Three-Dimensional Modeling of Continental Subduction and the Evolution of Ultra High Pressure Metamorphism

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Submitted on: 04/21/2008
Principal Investigator: Koons, Peter O.
Organization: University of Maine
Title: Three-Dimensional Modeling of Continental Subduction and the Evolution of Ultra High Pressure Metamorphism

Project Participants
Senior Personnel
Name: Koons, Peter
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Upton, Phaedra
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student
Name: Rodda, Charles
Worked for more than 160 Hours: Yes
Contribution to Project:
Field Work
Numerical Modeling
Analog Modeling
Laboratory work

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners
Geological Survey of Norway (NGU)

Other Collaborators or Contacts
Dr P Robinson; NGU, Trondheim, Norway
Structural and petrological field work
Dr M Terry, South Dakota School of Mines,
Structural evolution
Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

Activities
(This grant was originally proposed as a joint German DFG: US NSF project with overseas associates P. Robinson, NGU, Norway, and M Terry, Bayerisches Geoinstitut, Germany. Both associations have been productive. Although Terry left Bayerisches Geoinstitut before receiving DFG funding for this project, he, along with Robinson, advised our student and Terry worked in our numerical laboratory, using our facilities and contributing to several publications listed below).

Fieldwork:
(see previous reports)

Numerical Modeling
Rodda, Koons and Upton expanded the three-dimensional model of subducting continental material using both elasto-visco-plastic rheologies and viscous fluid rheologies that permit linkage of reaction and deformation via weakening and buoyancy relations to concentrate on the mechanics and petrology of separation during subduction. Rodda and Koons have explicitly linked the analytical Grashof (Gr = L^3g/μ^2Δρ^2) description with numerical solutions of viscous fluids. In each case, simultaneous solution for the conductive and advective components of heat flow permitted the tracking of the PT state of the numerical system. Results have been presented by Rodda et al. 2007 and in Rodda's thesis (in prep).

Analog Model
Quasi-scaled viscous analog modeling of subduction and separation was developed by Rodda in the Analog Modeling Facility at the University of Maine and identified the importance of the general mantle flow to the dip of the subducting slab.

Koons has used the analog models developed for the UHPM grant in undergraduate and graduate classes of tectonics and fluid dynamics and that can currently be viewed at:
http://www.geology.um.maine.edu/geodynamics/AnalogWebsite/html_files/crustal%20dynamics.html

Colleagues at the University of Maine have now incorporated analog modeling within their undergraduate classes, including subduction models derived from the UHPM models e.g.

Findings: (See PDF version submitted by PI at the end of the report)

Findings
One of the major development to come from this project has been the formulation of the Silicate Earth Global Circulation Model (SE GCM) in which the geological/tectonic history of the earth's crust can be linked to dynamic models of mantle convection over the last 100Myr. This concept grew from the recognition that resolution of mechanical issues governing flow in the mantle and deformation in the crustal behavior has progressed to the point that linkage of the two on a global scale is now possible. The nature and efficiency of these linkages between the two silicate masses form the subject of this emerging collaboration with Dr. P Bunge, Univ. Munich, and provide the basis for our proposed SE GCM that can permit investigation of geophysical and geochemical behavior at orogen scales for a period extending ~100Myr, marked by the approximate half life of the largest existing mantle convective limb, the Pacific Plate subduction boundaries.

A crucial step in the formulation of SE GCM has been the identification and quantification of reaction-influenced mechanics. Indications are that the further in PT space an assemblage is removed from equilibrium, the greater potential extreme discontinuous changes in viscosity associated with kinetics influencing both nucleation and growth leading to what we defined as Rheological Monsters.

As our modeling effort has progressed we concentrated increasingly on the equilibrium and non-equilibrium metamorphic processes that led to Flow Separation necessary to allow subducting continental material to detach from the negatively buoyant lithospheric slab and thereby reduce the uncertainty in trajectories introduced by rheologically monstrous behavior. Using the formulation introduced earlier (Koons et al., 2003) we have demonstrated that the step from sub-critical to super-critical in Grashof space (~ Buoyancy forces/Viscous forces = Gr = L^3g/μ^2Δρ^2) is sensitively dependent upon reaction rate in the densifying, eclogite forming reactions (Rodda et al, 2007). From experimental and natural observations, our collaborator, Dr M Terry, has substantiated the emerging view that the viscosity of high pressure omphacitic pyroxenes is lower than initially assumed. This lowered viscosity permits Flow Separation during the downward trajectory of the slab even though the same reactions increase the density of the crustal assemblages. Dr Terry has made significant advances in understanding the links among deformation and diffusion leading on from work earlier pursued by Koons in high pressure assemblages of the Western Alps (see list below)

The combined petrological, mechanical, and experimental approaches are yielding sufficient information that we can constrain the extent of rheological monsters and have some confidence in generalizing our findings from this grant to the rest of the earth via the SE GCM formulation.

We have identified a serious lack of information on one of the critical driving forces:
To what extent did the felsic crustal assemblages, that constitute the volumetric majority of the Western Gneiss, equilibrate to high and
Because the buoyancy driving force of the crustal material differs greatly as a function of the progression of the eclogitisation reactions, our calculations of flow separation are strongly dependent on our knowledge of the natural extent of this reaction. (Figures in attached report)

**Training and Development:**
Koons employed software formulations that he had developed for this project using the COMSOL platform in teaching at the NSF funded ISES Tectonic Exhumation in Colorado Springs, July 27-August 3, 2007. The ease of use and simple graphical user interface permitted ~ 20 senior graduate students from the US and overseas to investigate 2D and 3D mechanical and thermal problems. We believe that this was a very effective means of spreading quantitative knowledge throughout the tectonic community and bring solutions of higher order partial differential equations to the geological community.

The mechanical modeling and visualization software and hardware purchased and developed in part by this proposal has been used within the Numerical Facility for Geodynamics by ~ 10 undergraduate students from the University of Maine in 2007 and ~ 5 graduate students. In 2007-2008, we are currently scheduled to have graduate students and faculty visit from Lehigh University, University of Washington, Bates College, provisionally from Virginia Tech and University of Texas to use numerical modeling facilities for numerical exploration of subduction related mechanical problems.

**Outreach Activities:**

**Outreach**
The numerical and analog results have been widely used in outreach in presentations to K12 groups, undergraduate students (ERS 200, ERS 417, ERS 416, ERS 103) and graduate classes (ERS 602). Koons has used the analog modules in presentations at several undergraduate institutions in the state including: Colby College, Bates College, and University of Maine Farmington.

This proposal has funded 4 undergraduate students (Lee Wilson, Calvin Beebe, Dan Phillips, Nathan Mietkiewicz) from the University of Maine to work within the Numerical Facility at the University of Maine on modeling and visualization of results related to crustal subduction. Koons was an Invited Professor; Integrated Solid Earth Sciences; NSF- funded short course on Tectonic Exhumation in Colorado Springs, July 27-August 3, 2007 where the role of reaction in the balance of subduction and exhumation formed the main topic of his presentations.

Rodda is completing a GIS version of his field map to provide NGU with a digital version for compilation. (Due to family difficulties, completion and submission of the MSc thesis of C. Rodda with associated NGU map, expected 12/15/07, has been delayed. Currently we expect that Rodda will complete his requirements by 6/1/08.)

**Journal Publications**

Upton, P. Koons, P.O., "Three-dimensional geodynamic framework for the central Southern Alps, New Zealand; Integrating geology, geophysics and mechanical observations."
In: A continental plate boundary: Tectonics of South Island, New Zealand. AGU Geophysical Monograph Series 175, p. 253-270, vol. 175, (2007). Published,


Terry, M.P. and Heidelbach, F.,, "Deformation-enhanced metamorphic reactions and the rheology of high-pressure shear zones, Western Gneiss Region, Norway,", Journal of Metamorphic Geology, p. p. 3-18., vol. 24, (2006). Published,


Groome, W.G., Koons, P.O. and Johnson, S.E., "Metamorphism, transient mid-crustal rheology and the exhumation of high-grade metamorphic rocks.", Northeast Section Meeting, Geological Society of America, p . vol. , (2006). Published,

**Books or Other One-time Publications**

**Web/Internet Site**

URL(s):
http://www.geology.um.maine.edu/geodynamics/AnalogWebsite/Projects2005/Rodda_2005/index.html

Description:
This website contains results, descriptions and animations of scaled analog results of subduction, flow separation and exhumation. We use this site in teaching at undergraduate, graduate and k12 levels and it is accessed by numerous other earth science instructors.

**Other Specific Products**

**Contributions within Discipline:**
Discipline specific: Mechanics and Metamorphic petrology
We have produced the only fully three-dimensional solution currently available that can explore the coupled thermal and mechanical behavior of a continental subduction zone.
In addition we have helped to define the mechanical problem of continental subduction in terms of non-equilibrium petrological processes. In taking this approach, we have identified that the rheological behavior of the deep crust is inextricably linked to metamorphic transitions.

**Contributions to Other Disciplines:**

**Contributions to Human Resource Development:**
Koons employed software formulations that he had developed for this project using the COMSOL platform in teaching at the NSF funded ISES Tectonic Exhumation in Colorado Springs, July 27-August 3, 2007. The ease of use and simple graphical user interface permitted ~ 20 senior graduate students from the US and overseas to investigate 2D and 3D mechanical and thermal problems. We believe that this was a very effective means of spreading quantitative knowledge throughout the tectonic community and bring solutions of higher order partial differential equations to the geological community.

**Contributions to Resources for Research and Education:**
The analog modeling site has been used as a resource for defining the nature of UHPM formation at Graduate, Undergraduate and K12 levels.
http://www.geology.um.maine.edu/geodynamics/AnalogWebsite/Projects2005/Rodda_2005/index.html

**Contributions Beyond Science and Engineering:**
Categories for which nothing is reported:

Any Book
Any Product
Contributions: To Any Other Disciplines
Contributions: To Any Beyond Science and Engineering
Activities and Findings

Activities

(This grant was originally proposed as a joint German DFG: US NSF project with overseas associates P. Robinson, NGU, Norway, and M Terry, Bayerisches Geoinstitut, Germany. Both associations have been productive. Although Terry left Bayerisches Geoinstitut before receiving DFG funding for this project, he, along with Robinson, advised our student and Terry worked in our numerical laboratory, using our facilities and contributing to several publications listed below).

Fieldwork:

Upton: 5/30/06-6/10/06; Trondheim with P Robinson and S Buiter (NGU); Student Supervision in Western Norway with P Robinson and C. Rodda

Koons: 8/16/07-8/27/07: Student Supervision of C Rodda and Field observations with P Robinson (NGU) and C Rodda.

Rodda: 5/30/06-8/17/06: Field mapping of Western Gneiss Terrain collaborating with P Robinson and following suggestions of M Terry

Our field season in western Norway was successful with C Rodda spending ~ 12 weeks mapping the transition from subduction to exhumation structures at the margins of the UHP terrains (Figure 1).

Numerical Modeling

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Findings

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A crucial step in the formulation of SE GCM has been the identification and quantification of reaction-influenced mechanics. Indications are that the further in PT space an assemblage is removed from equilibrium, the greater potential extreme discontinuous changes in viscosity associated with kinetics influencing both nucleation and growth leading to what we defined as Rheological Monsters.

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The combined petrological, mechanical, and experimental approaches are yielding sufficient information that we can constrain the extent of rheological monsters and have some confidence in generalizing our findings from this grant to the rest of the earth via the SE GCM formulation.

We have identified a serious lack of information on one of the critical driving forces:

To what extent did the felsic crustal assemblages, that constitute the volumetric majority of the Western Gneiss, equilibrate to high and ultra-high pressure assemblages? Because the buoyancy driving force of the crustal material differs greatly as a function of the progression of the eclogitisation reactions, our calculations of flow separation are strongly dependent on our knowledge of the natural extent of this reaction.
**Field and Laboratory petrological results**

Thermobarometric studies of the exhumed ultramafic eclogite pods from the Nordfjord, Soroyane and Nordoyane areas place tight time constraints on subduction, UHP metamorphism and exhumation, with all but the final phase of exhumation occurring in ca. 12 million years. However, few structures apparently related to the descent phase of terrane evolution were observed during field studies. Rather, ubiquitous quartz-rod lineation and pervasive minor folding indicate top-to-the-west, relatively shallow unroofing of the subducted margin as indicated in a new bedrock map of a portion of the Norwegian coast. Many of the mapped units have been re-described, with emphasis put on those features that are of interest to the geophysical community.

**Outreach**

The numerical and analog results have been widely used in outreach in presentations to K12 groups, undergraduate students (ERS 200, ERS 417) and graduate classes (ERS 600). Koons has used the analog modules in presentations at several undergraduate institutions in the state including: Colby College, Bates College, and University of Maine Farmington.

Koons was an Invited Professor; Integrated Solid Earth Sciences; NSF- funded short course on *Tectonic Exhumation* in Colorado Springs, July 27-August 3, 2007 where the relationship between exhumation and reaction formed the main topic of his presentations.

Cooperation with Norwegian earth scientists, predominantly those with NGU affiliations, was established early in the field season and expanded with joint field trips with P Robinson (NGU). In addition, Upton presented a lecture at the Goldschmidt Lecture Series at NGU on 3D modeling. Dr Michael Terry, originally at Bayreuth and currently at South Dakota School of Mines, has been a fundamental collaborator on this project, interacting on field, modeling and theoretical issues has provided lectures and worked with students in Europe and the U S.

Rodda is completing a GIS version of his field map to provide NGU with a digital version for compilation.

*(Due to family difficulties, completion and submission of the MSc thesis of C. Rodda with associated NGU map, expected 12/15/07, has been delayed. Currently we expect that Rodda will complete his requirements by 6/1/08.)*

**Presentations and Publications**

**Publications**


Excursion guidebooks and articles:


Presentations


Rodda, Charles Ingalls; Koons, Peter; Johnson, Scott. Modeling ultra high pressure terrane evolution; initial results. Geological Society of America, Northeastern Section, 41st annual meeting, Camphill, PA, United States, March 20-22, 2006
Upton, P., 1st June 2006, Goldschmidt Lecture Series at NGU, Title: Three-dimensional geodynamic modeling of the Southern Alps of New Zealand: Integrating models and observations to understand crustal rheology and Three-dimensional modeling of continental subduction and the evolution of Ultra High Pressure metamorphism


Contributions

Discipline specific: Mechanics and Metamorphic petrology

We have produced the only fully three-dimensional solution currently available that can explore the coupled thermal and mechanical behavior of a continental subduction zone.

In addition we have helped to define the mechanical problem of continental subduction in terms of non-equilibrium petrological processes. In taking this approach, we have identified that the rheological behavior of the deep crust is inextricably linked to metamorphic transitions.

Human Resources:

Koons employed software formulations that he had developed for this project using the COMSOL platform in teaching at the NSF funded ISES Tectonic Exhumation in Colorado Springs, July 27-August 3, 2007. The ease of use and simple graphical user interface permitted ~ 20 senior graduate students from the US and overseas to investigate 2D and 3D mechanical and thermal problems. We believe that this was a very effective means of spreading quantitative knowledge throughout the tectonic community and bring solutions of higher order partial differential equations to the geological community.
FIGURES REFERRED TO IN TEXT

Figure 1

Figure 2
Figure 3

Figure 4
Figure 5: Three dimensional model of continental subduction developed using FLAC$^{3D}$.  
A: geometry used based on a generalised subduction zone. Upper crustal material has been subducted to depths of 125 km. The dashed box shows the location of the cross-sections shown in B, C, D and E.  
B: x velocity, red is material moving to the right and blue is material moving to the left. The upper crustal material that has been subducted forms a ‘channel’ in which it moves upward (C) and back towards the top of the subducting slab.  
C: vertical (z) velocity, red is material moving upward and blue is downward motion. The upper crustal material that has been subducted is moving upwards under its buoyancy.  
D: velocity vectors.  
E: Shear strain rate showing high strain zones on both edges of the subducted block of upper crustal material. The highest strain rate is found on its upper edge.
**Results**

Field Work: Throughout the field area, a northeast to southwest trending mineral lineation is nearly ubiquitous (Figure 1, 2). It is variably defined in the exposed bedrock units, ranging from mm-scale biotite lineation to dm-scale quartz rodding. Plunge is generally shallow to the northeast, though in places the lineation plunges shallowly to the southwest. This lineation has been observed throughout the area, and is thought to be related to late stage exhumation. It overprints all other local fabrics.

Numerical Modeling: The geometry of our present class of numerical models together with initial results are given in Figures 3, 4. This specific class of model is intended to test the hypothesis of the role of passive margin leading edge as a critical factor in the subduction of continental crust. In the results diagram, vertical displacement of subducted buoyant crustal material demonstrates the essence of separation at higher Grashof numbers.

Analog Modeling: In addition to the general flow patterns exhibited in the analog models, some insight was gained into the relative importance of boundary versus rheological conditions on kinematics of the crustal wedge both during subduction and during exhumation. Results and demonstrations are available at: [http://www.geology.um.main.edu/geodynamics/AnalogWebsite/Projects2005/Rodda_2005/index.html](http://www.geology.um.main.edu/geodynamics/AnalogWebsite/Projects2005/Rodda_2005/index.html)
Figure 3

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strain zones on both edges of the subducted block of upper crustal material. The highest strain rate is found on its upper edge.