maine
Project/Grant Period:	08/01/2009 - 07/31/2013
Reporting Period:	08/01/2012 - 07/31/2013
Submitting Official (if other than PD\PI):	Christopher C Gerbi Principal Investigator
Submission Date:	10/31/2013
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Christopher C Gerbi

Accomplishments

*** What are the major goals of the project?**

This project sought (1) to quantify the strength reduction allowing km-scale shear zone development under amphibolite facies conditions and (2) to identify the associated weakening mechanisms. We relied primarily on the Twelve Mile Bay Shear zone in the Grenville Province, Ontario, Canada, as the focus site for this work. As a result of

interpretations developed through the project, our focus broadened to include identification and quantification, where possible, of controls on rock strength in general in the viscous regime of continental crust.

Goals also included development of computational infrastructure and a video library for instructional purposes, as well as the involvement of a preservice K-12 teacher in the project.

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

Our major research activities centered around (1) developing the geologic context of the Twelve Mile Bay shear zone, (2) quantifying the weakening associated with shear zone development, (3) and identifying the controls on weakening and on rock strength in general. These activities resulted in eight journal publications, with three dominantly concerned with context, two with quantification of weakening, and three with strength-controlling mechanisms. These activities incorporated field work, numerical modeling, geochronology, metamorphic petrology, structural geology, and microstructural analysis.

Other activities include:
(1) Training graduate and undergraduate students in various aspects of research, including petrology, geochronology, and numerical modeling.
(2) Incorporating the results of the work in the April 2010 Earth Science Teachers Workshop at the University of Maine. Components included discussion of geochronology and what controls and changes rock viscosity.
(3) Beginning development of a numerical model that can be used in classes to explore the effect of shear zone formation on orogen development.
(4) Involving two high school students in measuring strain associated with large shear zones.
(5) Collecting videos and photos that can be used for instructional purposes.

We did not meet some of the original outreach goals. We did involve a graduate student in the Master of Science in Teaching program in Year 1, but we did not have interested MST students in the geoscience field in subsequent years. This is partly due to the funding of an NSF-sponsored Math-Science Partnership program at UMaine, which has tapped a lot of student resources that might otherwise have been available for projects such as this. We did, however, involve high school and undergraduate students in the research more than originally planned. In addition, partly in conjunction with the MSP, the PI has devoted a great deal of time to working with K-12 teachers on diverse Earth Science topics, including those related to this project. Development of a numerical model and visualization scheme continues, but we have not yet completed that component of the project primarily because we prefer to develop a strong physics-based model rather than simply a simulation, and the model development is more complicated than originally projected.

Specific Objectives:

The objectives we addressed for the research activities above include the following.

(1) Constrain the metamorphic and structural history of the field area.
(2) Constrain the timing of the major tectonic events.
(3) Evaluate whether the Twelve Mile Bay shear zone developed synchronously along its length.
(4) Determine the meso- and micro-scale processes, including reactions, structural changes, and deformation mechanisms, that acted to allow the Twelve Mile Bay shear zone to develop.

(5) Identify the macro-scale (tectonic-scale) processes that led to the Twelve Mile Bay shear zone.
(6) Generalize the shear zone formation processes so that we can predict other tectonic locations and conditions in which the similar weakening may occur.
(7) Evaluate methods for calculating the bulk strength of polyphase materials.
(8) Develop a numerical model exploring the effect of shear zone formation on orogen development.

Significant Results:

We found the Twelve Mile Bay shear zone to be an excellent natural laboratory in which to explore mechanisms for generating orogen-scale shear zones. We first describe the results that are significant for the geologic history of the field site and also lead to more general process-oriented interpretations and conclusions. We then list the results of the project that are of more widespread interest.

Background: The Twelve Mile Bay shear zone represents a kms-wide amphibolite facies structure that accommodated >100km of transport of the granulitic Parry Sound domain, now a klippe within the Central Gneiss belt of the southwest Grenville orogen in Ontario, Canada.

Local results: The intrusion of pegmatites along the length of the Twelve Mile Bay shear zone caused hydration in the adjacent, fairly dry host rocks. The hydration allowed metamorphism, reacting out clinopyroxene and garnet and growing primarily amphibole in the mafic layers. The felsic layers did not experience substantial mineralogical change. The magma for the pegmatites was not derived from a local source, but instead must have formed within a separate domain, likely the rocks that underlay the Parry Sound domain early in its transport history. The pegmatites are of the same age along the shear zone, indicating its synchronous development. The hydrated, retrograde metamorphosed margins of the pegmatites were weaker than the surrounding rock and became the locus of meter-scale shear zones. Approaching the core of the master shear zone from the margins, the meter-scale shear zones progressively widen and link, eventually coalescing into networks around relict granulitic panels. In the shear zone core, transposition and retrogression are complete, with no granulite relicts remaining. Although we can explain the shear zone development as a single episode of fluid-driven weakening, isotopic and geochronologic evidence suggests that the core of the Twelve Mile Bay shear zone experiences a second fluid infiltration, perhaps associated with the strong localization of deformation into the core of the shear zone. Thus the structures in the shear zone core may be younger than those on the margins; we were unable, however, to find appropriate geochronometers to test that hypothesis. In addition, early melting of the lithology that comprises part of the shear zone core may have provided an initial localization mechanism. The structural development of the shear zone network records an exceptional gradient of transposition and interconnections of meter-scale shear zones. The geometry of the meter-scale features mirrors that of the larger km-scale features, such as would be visible on seismic lines. Also, the style of meter-scale shear zone development, rotation, and linking in these layered granulite facies rocks contrasts with the structural style of similar layered rocks at amphibolite facies, which display a buckle-and-fold pattern. At the location near the margin of the shear zone where we did our quantitative evaluation, the bulk rock (hectare scale) containing meter scale shear zones was ~30% than the host. Closer to the core, the bulk rock was >75% weaker, and probably greater than 90% weaker than the protolith. To summarize, a carapace of hydrated, amphibolite facies rocks formed from and around the granulite facies core of the Parry Sound domain, part of a large nappe. The

hydration and retrogression was driven at least in part by the intrusion of water-rich magmas derived from outside the domain.

More general results: Our interpretations about the history and conditions of the Twelve Mile Bay shear zone lead to several results that apply well beyond the field area and the Grenville orogen. The results necessarily overlap to some degree, but here we discretize them into the major points.

1.Hydration, whether or not induced by pegmatite intrusion, of the margin of a nappe or other tectonically significant block can lead to substantial weakening and allow long distance transport of that block. Hydration is not commonly cited as a major mechanism for localization, in part because its effectiveness is probably limited to a few rock types, including granulites. However, long-distance transport is a feature of many orogen-scale numerical models, including some of those for the Grenville orogen. The process recorded by the Twelve Mile Bay shear zone may operate in other large orogens, affecting the kinematics and consequent distribution of rock types.
2.From a geometrical perspective, apparent truncation of layering or foliation by transposition can be scale-independent. Thus some deep crustal structures visible through remote sensing may be enigmatic unless viewed through the lens of transposition-truncation processes such as that described above. Development of the structural morphology may strongly depend on rock type: layered granulite and amphibolite rocks of essentially the same composition may deform quite differently as a result of their inherent differences in bulk properties and also propensity for reaction.
3.We developed a method for calculating the bulk strength of a polyphase composite. We then used that method to demonstrate that analytical determinations of bulk strength may be inaccurate largely because of the difficulty of incorporating phase topology into the calculations. Therefore, numerical determinations of bulk strength are more robust.

Key outcomes or Other achievements:

In addition to the principal scientific results highlighted above, this project incorporated and led to several related outcomes. One was the discovery of menzerite-(Y), a new species of garnet containing essential Y. The menzerite-(Y) bearing rocks are located within the core of the Parry Sound domain. The presence of this mineral provides excellent constraints on the metamorphic history of the containing units leading up to peak granulite facies conditions. A second outcome was that the PI, Nicholas Culshaw (Dalhousie University), and Jeffrey Marsh (Queens College) have been able to use the discoveries from this project as a launching point for continued investigation into the rheology, structural development, and petrological processes of deep orogenic crust, including specific studies within the Grenville Front Tectonic Zone and other shear zone systems in the Central Gneiss belt.

*** What opportunities for training and professional development has the project provided?**

Six graduate students and three undergraduates contributed to this project. All were at different stages in their educational careers so it is not possible to generalize the training to a great extent.

Charles Rodda – 3rd year M.S. student. Developed components of numerical models that included shear zones. Training related primarily to integrating geodynamics concepts into numerical modeling.

Azadeh Mashhadi – 1st year M.S. student from Iran. The primary training with Azadeh was learning the practice of science in American universities, with additional training in concepts related to rheology, analytical methods, and petrology.

Stephanie Mills – 1st year M.S. student with an education background. Stephanie served as a field assistant in Ontario. Although her research project is not complete yet, it is a follow-up to the findings described above, using natural microstructures from the Twelve Mile Bay shear zone. Training sponsored by this grant occurred in the topic areas related to the research, field methods, and also in the practice of science research.

Maura Foley – 1st year Ph.D. student. Maura's research relates to, but was not directly supported by, this project. She served as a field assistant with training focused largely on research methodology and deep crustal processes at the orogen scale.

*** How have the results been disseminated to communities of interest?**

We published research results from this project in eight journal articles and presented results in eleven posters and talks at international, national, and regional conferences. Results also served as a basis for visiting talks given at the Universities of Vermont and Massachusetts. In addition to the formal research presentations, the PI has reported results in two departmental talks and incorporated research results into classes, discussions with visiting school groups, and professional development activities with K-12 teachers.

Products

Books

Book Chapters

Conference Papers and Presentations

Mills, S.G., Gerbi, C., and Johnson, S.E. (2013). *Cathodoluminescence imaging of high-grade microstructures in quartz, Central Gneiss belt, Ontario, Canada*. GSA Northeast Section Meeting. Bretton Woods, NH. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Foley, M., Koons, P.O., and Gerbi, C. (2013). *Characterizing the 3-D influence of lower crustal localization on the surficial kinematics of an orogen*. GSA Northeast Section Meeting. Bretton Woods, NH. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Gerbi, C., Koons, P.O., Marsh, J.H., and Culshaw, N.G. (2012). *Impact of shear zone distribution in the middle to lower crust*. Structural Geology and Tectonics Forum. Williamstown, MA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Inventions

Nothing to report.

Journals

Gerbi, C. (2012). Evaluating the utility of a phase distribution parameter in calculating the bulk viscous strength of two-phase composites. *Journal of Structural Geology*. 39 224. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.jsg.2012.02.008

Marsh, J. H., Grew, E. S., Gerbi, C., Yates, M. G., and Culshaw, N.G. (2012). The petrogenesis of the garnet menzerite-(Y), end member Y2CaMg2Si3O12, and its bearing on the Y+HREE budget in granulite-facies rocks in the Parry Sound Domain, Grenville Province, Ontario. *Canadian Mineralogist*. 53 73. Status = PUBLISHED;

Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.3749/canmin.50.1.73

Marsh, J.H., Culshaw, N.G., and Gerbi, C.C. (2013). Timing and conditions of poly-phase metamorphism within the Twelve Mile Bay shear zone: implications for the evolution of mid-crustal decollement zones and western Grenville tectonics. *International Geology Review*. 55 525. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1080/00206814.2013.773768

Marsh, J.H., Gerbi, C., Culshaw, N.G., Wooden, J.L., and Clark, C. (2012). New in-situ zircon ages from the southern Parry Sound Domain, Grenville Province, Ontario, Canada: Constraints on the timing of metamorphism, dike emplacement, and shearing along the Twelve Mile Bay shear zone. *Precambrian Research*. 192-195 142. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.precamres.2011.10.017

Licenses
Nothing to report.

Other Products
Software or Netware.

This is a Matlab-based GUI for analyzing the bulk properties and internal stress-strainrate patterns in aggregates of power-law materials. It is nearing release in a beta version, via sharing individually with colleagues and the website: http://umaine.edu/mecheng/faculty-and-staff/senthil-vel/software/.

Other Publications

Patents
Nothing to report.

Technologies or Techniques
Nothing to report.

Thesis/Dissertations

Websites
Nothing to report.

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Gerbi, Christopher	PD/PI	2
Yates, Martin	Other Professional	1
Foley, Maura	Graduate Student (research assistant)	1
Mashhadi, Azadeh	Graduate Student (research assistant)	3
Mills, Stephanie	Graduate Student (research assistant)	6
Rodda, Charles	Graduate Student (research assistant)	1

Full details of individuals who have worked on the project:

Christopher C Gerbi
Email: christopher.gerbi@maine.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 2

Contribution to the Project: Oversaw the research program; developed numerical protocol for quantitative strength analysis; assisted in petrological and structural analyses; performed field work for mapping and sample collection; facilitated electron microscopy analyses.

Funding Support: This grant, University of Maine.

International Collaboration: Yes, Canada
International Travel: Yes, Canada - 0 years, 2 months, 0 days

---

Martin Yates
Email: yates@maine.edu
Most Senior Project Role: Other Professional
Nearest Person Month Worked: 1

Contribution to the Project: Assisted with electron beam microanalysis.

Funding Support: This grant; University of Maine

International Collaboration: No
International Travel: No

Maura Foley
Email: maura.foley@maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Field assistant; contributed to orogen-scale numerical modeling.

Funding Support: This grant, teaching assistantship.

International Collaboration: Yes, Canada
International Travel: Yes, Canada - 0 years, 1 months, 0 days

---

Azadeh Mashhadi
Email: azadeh.mashhadi@maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Reviewed shear zone formation mechanisms and mineral deformation mechanisms.

Funding Support: This grant.

International Collaboration: No
International Travel: No

Stephanie Mills
Email: stephanie.g.mills@maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: Field assistant. Then as research assistant documenting quartz microstructures across shear zone strain gradients and determining their causative mechanisms and how the microstructures relate to the bulk rock rheology.

Funding Support: This grant, teaching assistantship, other NSF grant to the PI.

International Collaboration: Yes, Canada
International Travel: Yes, Canada - 0 years, 1 months, 0 days

---

Charles Rodda
Email: charles.rodda@maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Developed components of numerical models that included shear zones.

Funding Support: This grant.

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Dalhousie University	Academic Institution	Halifax, Nova Scotia
University of Texas	Academic Institution	Austin, TX

Full details of organizations that have been involved as partners:

Dalhousie University

Organization Type: Academic Institution
Organization Location: Halifax, Nova Scotia

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Ongoing collaboration with Nicholas Culshaw

---

University of Texas

Organization Type: Academic Institution
Organization Location: Austin, TX

Partner's Contribution to the Project:

Collaborative Research

More Detail on Partner and Contribution: Ongoing collaboration with Jeffrey Marsh (now at Queen's College).

What other collaborators or contacts have been involved?

YES

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The direct research results from this project impact others interested in the geological history of the Grenville orogen and those interested in deep crustal rheology. The Grenville orogen serves as probably the most cited ancient analogue for large orogens, of the dimensions of today's Himalaya. The large-scale tectonic processes are not deducible from a single study but instead rely on a body of literature built up from numerous investigations across the orogen. Our contribution, particularly related to the chronological, structural, and petrological history, provides more context and background for future integrative studies.

From the perspective of process-oriented research, our project results highlight the following points of interest to others in tectonics:
1.Despite their geodynamic significance, there seems to be little systematic investigation of the origins of km-scale shear zones.
2.Quantification of bulk weakening reveals uncertainties at many scales of mechanical data, including of deformation mechanisms, mineral flow laws, and aggregation of mineral flow laws to rock flow laws.
3.Developing parameterizations for strain localization into orogen-scale numerical models must be able to incorporate multiple weakening mechanisms.

What is the impact on other disciplines?

From the research perspective, the impact of this project beyond tectonics primarily includes the reinforcement of the integrated nature of geological processes. Although aspects of this work affect mineralogy, petrology, and geophysics, the bulk of the work applies most directly to tectonics. The work has, however, led to collaboration with mechanical engineers, as we develop methods for quantification of the bulk strength of polyphase materials. This direction may lead to advances in quantifying the physical properties of natural and synthetic materials with engineering applications.

What is the impact on the development of human resources?

As stated previously, the project has involved training for six graduate students and three undergraduates. Emphasis in all of their work was documenting and following valid protocols so that their data and interpretations have long-term value and the communication of scientific ideas. Both of those lines of training are difficult to quantify, but we anecdotally can trace improvements in both of those areas with the students involved. Of particular note is that this project allowed us to leverage campus-administered EPSCoR funding to allowing two high school students to come in the field in Summer 2011. The Master of Science in Teaching student now works at a position at the interface between education and research.

What is the impact on physical resources that form infrastructure?

This project supported many laboratories, both at UMaine and at other institutions within the U.S. and Canada.
– UMaine: scanning electron microscope, electron microprobe, rock preparation, microstructural, analog materials, numerical modeling, and stable isotope laboratories
– Stanford/USGS: SHRIMP-RG

– University of Western Ontario (Canada): oxygen isotope laboratory
– John de Laeter Center for Isotope Research, Curtain University, Australia

What is the impact on institutional resources that form infrastructure?
Nothing to report.

What is the impact on information resources that form infrastructure?

This project has led to the PI's involvement in the development (still in its early stages) of a shear zone database for the structural geology/tectonics community.

What is the impact on technology transfer?
Nothing to report.

What is the impact on society beyond science and technology?

As with many projects such as these, we cannot point to an immediate, direct impact. The project and the legacies of the students involved continues to raise awareness of the scientific process. For the Parry Sound area, images of the island and field area published and presented as part of research and/or more general public talks also serve to promote tourism in the area.

Changes/Problems

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them
Nothing to report.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.

Special Requirements

Responses to any special reporting requirements specified in the award terms and conditions, as well as any award specific reporting requirements.
Nothing to report.