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Kinematic Vorticity Gauges and the Rheology of Mylonitic Shear Zones

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Final Report for Period: 08/2011 - 07/2012

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Principal Investigator: Johnson, Scott E.

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Organization: University of Maine

Submitted By:

Johnson, Scott - Principal Investigator

Title:

Kinematic Vorticity Gauges and the Rheology of Mylonitic Shear Zones

Project Participants

Senior Personnel

Name: Johnson, Scott

Worked for more than 160 Hours: Yes

Contribution to Project:

Johnson is the PI, and oversees all aspects of the project.

Name: Yates, Martin

Worked for more than 160 Hours: Yes

Contribution to Project:

Marty manages our electron beam facilities in the Department of Earth Sciences. He is also an accomplished mineral chemist. He plays an essential role in the work of my graduate students, and the success of this and many other projects.

Post-doc

Graduate Student

Name: Naus-Thijssen, Felice

Worked for more than 160 Hours: Yes

Contribution to Project:

Felice is the primary graduate student funded by this project in year 1. Her role is to conduct numerical sensitivity analyses of clast kinematics, and make use of our new SEM to with EBSD and CL to examine the deformation mechanisms in these rocks.

Name: Price, Nancy

Worked for more than 160 Hours: No

Contribution to Project:

Nancy is working on a different project - dynamics of the Norumbega Fault System. Her work overlaps a bit with this project, and so she has been a very important contributor in identifying good locations for field sampling, and for developing SEM protocol for these rocks.

Name: Marsh, Jeffrey

Worked for more than 160 Hours: No

Contribution to Project:

Jeff made some important early contributions to the numerical modeling of clast kinematics.

Name: Song, Won Joon

Worked for more than 160 Hours: Yes

Contribution to Project:

Won Joon is a PhD student working with the PI. His role is to help complete the SEM-based analysis of the rock fabrics and the numerical modeling of shear zone strength.

Name: Roy, Samuel

Worked for more than 160 Hours: Yes

Contribution to Project:

Sam was a MS student working with the PI. His role was to help complete the SEM-based analysis of the rock fabrics and the

numerical modeling of clast lubrication.

Undergraduate Student

Name: Lenferink, Hendrik

Worked for more than 160 Hours: No

Contribution to Project:

Hendrik made some important early contributions to the numerical modeling of clast kinematics, and also to the statistical analysis of vorticity gauges.

Technician, Programmer

Other Participant

Name: Vel, Senthil

Worked for more than 160 Hours: No

Contribution to Project:

Senthil Vel is a Professor of Mechanical Engineering at the University of Maine. He has guided the development of finite element codes designed to calculate grain-scale stress/strain distributions in rocks using EBSD data, and from this information calculate precise seismic wave speeds.

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

We have developed two important collaborations as part of this project. (1) Professor David P. West Jr. (Middlebury College) is collaborating with us on geological aspects of our study of kinematic vorticity in the Sandhill Corner Mylonite Zone. (2) Professor Senthil S. Vel (UMaine Mechanical Engineering) is collaborating with us in the development of finite element methods for calculating precise rheological properties from polycrystalline rocks, beginning with the elastic field.

Regarding contacts, I have been contacted by several leading practitioners of vorticity analysis seeking advice on how to implement the techniques we have published.

Activities and Findings

Research and Education Activities:

We used this funding to focus primarily on two research problems.

(1) The presence of relatively large mineral clasts (typically of plagioclase) in mylonitic shear zones should actually lead to an increase in the flow strength of the zone. However, our work has shown that these clasts are typically 'lubricated' so that there is no longer a perfect viscous stress coupling along the matrix/clast boundary. This loss of continuity causes slip at the boundary, and this slip actually has the effect of lowering the bulk viscosity of

the shear zone. We conducted numerical modeling analyses of this problem in which we embedded numerous elliptical clasts in a viscous matrix, and then varied the degree of matrix/clast coupling to quantitatively evaluate the effect on shear zone strength. Our work this year has confirmed earlier, very preliminary results that shear zone weakening of between 8% and 20% can be achieved, depending on the volume proportion of clasts and the degree of matrix/clast coupling. This is an important find, because it is possible then that a shear zone with lubricated clasts can actually have a lower flow strength than a shear zone with no clasts.

(2) We have also investigated the role of rheological anisotropy in deforming rocks in the partitioning of vorticity. In order to develop the methodology for this work we have focussed on instantaneous solutions. For instantaneous solutions, the elastic and viscous tensors are identical for a Poisson ratio of 0.5. Thus, we have limited our work to the elastic field for this particular project, though we are working towards time-dependent solutions in the future. What we have found is that the anisotropy imparted by deformation and metamorphic fabrics in rocks has a large effect on the grain-scale distribution of stress and strain. These grain-scale effects sum to a significant bulk effect. We are developing computational methods (discussed more in the 'findings' below) that allow calculation full-field solutions for stress and strain, and from that we can calculate rotational strain quantities and, for instantaneous solution, rate quantities like vorticity. In addition, we have discovered several other, very fruitful avenues of research that we can branch into from these findings, and the one that we have pursued first is the effect of microstructural anisotropy on the bulk elastic properties of rocks. Working with Professor Senthil Vel in Mechanical Engineering, University of Maine, we are developing software designed specifically to take EBSD maps of polymineralic rocks into our computational code and calculate bulk properties such as the elastic stiffness tensor, viscosity tensor, thermal conductivity and thermal expansion. We are developing these ideas through separate NSF proposals, and recently had one funded to investigate the role of rock microstructures on seismic wave speed anisotropy. Meanwhile, under the current grant, I was invited to speak at a Pardee Symposium at the 2009 annual GSA meeting, and at the recent Penrose meeting on shear zone evolution in Cadaques, Spain (late June, 2011).

Findings:

The major finding in this project are as follows.

(1) The clast method of vorticity analysis is deeply compromised by imperfect viscous coupling between the clast and the surrounding matrix minerals. This is important. At the recent Penrose meeting on shear zones, several researchers who have used the clast-based vorticity gauge acknowledged that they will probably have to stop using it. Hopefully, then, energy will go into developing alternative methods for vorticity analysis in clast-rich rocks.

(2) The loss of viscous stress coupling at the boundaries of clasts and matrix minerals in mylonitic rocks can actually decrease the flow strength of the shear zone by up to 20% given 25 volume % of

ellipsoidal clasts. This finding is important. Large mylonitic shear zones generally identify the base of seismogenic faults. The strength of seismogenic faults is a hotly-debated topic, but comprehensive assessment of fault strength requires knowledge not just of the brittle/frictional strength near the surface, but also the viscous strength at depth in the frictional to viscous transition. Our results provide new information on the potential strengths of the shear zone, which can be integrated into fully-coupled crustal models of seismogenic fault strength.

(3) We have found that anisotropy arising from rock microstructure has a profound effect on the distribution and magnitudes of stresses and strains. This point in itself is not new, but what is new is how we make the calculations. Working with Professor Vel, we have brought a very precise and robust mathematical technique known as asymptotic expansion homogenization to the problem. This method allows full-field calculations of stress, strain and thermal quantities, and from that of course we can calculate rotational strain and rate quantities like vorticity.

We have developed the computational methods for performing these calculations directly from EBSD maps. When we realized the value of this methodology, we immediately developed applications to seismic wave anisotropy and have published on this application. We are also applying these methods to the calculations of thermal conductivities and expansions. Although these applications are being pursued through different NSF proposals, their origins are in this proposal and so it is relevant to report here on their development.

Training and Development:

The students are gaining research experience by interacting with the PI, Yates, and collaborators and gaining skills on a range of analytical equipment including electron microprobe, SEM-EBSD, XRF and FTIR. They are also incorporating numerical modeling into their dissertation work.

The undergraduate student received the same opportunities and training. Owing to the collaboration with Professor Senthil Vel in Mechanical Engineering, we now have engineering and Earth science students working together on various topics, and this has led to a rich and fruitful interaction of our two research groups.

Outreach Activities:

We are developing software for the community that can be used to calculate the bulk properties of rocks and seismic wave speeds from EBSD maps using asymptotic expansion homogenization coupled with finite elements. We unveiled a Beta version of this software at the 2011 Annual GSA meeting in Minneapolis, and are preparing to distribute the software to a few labs for final testing before we release it openly to the community. This software has been fully developed under separate NSF funding, but the origins of this software lie in this project.

Journal Publications

Johnson, S.E., Lenferink, H.J., Price, N.A., Marsh, J.H., Koons, P.O. West, D.P., Jr., and Beane, R., "Clast-based kinematic vorticity gauges: the effects of slip at matrix/clast interfaces", *Journal of Structural Geology*, p. 1322, vol. 31, (2009). Published, 10.1016/j.jsg.2009.07.008

Johnson, S.E., Lenferink, H.J., Marsh, J.H., Price, N.A., Koons, P.O. and West, D.P., Jr., "Kinematic vorticity analysis and evolving strength of mylonitic shear zones: new data and numerical results", *Geology*, p. 1075, vol. 37, (2009). Published, 10.1130/G30227A.1

Goupee, A.J., Naus-Thijssen, F.M.J., Vel, S.S., and Johnson, S.E., "The influence of microstructure on seismic wave speed anisotropy in the crust: Computational analysis of quartz-muscovite rocks", *Geophysical Journal International*, p. 609, vol. 185, (2011). Published, 10.1111/j.1365-246X.2011.04978.x

Naus-Thijssen, F.M.J., Goupee, A.J., Johnson, S.E., Vel, S.S., C.C. Gerbi, "The influence of crenulation cleavage development on the bulk elastic and seismic properties of phyllosilicate-rich rocks", *Earth and Planetary Science Letters*, p. , vol. 311, (2011). Published, 10.1016/j.epsl.2011.08.048

Price, N.A., Johnson, S.E., Gerbi, C.C., & D.P. West Jr., "Identifying deformed pseudotachylite and its influence on the strength and evolution of a crustal shear zone at the base of the seismogenic zone", *Tectonophysics*, p. 63, vol. 518-521, (2012). Published, 10.1016/j.tecto.2011.11.011

Naus-Thijssen, F. M. J., Goupee, A. J., Vel, S. S. and Johnson, S. E., "The influence of microstructure on seismic wave speed anisotropy in the crust: computational analysis of quartz-muscovite rocks.", *Geophysical Journal International*, p. 609, vol. 185, (2011). Published, 10.1111/j.1365-246X.2011.04978.x

Roy, S. G., Johnson, S.E., Koons, P. O., and Jin, Z.-H., "Fractal analysis and thermal-elastic modeling of a subvolcanic magmatic breccia: the role of post-fragmentation partial melting and thermal fracture in clast size distributions.", *Geochemistry Geophysics Geosystems*, p. , vol. 13, (2012). Published, 10.1029/2011GC004018

Frieman, B.M., Gerbi, C.C., Johnson, S.E., "The effect of microstructural and rheological heterogeneity on porphyroblast kinematics and bulk strength in porphyroblastic schists", *Tectonophysics*, p. , vol. , (2013). Accepted,

Books or Other One-time Publications

Johnson, S.E., Vel, S.S., Gerbi, C., Cook, A., Song, W.J., Naus-Thijssen, F.M.J., Goupee, A.J., "Microscale stress and strain distributions, fabric evolution, and crustal seismic anisotropy.", (2011). Abstract, Published
Bibliography: *The Interrelationships Between Deformation and Metamorphism*, an international conference held in honor of T.H. Bell, Granada, Spain, May 23-26, 2011.

Johnson, S.E., Vel, S.S., Gerbi, C., Song, W.J., Okaya, D.A., Cook, A., "The effects of strain localization and shear zone development on elastic anisotropy at a variety of scales.", (2011). Abstract, Published
Bibliography: Geological Society of America Penrose Meeting, Cadaques, Spain, June 27 ? July 2, 2011.

Price, N.A., Johnson, S.E., & Gerbi, C.C., "The influence of pseudotachylite on the strength and evolution of a crustal shear zone at the base of the seismogenic zone.", (2011). Abstract, Published
Bibliography: Geological Society of America Penrose Meeting, Cadaques, Spain, June 27 ? July 2, 2011.

Johnson, S.E., Naus-Thijssen, F.M.J., Vel, S.S., Okaya, D., "Numerical modeling of microstructural processes and fabric evolution: an essential step in exploring crustal seismic anisotropy.", (2009). Abstract, Published
Bibliography: Geological Society of America Abstracts with Programs, Vol. 41, No. 7, p. 341.

Naus-Thijssen, F.M.J., Goupee, A.J., Johnson, S.E. and Vel, S.S., "Computational Modeling of Rock Fabrics: Implications for Seismic Anisotropy in the Crust.", (2009). Abstract, Published
Bibliography: *Eos Transactions, American Geophysical Union*, Vol. 90, Fall Meeting Supplement, paper no. DI41B-1804.

Frieman, Ben M., Johnson, Scott E., Gerbi, Christopher, "Rheological heterogeneity, strain partitioning, shear stress coupling, and kinematics in porphyroblastic schists", (2012). Abstract, Published
Bibliography: Geological Society of America Abstracts with Programs, Vol. 44, No. 2, p. 106.

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

We developed new techniques for evaluating the kinematic vorticity number in clast-bearing mylonite zones.

We developed new techniques for evaluating the strength of clast-bearing mylonite zones.

We developed new techniques for assessing the effects of material anisotropy on the distribution of elastic stresses and are planning to distribute a community code that calculated seismic velocities from EBSD data files.

Contributions to Other Disciplines:

Our work on elastic anisotropy will contribute in very significant ways to geophysics and computational mechanics of composite materials (a subdiscipline of mechanical engineering and/or materials science).

Contributions to Human Resource Development:

This project partly supported the dissertation work of 4 PhD students, one Masters student and 1 undergraduate student. It also helped to maintain employment of a technical staff member in Earth Sciences.

Contributions to Resources for Research and Education:

The software we developed for the analysis of material anisotropy from thin sections will be made open-source accessible to all researchers and educators.

Contributions Beyond Science and Engineering:

Conference Proceedings

Categories for which nothing is reported:

Organizational Partners

Any Web/Internet Site

Any Product

Contributions: To Any Beyond Science and Engineering

Any Conference