11-10-2015

Integrated Analytical-Computational Analysis of Microstructural Influences on Seismic Anisotropy

Scott E. Johnson
Principal Investigator; University of Maine, Orono, johnsons@maine.edu

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

Andrew J. Goupee
Co-Principal Investigator; University of Maine, Orono, agoupe91@maine.edu

Senthil Vel
Co-Principal Investigator; University of Maine, Orono, senthil.vel@maine.edu

Preview of Award 1118786 - Final Project Report

Cover

Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	1118786
Project Title:	Integrated Analytical-Computational Analysis of Microstructural Influences on Seismic Anisotropy
PD/PI Name:	Scott E Johnson, Principal Investigator Christopher C Gerbi, Co-Principal Investigator Andrew Goupee, Co-Principal Investigator Senthil Vel, Co-Principal Investigator
Recipient Organization:	University of Maine
Project/Grant Period:	08/15/2011 - 07/31/2015
Reporting Period:	08/01/2014 - 07/31/2015
Submitting Official (if other than PD\PI):	Scott E Johnson Principal Investigator
Submission Date:	11/10/2015
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Scott E Johnson

Accomplishments

* What are the major goals of the project?

The principal aims of this project are to: (1) scale up a preliminary method to determine the bulk stiffness of rocks by integrating electron backscatter diffraction and computational approaches, and (2) apply this integrated framework to investigate the effect of fabrics and shear zones on the bulk elastic anisotropy of continental crustal volumes. In addition, we (3) developed new computational methods for calculating bulk properties of polymineralic lithospheric rocks that flow by power law creep, and (4) built fracture propagation into our models to explore their effects on anisotropy and on the development of damage zones caused by both thermal and mechanical loading.

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

Major Activities:

(1) Method and software development for bulk stiffness and seismic anisotropy calculations.

PhD students Alden Cook and Won Joon Song completed development (Cook) and testing (Song) of a computational toolbox designed for analysis of real and synthetic polycrystalline rock microstructures. The software is capable of importing EBSD information for a rock sample from different SEM-based sotware tools and determining the corresponding effective properties, including elastic stiffnesses, wave speeds, and anisotropies. We distributed the program to a small group of researchers for testing and now it is freely available to the scientific community. We were invited to speak at AGU in December of 2014 on our new methods and software.

(2) Application of this new computational toolbox.

PhD student Won Joon Song has collected shear zone samples from the Grenville Orogen in Canada, and used our new computational methods to determine the bulk elastic properties and seismic anisotropy of these rocks and the host rocks that surround the shear zones. The goal with this work is to conduct sensitivity analysis to explore the effects of these shear zones on the bulk elastic properties of the lower crust. Whether or not these shear zones impart a strong anisotropy to the bulk crust will depend on how their individual stiffness tensors integrate with one another and the surrounding rocks between the shear zones. Fabric orientations play a critical role. Many of the shear zones have fabric that effectively work to cancel out the pre-existing anisotropy. Thus, it is possible for a lower crustal volume to appear nearly isotropic, even though at a finer scale it is composed of packages of rock with moderate anisotropy. An interesting outcome from Won Joon's work is that our method of calculation - using Asymptotic Expansion Homogenization (AEH) - leads to noticably different results when compared to standard approximations (e.g., Voigt, Reuss, Hill methods) for samples with particular microstructure. The AEH method makes a precise calculation that accounts for the interactions of grains in the aggregate, and we have now identified samples where we can demonstrate this effect, and therefore the value of using our method.

(3) New computational methods for calculating the bulk effective viscosity of polymineralic rocks deforming by "power law" creep.

One of the long-standing and limiting unknowns in deformation studies is how to describe a collection of minerals with known dislocation creep flow laws using a single flow law. Numerous mixing rules have been proposed over the past 20 years, but there is no concensus regarding the right approach. PhD student Alden Cook has developed new software tools that allow the calculation of bulk effective viscosity given an aggregate of minerals of known effective viscosity. Our software will also calculate stress/strain relationships, and map all fields at the grain scale. The software is freely available, and we demonstrated it at the Gordon Research Conference in August of 2014. One of the interesting discoveries we have made is as follows. For a given microstructure, the slope of the composite strength curve in log stress – log strain rate space changes across the equiviscous point. So for rocks in which the equiviscous points of constituent mineral pairs lie between the experimental and natural conditions, extrapolation can cause large errors, particularly in the stress exponent. We have published two papers that detail our findings and methodologies.

(4) Building fracture propagation into our models to explore their effects on anisotropy and on the development of damage zones arising from thermal and mechanical loading.

The major rock-forming minerals possess anisotropic elastic constants and thermal expansion coefficients. When subjected to a load, such as that caused by a rapid temperature change or the passage of seismic waves, each crystal in the polycrystalline volume changes its dimension by different amounts in different directions. Owing to the GPa-level elastic moduli of these minerals, the interactions of the different grains can readily lead to tensile grain-scale principal stresses well in excess of their tensile strengths, even when the macroscale principal stresses are all compressive. As part of our ongoing research, we decided to build fracture propagation into our microstructure analysis code. PhD student Alden Cook is working on the final version of the code, which will be finished before he defends his dissertation in December, 2015. PhD student Bora Song has been working on damaged rocks that host a basaltic dike swarm on the Schoodic Peninsula, Maine. The host rock is a medium-grained, homogeneous granite that shows a gradient in damage features adjacent to the dikes. These features include pervasive microcracking and pulverization, and also show parallel deformation feature in quartz. Bora has been using our computational tools to examine the local grain-scale stresses caused by anisotropic thermal expansion of the granite. In addition, Bora is conducting a detailed investigation of damage microstructures around a strand of the Norumbega Fault in Maine - the Norumbega is probably the best ancient analog for the San Andreas Fault currently exposed at Earth's surface. She has conducted particle size distribution analyses for shattered garnet grains at different distances from the fault core. Samples within approximately 60 meters of the fault core show fractal dimensions well into the explosive regime, presumably owing to conversion of high-frequency seismic energy into fracture propagation and creation of surface energy. Bora is working with Alden to simulate progressive damage in these rocks with the goal of extending our understanding of fault damage zones to depths corresponding to the base of the seismogenic zone.

Specific Objectives:

Significant Results:

Key outcomes or Other achievements:

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

The students involved in this project were provided with rich opportunities for learning both analytical methods via the

SEM/EBSD system, and numerical/computational methods using finite elements and Matlab-based GUI development. The geologists in the group (PhD students Bora Song and Won Joon Song) also conducted field work and developed new methods of sample preparation for EBSD analysis. All students have had opportunities to attend workshops and conferences both in the USA and abroad. Scott johnson and Chris Gerbi used the Power Law Toolbox developed under this grant in a graduate level course this past year.

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

We publish our results in leading journals, and present at major conferences every year.

Partly through the current grant funding, we now have two software and source code packages freely available to the public through this web site:

http://umaine.edu/mecheng/faculty-and-staff/senthil-vel/software/

One is a toolbox for calculating elastic and seismic properties of rock or other samples, and the other is a toolbox for evaluating the mechanics of aggregates composed of materials that flow by power law creep.

Products

Books

Book Chapters

Johnson, S.E. (2015). Various Structures. *Atlas of Structural Geology* . Status = PUBLISHED; Acknowledgement of Federal Support = No ; Peer Reviewed = Yes

Conference Papers and Presentations

Cook A.C., Vel S.S., Johnson S.E., Gerbi C. (2014). *Computational modelling of brittle damage in polycrystalline materials*. Gordon Research Conference on Rock Deformation. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Song, B.R., Johnson, S.E., Song, W.J., Gerbi, C.C. (2015). *Damage microstructures in garnet and feldspar preserve coseismic cycles at mid-crustal depths in an ancient strike-slip fault system in south-central Maine*. Geological Society of America. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Johnson, S.E., Vel, S.S., Cook, A.C., Song, W.J., Gerbi, C.C., Okaya, D. (2014). *ESP Toolbox: A computational framework for precise, scale-independent analysis of bulk elastic and seismic properties*. American Geophysical Union. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Song, W., Gerbi, C., Johnson, S.E., Vel, S.S. (2014). *Effects of Shear Zone Development on Seismic Anisotropy in the Lower Grenvillian Crust*. American Geophysical Union. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Vel, S.S., Johnson, S.E., Vel, S.S., Okaya, D., Cook, A.C. (2014). *Homogenization of heterogeneous elastic materials with applications to seismic anisotropy*. American Geophysical Union. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Gerbi, C., Johnson, S.E., Cook., A.C., and Vel., S.S. (2015). *Phase morphology and bulk strength in power-law materials*. European Geosciences Union General Assembly. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Gerbi, C., Marsh, J.H., Johnson, S.E., Culshaw, N.G., Shulman, D.J., Song, W.J., and Foley, M.B. (2015). *Rheological predictability in the viscous regime*. Geological Society of America. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Johnson, S.E., Song, W.J., Song, B.R., Price, N.A., Gerbi, C.C.,West, D.P. Jr. (2014). *Seismogenic cycles, quartz microstructures and localization at the frictional to viscous transition in an exhumed, large-displacement, seismogenic strike-slip fault*. American Geophysical Union. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes

West, D.P. Jr., Pollock, S.G., Song, W.J., Price, N.A., Johnson, S.E. (2014). *The Ray Corner high strain zone of the Norumbega Fault System in Maine: A complex history of ductile shear, brittle deformation, and paleoseismicity*. American Geophysical Union. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Inventions

Journals

Cook, A.C., Vel, S.S., Gerbi, C.C., Johnson, S.E. (2014). Computational analysis of non-linear creep in polyphase aggregates; Influence of phase morphology.. *Journal of Geophysical Research*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI:

Gerbi, C., Johnson, S.E., Cook, A.C., Vel, S.S. (2015). Effect of phase topology on bulk strength for power-law materials.. *Geophysical Journal International*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Jin, Zhi-He, Johnson, Scott E. (2016). Fluid transport through buoyancy-driven crack propagation in transversely isotropic rocks and sediments. *Geophysical Journal International*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Johnson, S.E., Song, W.J., Price, N.A., Gerbi, C.C. (2016). Persistent memory of the earthquake cycle in a deeply exhumed continental strike-slip fault.. *Nature*. . Status = OTHER; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI:

Okaya, D.A., Vel, S.S., Johnson, S.E., Song, W.J. (2016). The modification of crustal seismic anisotropy by geological structures ("Structural Geometry Anisotropy"). *Journal of Geophysical Research*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Price, N.A., Johnson, S.E., Song, W.J., Gerbi, C.C., Beane, R.J., West, D.P. Jr. (2016). Quartz recrystallization fabrics from sheared quartz ribbons with a strong pre-existing crystallographic preferred orientation. *Tectonophysics*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Song, W.J., Vel, S.S., Okaya, D.A., Johnson, S.E. (2016). Effect of fold structures on seismic anisotropy in continental crust. *Journal of Geophysical Research*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Vel, S.S., Cook, A.C., Johnson, S.E., Gerbi, C. (2016). Computational framework for the homogenization and microstructural thermomechanical analysis of textured polycrystalline materials. *Computational Materials Science*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Licenses

Other Products

Software or Netware.

The GUI software is a standalone interface for the analysis of nonlinear creep in polyphase aggregates using Asymptotic Expansion Homogenization (AEH). The AEH method, which uses a finite element mesh, provides accurate results since it explicitly accounts for the morphology and interaction of phases. The user need only provide an image of the sample and the phase power law parameters in axial form. The package contains a Matlab-based graphical user interface (GUI) which has been designed for ease of use and efficiency. Post-analysis options allow the user to plot the bulk flow relations for the aggregate in either linear and $\log_{10}$ space, as well as visualize local fluctuations in fields such as stress, strain rate and viscosity via contour plots. Results can be exported with publication quality by using built-in Matlab functions. A built-in tutorial in included in the GUI software.

http://umaine.edu/mecheng/faculty-and-staff/senthil-vel/software/

Software or Netware.

The GUI software is a standalone interface for the calculation of bulk elastic and seismic properties of heterogeneous and polycrystalline materials using image or EBSD data. The GUI includes a number of different homogenization techniques, including Voigt, Reuss, Hill, geometric mean, self-consistent and Asymptotic Expansion Homogenization (AEH) methods. The AEH method, which uses a finite element mesh, is more accurate than the other methods since it explicitly accounts for grain-scale elastic interactions. The user need only specify the microstructure and material properties of the individual minerals or phases. Once homogenization is performed, the bulk elastic stiffnesses and average density are used to compute seismic wave speeds and anisotropies. A post-processing interface allows the user to visualize seismic results as equal-area projections or contoured spheres. Results can be exported with publication quality in a number of different formats.

The software and source code are freely available at this website:

http://umaine.edu/mecheng/faculty-and-staff/senthil-vel/software/

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

Websites

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Johnson, Scott	PD/PI	2
Gerbi, Christopher	Co PD/PI	2
Goupee, Andrew	Co PD/PI	0
Vel, Senthil	Co PD/PI	2
Cook, Alden	Graduate Student (research assistant)	8
Song, Won Joon	Graduate Student (research assistant)	8
Song, Bo Ra	Graduate Student (research assistant)	8

Full details of individuals who have worked on the project:

Scott E Johnson
Email: johnsons@maine.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 2

Contribution to the Project: Structural geology and microstructural analysis and modeling with an emphasis on the rheology of Earth materials.

Funding Support: None

International Collaboration: No
International Travel: No

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

Contribution to the Project: EBSD, mineralogy, petrology and microstructural analysis with an emphasis on the rheology of Earth materials.

Funding Support: None

International Collaboration: No
International Travel: No

Andrew Goupee
Email: agoupe91@maine.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 0

Contribution to the Project: Computational mechanics with an emphasis on random heterogeneous materials and polymineralic rocks.

Funding Support: None

International Collaboration: No
International Travel: No

Senthil Vel
Email: senthil.vel@maine.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 2

Contribution to the Project: Theoretical and computational mechanics with an emphasis on multiscale analysis of composite materials and polymineralic rocks

Funding Support: None

International Collaboration: No
International Travel: No

Alden Cook
Email: alden_cook@umit.maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 8

Contribution to the Project: Alden Cook is a mechanical engineering student who is developing advanced computational tools for the analysis of synthetic and real rock microstructures to better understand the seismic response of rock samples. He is also working on the role of grain-scale stresses in promoting microfracture and damage zone development adjacent to major seismogenic faults. He is being jointly advised by Drs Vel and Johnson.

Funding Support: Michael J. Eckardt Dissertation Fellowship

International Collaboration: No
International Travel: No

Won Joon Song
Email: wonjoon.song@maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 8

Contribution to the Project: Won Joon is an Earth Sciences PhD student conducting research on the seismic anisotropy of geological structures (e.g., folds and shear zones) and microstructures (e.g., foliations and microfolds). His field area is in the Canadian Grenville where he is evaluating the role of shear-zone anisotropy in the bulk anisotropy of the lower continental crust. He is being jointly advised by Drs Johnson and Gerbi.

Funding Support: Teaching Assistantship.

International Collaboration: No
International Travel: No

Bo Ra Song
Email: bora.song@maine.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 8

Contribution to the Project: Bora is an Earth Sciences PhD student conducting research on rock damage caused my thermla and mechanical stresses (earthquakes, igneous intrusions). Her field areas are the Schoodic dike swarm and Norumbega Fault, both located in Maine. She is being advised by Dr. Johnson.

Funding Support: Teaching Assistantship.

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Universitat Autonoma de Barcelona	Academic Institution	Barcelona, Spain

University of Southern California	Academic Institution	Los Angeles, CA

Full details of organizations that have been involved as partners:

Universitat Autonoma de Barcelona

Organization Type: Academic Institution
Organization Location: Barcelona, Spain

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: We are working with Dr. Albert Griera to develop time-dependent microstructural models aimed at evaluating the role of competing microstructural processes in the development of rock CPO.

University of Southern California

Organization Type: Academic Institution
Organization Location: Los Angeles, CA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: This project is related to a larger collaborative effort between the PIs and Dr. David Okaya, Research Associate Professor of Earth Sciences at USC. We are working with him to study the propagation of seismic waves through anisotropic rocks using his 3D anisotropic finite difference wave propagation code.

What other collaborators or contacts have been involved?
Nothing to report

Impacts

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

The graphical user interfaces and computational engines we have developed for calculating (a) bulk elastic properties and seismic wave speed from EBSD-derived rock data, and (b) bulk viscosities and stress/strain-rate relationships in aggregates of power law materials, will have an important impact on the geological and geophysical communities. The software packages are comprehensive, easy to use, and provides precise calculations owing to the use of asymptotic expansion homogenization methods as opposed to Voigt- and Reuss-type approximations.

What is the impact on other disciplines?

The computational tools we have developed are mainly for the Earth Sciences community, but are designed to be easily expanded for the Materials Science and Engineering communities. Given that we are an Earth Sciences/Engineering team, this extension into other disciplines is a natural result of our collaboration.

What is the impact on the development of human resources?

Three PhD students are involved in this project, and they are receiving excellent training in both Earth science and computational mechanics disciplines. They are also becoming experts with SEM/EBSD methods as well as integrating geological field work into the research.

What is the impact on physical resources that form infrastructure?

This project funded a computer workstation for development and execution of our software products.

What is the impact on institutional resources that form infrastructure?

This project helped to support the electron beam instrumentation in the School of Earth and Climate Sciences.

What is the impact on information resources that form infrastructure?

We have developed open-source software products that are available through a website that we created specifically for this purpose.

What is the impact on technology transfer?

Our open source software is available to the commercial and private sectors.

What is the impact on society beyond science and technology?

Nothing to report.

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.

RSR Award Detail

Research Spending & Results

Award Detail

Awardee:	UNIVERSITY OF MAINE SYSTEM
Doing Business As Name:	University of Maine
PD/PI:	Scott E Johnson (207) 581-2142 johnsons@maine.edu
Co-PD(s)/co-PI(s):	Senthil Vel Christopher Gerbi Andrew Goupee
Award Date:	08/07/2011
Estimated Total Award Amount:	$ 298,171
Funds Obligated to Date:	$ 223,628 FY 2011=$223,628
Start Date:	08/15/2011
End Date:	07/31/2015
Transaction Type:	Grant
Agency:	NSF
Awarding Agency Code:	4900
Funding Agency Code:	4900
CFDA Number:	47.050
Primary Program Source:	040100 NSF RESEARCH & RELATED ACTIVIT
Award Title or Description:	Integrated Analytical-Computational Analysis of Microstructural Influences on Seismic Anisotropy
Federal Award ID Number:	1118786
DUNS ID:	186875787
Parent DUNS ID:	071750426
Program:	TECTONICS
Program Officer:	David Fountain (703) 292-8552 dfountai@nsf.gov

Awardee Location

Street:	5717 Corbett Hall
City:	ORONO
State:	ME
ZIP:	04469-5717
County:	Orono

Country:	US
Awardee Cong. District:	02

Primary Place of Performance

Organization Name:	University of Maine
Street:	5717 Corbett Hall
City:	ORONO
State:	ME
ZIP:	04469-5717
County:	Orono
Country:	US
Cong. District:	02

Abstract at Time of Award

The magnitudes, orientations and spatial distributions of elastic anisotropy in Earth?s crust and mantle carry valuable information about gradients in thermal, mechanical and kinematic parameters arising from mantle convection, mantle-crust coupling and tectonic plate interactions. Relating seismic signals to deformation regimes requires knowledge of the elastic signatures (bulk stiffnesses) of different microstructures that characterize specific deformation environments, but the influence of microstructural heterogeneity on bulk stiffness has not been comprehensively evaluated. The objectives of this project are to: (1) scale up a preliminary method to determine the bulk stiffness of rocks using integrated analytical (electron backscatter diffraction) and computational (asymptotic expansion homogenization) approaches that fully account for the grain-scale elastic interactions among the different minerals in the sample; (2) apply this integrated framework to investigate the effect on elastic anisotropy of several common crustal microstructures; (3) integrate time-dependent microstructure modeling with bulk stiffness calculations to investigate the effects of strain- and process-dependent microstructure evolution on elastic anisotropy in mantle rocks; and (4) disseminate open-source software for the calculation of bulk stiffnesses from electron backscatter diffraction data and creation of synthetic (computer generated) microstructures that can be used in sensitivity analyses among other applications. Because commonly used methods, such as the Voigt, Reuss and Voigt-Reuss-Hill averages, for calculating bulk rock stiffnesses do not account for elastic interactions among the constituent minerals, they exhibit marked, non-systematic differences from stiffnesses obtained using asymptotic expansion homogenization.

These objectives are important because the results would substantially improve understanding of the nature of seismic anisotropy in the Earth's crust, which is composed of rocks dominated by low symmetry minerals with complex structures. Traditional methods for performing these calculations do not easily incorporate these effects. This project will develop an elegant, easily-implemented alternative method for anisotropic materials. The scientific results and computational tools that result from this project will have global application across a number of solid Earth and engineering disciplines. Open-source codes developed in this project will made available through existing open-source ELLE platform. Classroom exercises developed for Earth Science and Mechanical Engineering courses that employ this software will be make available to the community, probably through the Science Education Resource Center website at Carleton College.

Publications Produced as a Result of this Research

Gerbi, C., Johnson, S.E., Cook, A.C., Vel, S.S. "Effect of phase topology on bulk strength for power-law materials." GEOPHYSICAL JOURNAL INTERNATIONAL, v. , 2015, p.

Cook, A.C., Vel, S.S., Gerbi, C.C., Johnson, S.E. "Computational analysis of non-linear creep in polyphase aggregates; Influence of phase morphology." JOURNAL OF GEOPHYSICAL RESEARCH, v. , 2014, p.

Project Outcomes Report

Disclaimer

Images (1 of 2)

Energy from earthquakes, or deliberate explosions used by geophysicists to study Earth's interior, travel through Earth in the form of elastic seismic waves. The velocity of these waves is controlled by the rock type, and the orientations and arrangements of the constituent minerals. Thus, seismic waves generally travel at different speeds in different directions in Earth, and this property is known as seismic anisotropy. This is important for a variety of reasons, including the following example. The most common minerals in rocks of Earth's crust tend to become aligned during flow caused by the interaction of tectonic plates. Thus, seismic anisotropy in Earth volumes can inform us about tectonic flow that occurs below the surface, where we cannot directly observe it. It therefore forms an important "remote sensing" tool for interrogating plate tectonic processes.

The principal aims of this study were to: (1) scale up a preliminary method for determining the bulk elastic and seismic properties of rocks by integrating electron backscatter diffraction and computational approaches, and (2) apply this integrated framework to investigate the effect of different types of rocks on the propagation of seismic waves. Major findings or results of this work include the following.

1. We have developed a user-friendly, open-source software package that calculates precise bulk elastic properties from real rocks using data collected by the method of electron backscatter diffraction. These data are gathered from thin slices of the rocks, which are placed in a scanning electron microscope. A method called electron backscatter diffraction is used to determine the crystal orientations of all the minerals in the slice. These data are transferred to the open-source software package we have developed where a robust mathematical method know as assymptotic expansion homogenization is used to calculate the bulk three-dimensional elastic constants for the rock sample. A suite of tools that come with our software can then be used to calculate seismic anisotropy and a number of other important parameters, and visualization tools allow the information to be presented in a variety of publication-quality graphical forms. The attached figures show snapshots of the graphical user interface for the software package, which was implemented in the Matlab programming environment.

2. We have used our software package to examine the influence of various types of rocks and various types of tectonically-induced mineral alignments on seismic anisotropy. Our results indicate that the anisotropy of seismic wave propagation is strongly influenced by the mineralogy and microstructure of rocks.

3. We have developed new mathematical techniques for evaluating the effects of large-scale tectonic structures, such as folds, on seismic anisotropy. Different fold geometries, including sinusoidal, chevron, parabolic, box and cuspate folds have been evaluated with the result that these different folds have different effects on the seismic anisotropy, and it might therefore be possible to identify them from seismological data.

The overall broader impacts of this research are described below.

1. This project supported in whole or part the thesis work of three international Ph.D. students, including one female student. This training included interaction with the PIs in the field, in numerical modeling, and in the use of the electron microprobe and scanning electron microscope.

2. This project supported in part the development of two open-source software packages used to evaluate the elastic and viscous properties of rocks. Both of these software packages are used in courses taught by the PIs.

3. Grant funded research lead to two published papers, five papers submitted for publication, one paper in preparation, one published book chapter section, users manuals for the software packages noted above, and numerous abstracts for talks and posters presented at national and international geological and geophysical conferences.

4. Interaction among PIs and students strengthened collaborations between Earth Sciences and Engineering disciplines, and supported the electron beam facilities at the University of Maine.

Last Modified: 10/30/2015
Modified by: Scott E Johnson