

2014 CIG Mantle and Lithospheric Dynamics Workshop
4-8 May 2014
Banff Park Lodge
Banff, Alberta Canada

Agenda

Sunday, May 4

- 4:00p** Registration
- 6:00p** Plenary Session
- 8:30p** Ice Breaker

Monday, May 5

- AM** **8:15** Welcome
- 8:30** *Twenty years: Looking Back and Looking Forward*, Louis Moresi
- 9:15** *Scientific Drivers for High-Resolution Non-Newtonian Subduction Modeling*, Margarete Jadamec
- 10:00** Break
- 10:30** Poster Pop-ups – Computational Modeling
- 11:15** *Mantle Convection Simulation in ASPECT*, Timo Heister
- noon** Lunch
- PM** **1:30** *Recent Advances in Modelling Thermo-chemically Coupled Magma Dynamics in a Visco-elasto-plastic Rock Matrix*, Tobias Keller
- 2:15** Future Directions (*discussion*)
- 3:00** Break
- 3:30** General Poster Session
CGU Solid Earth (*concurrent talks*)

---- dinner on your own ----

- 7:30** ASPECT Tutorial

Tuesday, May 6

- AM** **8:30** *Differentiation Processes in the Early Earth and Their Impact on the Evolution of Mantle Convection*, Ulrich Hansen
- 9:15** *Convection Modeling Versus Thermal History Energy Balance*, Scott King
- 10:00** Break
- 10:30** Poster Pop-ups – Mantle Convection
- 11:15** *Controls on Long-wavelength Mantle Structure and Plate Motions and Their Implications for Evolution of the Earth's Mantle Structure Since the Early Paleozoic*, Shijie Zhong
- noon** Lunch
- PM** **1:30** *Paleozoic Plate Motion History and the Longevity of Deep Mantle Heterogeneities*,

Abigail Aller
2:15 Future Directions (*discussion*)
3:00 *Break*
3:30 Poster Session
CGU Solid Earth (*concurrent talks*)

evening CGU Banquet

Wednesday, May 7

AM **8:30** *The Roles of Magmatism, Fault Strength and Crustal Flow in Lithospheric Extension,*
Roger Buck
9:15 *Continental Subduction and (ultra)High-pressure Rock Exhumation: Contrasting*
Numerical Models Based on the Alps and Caledonides, Jared Butler
10:00 *Break*
10:30 Poster Pop-ups – Lithospheric Evolution
11:15 *Implication of Flow in the Lower Crust on Strain Localization Across Time and Length*
Scales, Laetitia Le Pourhiet

noon *Lunch*

PM **1:30** *3-D Geodynamic Models of the India-Eurasia Collision Zone: Investigating the Role of*
Lithospheric Strength Variation, Lucy Flesch
2:15 Future Directions (*discussion*)
3:00 *Break*
3:30 Poster Session
CGU Solid Earth (*concurrent talks*)

List of Abstracts

MONDAY, MAY 5: Advancing the state of the art in computational modeling of mantle and lithosphere dynamics

Keynote

1. Louis Moresi *Twenty years: Looking Back and Looking Forward*
2. Margarete Jadamec *Scientific Drivers for High-Resolution Non-Newtonian Subduction Modeling*
3. Timo Heister *Mantle Convection Simulation in ASPECT*
4. Tobias Keller *Recent advances in modelling thermo-chemically coupled magma dynamics in a visco-elasto-plastic rock matrix*

Posters

- Arrial, P-A. *On the sensitivity of 3D thermal convection codes to numerical discretization: A model intercomparison*
- Butler, S.L *Mantle Convection Modelling Using Comsol Multiphysics*
- Huettig, C. *Proper velocity interpolation for viscosity-carrying particles*
- May, D. A. *An Efficient Implementation of a $Q_2 - P_1$ Finite Element Discretisation and Preconditioner for Variable Viscosity Stokes Problems*
- Qin, C. *A perturbation method and its application: elastic tidal response of a laterally heterogeneous planet*

TUESDAY, MAY 6: New insights from mantle convection modeling: Exploring mantle dynamics from the lithosphere to the base of the mantle

Keynote

1. Ulrich Hansen *Differentiation Processes in the Early Earth and their Impact on the Evolution of Mantle Convection*
2. Scott King *Convection Modeling Versus Thermal History Energy Balance*
3. Shijie Zhong *Controls on Long-wavelength Mantle Structure and Plate Motions and Their Implications for Evolution of the Earth's Mantle Structure since the Early Paleozoic*
4. Abigail Aller *Paleozoic Plate Motion History and the Longevity of Deep Mantle Heterogeneities*

Posters

- Arredondo, K. *Dynamic Linkages Between the Transition Zone & Surface Plate Motion in 2D Models of Subduction*
- Conrad, C.P. *Dynamic Topography and Sea Level above Stable Antipodal Mantle Upwellings*
- Heron, P.J. *Influences on the positioning of mantle plumes following supercontinent formation*
- Hu, J. *Investigating Mechanisms of South American Flat Subduction*
- Li, M. *Three dimensional morphology and dynamics of ultra-low velocity zones*
- Liu, X. *Influence of Chemical Piles on Convective Structure and the Geoid from 3D Spherical Mantle Convection Models*
- Maguire, R. *Modeling laboratory plumes with numerical techniques: validation, verification and the determination of specific heat*
- Nakagawa, T. *Deep mantle structures and CMB heat flux derived from surface plate motions*
- O'Farrell, K.A. *Thermal structure in large lower mantle viscosity convection models*
- Plesa, A. *The role of non-Newtonian rheology on the thermal evolution of stagnant-lid bodies*
- Rosas, J. *Three-Dimensional Thermal Structure of the Central America Subduction Zone*
- Trim, S.J. *Effect of continental lithosphere and deep mantle compositional heterogeneities on the surface mobility of terrestrial planets*
- Volk, K.E. *Generating 3D Models for the Alaska-Aleutian Subduction System*
- Zhou, Q. *Oceanic asthenosphere subduction and intraplate volcanism*

WEDNESDAY, MAY 7: Geodynamics of lithosphere evolution: Numerical models and observational constraints

Keynote

1. Roger Buck *The roles of magmatism, fault strength and crustal flow in lithospheric extension*
2. Jared Butler *Continental subduction and (ultra)high-pressure rock exhumation: contrasting numerical models based on the Alps and Caledonides*
3. Laetitia Le Pourhiet *Implication of flow in the lower crust on strain localization across time and length scales*
4. Lucy Flesch *3-D geodynamic models of the India-Eurasia collision zone: investigating the role of lithospheric strength variation*

Posters

- Adam, C. *Seafloor subsidence and mantle dynamics*
- Ahamed, S. *Incorporating elastic and plastic work rates into energy balance for long-term tectonic modeling*
- Currie, C. *Gravitational removal of magmatic arc roots in Cordilleran orogens*
- Feng, L. *Evolution of multiple décollements in a thrust system: A numerical approach*
- Green, A.M. *Interpretation of EarthScope Magnetotelluric Data for the Northwestern United States*
- Holt, A.F. *Mantle flow and overriding plate stress state in 3-D models of thermo-mechanical subduction*
- Liu, S. *Farallon Plate subduction dynamics and the Laramide orogeny: Numerical models of flat subduction*
- Miller, M.S. *Lithospheric structure of northwest Africa: Insights into the tectonic history and influence of mantle flow on large-scale deformation*
- Wang, H. *What Resists Orogenic Shortening: Topography or Mantle Lithosphere?*
- Wu, G. *The origin of core complexes in the US Cordillera and the Aegean*

Abstracts

Advancing the state of the art in computational modeling of mantle and lithosphere dynamics

The use of numerical modeling to understand geological processes has a long and rich history in the Earth sciences. Through continual exposure, education and the ever increasing availability of large scale computer resources, the computational geodynamic community continues to develop at an ever increasing rate. This session highlights computational advances in all areas related to numerical modeling the dynamics of the lithosphere, mantle and fluid/melt transport. We seek contributions from all aspects of geodynamic computations including: accurate, robust multiscale discretizations; development of efficient, scalable solvers; utilization of next generation hardware; efficient and flexible implementations for the community; data assimilation with uncertainty quantification and techniques for three-dimensional visualization of big data.

Twenty years: Looking Back and Looking Forward

Louis Moresi^{1,2}

¹School of Earth Sciences, University of Melbourne, Melbourne, Australia,

²Seismological Laboratory, Caltech, Pasadena, CA (Visitor)

louis.moresi@unimelb.edu.au

ABSTRACT

In geodynamics, there has been a very long history of innovation in numerical methods and implementation that goes hand in hand with scientific breakthroughs. This would be true of any of the long lasting software packages in geodynamics, but CITCOM has been especially favoured by the geodynamics community and we can learn many lessons by looking back at the developments of various branches of the CITCOM family tree over the past 20 years.

Two main branches of development have been 1) to tackle global, compressible convection problems with high-resolution, parallel spherical models (CITCOMS) with realistic geometry, workflows connecting to global datasets, and long equilibration times; and 2) to look at complex rheology including history dependence, elasticity, anisotropy (ELLIPSIS, UNDERWORLD).

Increasingly it is possible to meet both these requirements at once and incorporate other effects such as free surfaces, coupling to surface process models, mineral physics and geological history databases. The use of high performance libraries allows smaller and more flexible codes with features such as adaptivity, flexible solver composition. Mantle models are becoming a basic tool of geology, but to really cross into the mainstream, robust data assimilation / solution steering is a necessity.

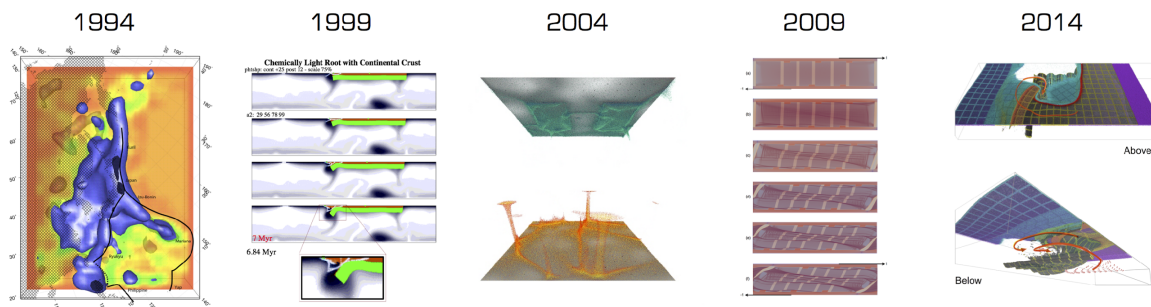


Figure 1 — One branch of the family tree: 20 years of models for Citcom / Ellipsis / Underworld showing a progression in resolution, solver robustness, parallel efficiency, and rheological complexity yet somehow ending up back exactly where we started !

Scientific Drivers for High-Resolution Non-Newtonian Subduction Modeling

M. A. Jadamec¹

¹Brown University, Department of Geological Sciences, Margarete_Jadamec@Brown.edu

Geologic and geophysical observables indicate spatial variations in both the physical properties and morphology of the lithosphere in subduction zones. In addition, rock deformation experiments indicate the uppermost mantle deforms primarily by non-linear viscous flow, implying spatially variable and complex zones of mantle deformation encompassing the subducting slab. The incorporation of both the geometric complexity and non-linearity pose a challenge for mantle convection codes. However, it is these particular features about the Earth that can have a first order effect on subduction dynamics and therefore provide a critical scientific driver to advance both high-performance computing and numerical methods in subduction research. I will present high-resolution 3D numerical models that examine the effect of observationally based slab geometry, multiple subducting plates, and variations in overriding plate thickness on subduction related deformation of plate margins. Specific examples include the Alaska and Central America subduction systems. In addition, I will highlight future directions in subduction modeling, and how these can be advanced by the increased incorporation of observational data, high-performance computing, focused numerical algorithms, and 3D interactive data visualization.

Mantle Convection Simulation in ASPECT

Timo Heister¹

¹Clemson University, Clemson, USA, heister@clemson.edu

ABSTRACT

ASPECT (Advanced Solver For Problems in Earth's convecTion) is a finite element code in development for the simulation of thermal convection in the Earth's mantle. It is a community project developed in the open and supported by CIG.

In this talk we will highlight the modern numerical methods employed for accurate and efficient simulations. This includes higher order discretizations, adaptive mesh refinement, and (non)linear solvers. Even with adaptive mesh refinement, accurate simulations require millions of unknowns to adequately describe the physical phenomena. Scalability tests show that ASPECT can scale to thousands of cores and hundred millions of unknowns and more.

Additionally, we will discuss recent developments in ASPECT regarding compositional fields, compressibility, and simulations performed. Finally, some future plans are discussed.

M. Kronbichler, T. Heister, and W. Bangerth:
High Accuracy Mantle Convection Simulation through Modern Numerical Methods
Geophysical Journal International, 2012, 191, 12-29.

W. Bangerth, T. Heister and others:
Aspect: Advanced Solver for Problems in Earth's ConvecTion.
<http://www.dealii.org/aspect/>, 2014.

Recent advances in modelling thermo-chemically coupled magma dynamics in a visco-elasto-plastic rock matrix

Tobias Keller¹

¹University of Oxford, Department of Earth Sciences, FOALAB, tobias.keller@earth.ox.ac.uk

ABSTRACT

Many prominent geodynamic problems such as subduction zones, plate collision and orogeny formation, mid-ocean ridges, continental rifting, etc. involve a significant amount of active magmatism. However, most numerical simulations used to address such problems focus on the deformation of the solid rock phase only, sometimes taking into account magma dynamics in the form of some parameterization. On the other hand, simulations specifically developed for magma dynamics problems have largely been restricted to the context of mantle dynamics and are not designed to deal with brittle tectonic deformation of the rock matrix as it occurs in a tectonically active lithosphere and crust.

Here, a 2-D finite-element marker-in-cell numerical method is presented capable of simulating thermally and compositionally coupled two-phase flow problems in a realistically deforming mantle, lithosphere and crust. The modelling approach is based on a set of equations for the conservation of mass, momentum, energy and composition, completed by constitutive laws for visco-elasto-plastic shear and compaction stresses and a thermodynamic equilibrium condition describing the simplified petrology of a dunite-basalt system depending on temperature, pressure and composition (SiO_2 content). The simulation code is written in Matlab and is capable of solving up to 500k degrees of freedom (requiring 2m marker particles) within few minutes per time step on a standard desktop computer. Long-term simulations of that size require run times of one to three weeks.

The problems that are currently being addressed with this novel method include the description of modes of melt transport across the lithosphere-asthenosphere boundary (LAB), where the host rock transitions from ductile to brittle modes of deformation. Most notably, the emergence of channeling instabilities around the LAB provides a mechanism for smaller volumes of melt to be extracted on separate pathways from a larger melt source in the asthenosphere, leading to a series of small, confined eruptions on the surface, as it is found in many monogenetic volcanic fields around the world.

On the sensitivity of 3D thermal convection codes to numerical discretization: A model intercomparison

P-A. Arrial¹, N. Flyer², G. B. Wright³ and L. H. Kellogg⁴

¹University of California Davis, Department of Earth and Planetary Science, parrial@ucdavis.edu

²NCAR, Institute for Mathematics Applied to Geosciences, flyer@ucar.edu

³Boise State University, Department of Mathematics, gradywright@boisestate.edu

⁴University of California Davis, Department of Earth and Planetary Science, kellogg@ucdavis.edu

ABSTRACT

Fully 3D numerical simulations of thermal convection in a spherical shell have become a standard for studying the dynamics of pattern formation and its stability under perturbations to various parameter values. The question arises as to how does the discretization of the governing equations affect the outcome and thus any physical interpretation. This work demonstrates the impact of numerical discretization on the observed patterns, the value at which symmetry is broken, and how stability and stationary behavior is dependent upon it. Motivated by numerical simulations of convection in the Earth's mantle, we consider isoviscous Rayleigh-Bénard convection at infinite Prandtl number, where the aspect ratio between the inner and outer shell is 0.55. We show that the subtleties involved in development mantle convection models are considerably more delicate than has been previously appreciated, due to the rich dynamical behavior of the system. Three codes with different numerical discretization schemes are compared: an established, community-developed, and benchmarked finite element code (CitcomS), a novel spectral method that combines Chebyshev polynomials with radial basis functions (RBF), and a new finite element code (ASPECT) using modern numerical methods like adaptative mesh refinement or higher order polynomial degree for temperature and velocity discretization.

A full numerical study is investigated for the following three cases. The first case is based on the cubic (or octahedral) initial condition (spherical harmonics of degree $\ell=4$). How variations in the behavior of the cubic pattern to perturbations in the initial condition and Rayleigh number between the two numerical discretizations is studied. The second case investigates the stability of the dodecahedral (or icosahedral) initial condition (spherical harmonics of degree $\ell=6$). Although both methods converge first to the same pattern, this structure is ultimately unstable and systematically degenerates to cubic or tetrahedral symmetries, depending on the code used. Lastly, a new steady state pattern is presented as a combination of order 3 and 4 spherical harmonics leading to a five cell or a hexahedral pattern and stable up to 70 times the critical Rayleigh number. These tests demonstrate the stability of solutions at different Ra and with different methods, and may prove useful in future efforts to validate and benchmark 3D codes for modeling mantle convection.

Mantle Convection Modelling Using Comsol Multiphysics

S.L Butler¹

¹ University of Saskatchewan, Department of Geological Sciences, sam.butler@usask.ca

ABSTRACT

Comsol Multiphysics is a commercial finite-element modeling package that allows users to build complex numerical models through a GUI or through scripting. Comsol contains some prebuilt physics modules and by combining the Laminar Flow module with the Heat Transfer module, a basic mantle convection model can be created in a matter of minutes. In this poster I will describe some mantle convection simulations that I have used for both teaching and research that were created using Comsol. I will compare the results of the Comsol models with a number of published benchmarks from the literature. I will also show results that include such modeling complexities as mantle phase transitions, depth and temperature-dependent viscosity, mobile rigid plates and cylindrical and 3D geometry.

Proper velocity interpolation for viscosity-carrying particles

C. Huettig¹ and N. Tosi¹

¹German Aerospace Center (DLR) Berlin, christian.huettig@dlr.de

ABSTRACT

Most mantle-convection codes use sophisticated particle methods to track and simulate complex effects like melt, plates or other chemical heterogeneities within a fixed Eulerian system. These effects often alter the viscosity, so the particles carry indirectly viscosity information.

To move a particle within the simulation space, usually the velocities closest to the particle are involved by some kind of linear interpolation, combined with a Runge-Kutta scheme to advance properly in time. For constant viscosity this is a valid assumption, but an unnecessary error is introduced for varying viscosities. The interpolation of the shear part from the velocity field (perpendicular to the viscosity gradient) depends on the viscosity of the particle as well as the viscosities of the velocity nodes.

We derived an analytical formulation to interpolate the shear velocity from Couette-flow. The theoretical difference to pure linear interpolation is visible in the figure, and we will further show the difference in cases of two-phase flow and the effect on entrainment rates for various resolutions.

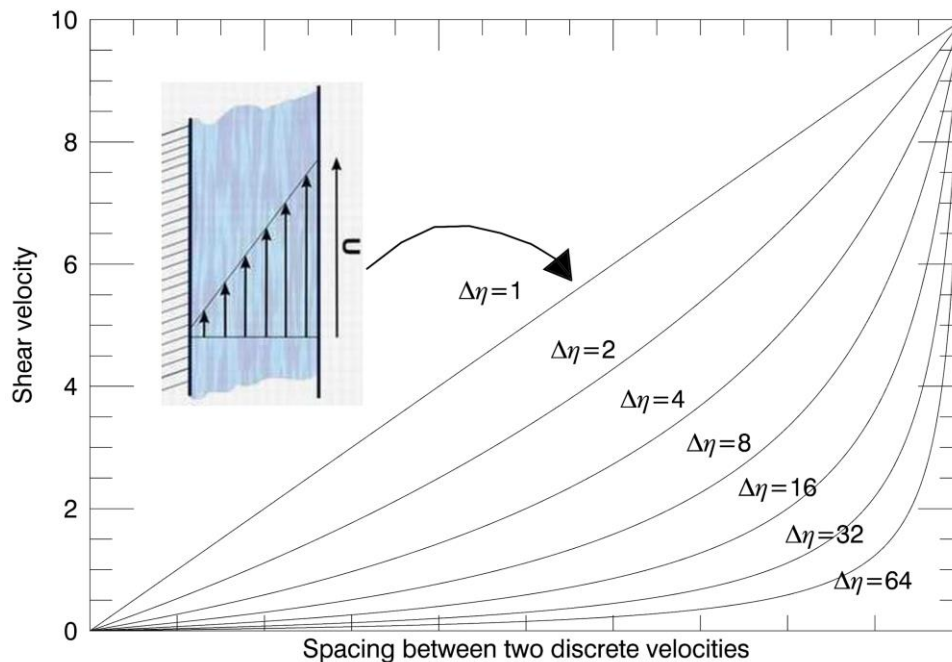


Figure 1: Interpolation between two shear velocities for various viscosity contrasts. The higher viscosity is on the left side.

An Efficient Implementation of a $Q_2 - P_1$ Finite Element Discretisation and Preconditioner for Variable Viscosity Stokes Problems

Dave A. May¹, Jed Brown², Laetitia Le Pourhiet³

¹Institute of Geophysics, ETH Zurich, dave.may@erdw.ethz.ch

²Mathematics and Computer Science Division, Argonne National Laboratory and Department of Computer Science, University of Colorado Boulder, jedbrown@mcs.anl.gov

³ISTEP, UMR 7193, UPMC Universite Paris 6, CNRS, FR-75005, Paris, France, laetitia.le_pourhiet@upmc.fr

ABSTRACT

We describe a numerical method suitable for studying 3D non-linear, large deformation processes associated with crustal and lithospheric deformation. The method employs a combination of mixed finite elements for the flow problem, coupled to the Material-Point-Method for representing material state and history variables. The computational methodology is intended to simultaneously satisfy all of the geodynamic modelling requirements. Particular emphasis is given to the development of non-linear solvers and preconditioners which are performant, practical and highly scalable—thereby enabling high resolution 3D simulations to be performed using massively parallel computational hardware.

We have made a number of fundamental design choices which result in a fast, highly scalable and robust $Q_2 - P_1$ finite element implementation which is suitable for solving a wide range of geodynamic applications. Specifically these choices include: (i) utilizing an inf-sup stable mixed finite element (with a unmapped pressure space) which provides a reliable velocity and pressure solution; (ii) expressing the problem in defect correction form so that Newton-like methods can be exploited; (iii) making extensive use of matrix-free operators that exploit local tensor products to drastically reduce the memory requirements, improve performance by 5–10× to attain 30% of Haswell FPU peak using AVX/FMA intrinsics, and improve on-node scalability of the sparse matrix-vector product; (iv) deferring a wide range of choices associated with the solver configuration to run-time.

The performance characteristics of our hybrid geometric multi-grid preconditioning strategy is presented. The robustness of the preconditioner with respect to the viscosity contrast and the topology of the viscosity field, together with the parallel scalability is demonstrated. We will highlight the benefits of using hybrid coarse grid hierarchies consisting of a combination of Galerkin, assembled and matrix-free operators. The merits of using aggressive coarsening strategies will also be discussed. Examples of 3D continental rifting and visco-plastic folding experiments will be presented to demonstrate the efficiency of the new methodology.

A perturbation method and its application: elastic tidal response of a laterally heterogeneous planet

C. Qin, S.J. Zhong, and J. Wahr

University of Colorado at Boulder, Department of Physics, chuan.qin@colorado.edu

ABSTRACT

Theory has been long established for computing the elastic response of a spherically symmetric terrestrial planetary body to both body tide and surface loading forces. However, for a planet with laterally heterogeneous mantle structure, the response is usually computed using a fully numerical approach. Here, we present a semi-analytical method based on the second-order perturbation theory to solve for the elastic response of a planetary body with lateral heterogeneities in its mantle (i.e. 3-D). We use our perturbation method to study the high-order tidal effects caused by mode coupling between the tidal force and the laterally heterogeneous elastic structure of the mantle.

We apply our perturbation method to compute the tidal response of the Moon in which small long-wavelength lateral heterogeneities are assumed to exist in the elastic moduli of the mantle. The tidal response of the Moon is determined mode by mode, for lateral heterogeneities with different depth ranges within the mantle and different horizontal scales. We show remarkable agreement between our perturbation method solutions and the numerical results from the 3-D finite element code CitcomSVE, thus providing the first true 3-D benchmark for CitcomSVE. In addition to forward calculations, we also adapt our perturbation method for inverse modeling to constrain the long-wavelength elastic structure of the lunar mantle, based on the high-accuracy tidal Love number solutions from the GRAIL mission. The small differences between the GRAIL's degree-2 Love number solutions, i.e. k_{20} , k_{21} , k_{22} , can be attributed to the gravitational tidal effects of a laterally varying Moon. We seek for the longest-wavelength lunar mantle structure that can best fit the GRAIL's k_2 values, by Monte Carlo sampling the amplitude of each eigenstructure. We conclude that our perturbation method provides accurate results, and are more efficient than fully numerical approaches in (1) solving mode couplings, (2) forward calculations of tidal response, and (3) inverse modeling based on space mission data.

New insights from mantle convection modeling: Exploring mantle dynamics from the lithosphere to the base of the mantle

Modeling of mantle convection remains a powerful tool to explore the dynamics of Earth's interior. Moreover, examining distinct convective processes in the mantles of other terrestrial planets, both within and beyond the solar system, has gained increasingly greater attention. This session is intentionally broad in scope, and it aims to cover the full range of new scientific advances obtained through geodynamical modeling, from either numerical or laboratory experiments. We welcome contributions from all areas of mantle convection modeling, covering all regions from the lithosphere to the bottom of the mantle.

Differentiation Processes in the Early Earth and their Impact on the Evolution of Mantle Convection

Ulrich Hansen

Institute of Geophysics, Westfälische Wilhelms-University Munster

Corrensstr. 24, 48149 Munster

Phone: 49251 83 33590, Fax: 49251 83 36100, Email: hansen@earth.uni-muenster.de

Most models of Earth's formation assume a collision of the Earth with a Mars-sized impactor, resulting in a global magma ocean. Differentiation processes during this period are of key importance for the Core-formation and they further determine the initial conditions for mantle convection. Convection in the magma ocean was most likely very vigorous and differed from today's style of creeping flow at least in two aspects. First, due to low viscosity, the flow in the magma ocean is characterized by a low, rather than by a virtually infinite Prandtl number. Further, convection in the magma ocean is, likely to be influenced by rotation. This is again due to the low viscosity and due to the higher rotation rate of the Earth during that period. To study the differentiation processes in a vigorously convection magma ocean being significantly influenced by rotation, we employed a 3D numerical model, which consists of two parts. The fluid model is based on a Finite Volume Discretization and allows for the solution of the equations, describing convection at low Prandtl number under rotation. A discrete element model is used to simulate the behavior of particles within the flow. The particles can form, vanish, shrink or grow. They interact with the flow through gravitational-, drag-, and Coriolis forces. Additionally, they do interact with themselves as modeled by a collision algorithm. The model allows for different tilt-angles of the rotation axis. In this study we examined two scenarios: the case of the rotational axis being aligned with gravity, resembling the situation at the pole, and, the case of the rotational axis being perpendicular to gravity, i.e. the equatorial situation. In both scenarios we studied the effect of different rotation rates on the differentiation process. At the pole, particles are kept in suspension at low rotation rates, while they settle at the bottom of the magma ocean for higher rotation rate. At the equator the picture is more complex: At low rotation all particles settle at the bottom, at higher rotation rate they form a layer of significant thickness and at the highest rotation rate the particles form, a ribbon-type structure in the middle of the box. Obviously, rotation could lead to asymmetrical differentiation of the magma ocean. This can determine the composition of the early mantle and can also explain a localized nature of a dense layer at the Core-mantle Boundary. After Crystallization the scenario is resembled by a compositionally stable stratified mantle, heated from the underlying core. Employing models of double diffusive convection we show, that especially for material with strongly temperature dependent viscosity, layer formation is a generic process. Under these circumstances many commonly assumed features of mantle convection (partially or fully layered, dense hill-like structures at the CMB) do free and easily evolve.

Convection Modeling Versus Thermal History Energy Balance

Scott D. King

Department of Geosciences, Virginia Tech, Blacksburg, VA 24061, USA
Phone: 540-231-9854 Fax: 540-231-3386 Email: sdk@vt.edu

Thermal history calculations are based on balancing the flux of heat into and out of the mantle with the heat generated internally due to the decay of radiogenic elements [1]. In order to generate a tractable equation, a relationship between the surface heat flow and temperature is necessary. Often this is a relationship between the Nusselt number and Rayleigh number and variants of this relationship have been proposed based on both theory and numerical experimentation [1, 2, 3]. The power of thermal history calculations is that they can explore a large parameter space with minimal computational resources; however they provide only an average mantle temperature as a function of time.

3D spherical-shell convection calculations, which solve the conservation of mass, momentum and energy, are becoming increasingly prevalent. However two important aspects of thermal history modeling are infrequently employed in 3D convection calculations: a cooling core boundary condition and decreasing radiogenic heating with time. In many recent investigations the time-span of interest is such that these do not vary significantly.

This raises an interesting question: Just how comparable are thermal history calculations and 3D spherical-shell convection calculations? In this presentation I will compare 3D convection and thermal history calculations with the same properties. These will include temperature and pressure dependent rheology and a 'mobile lid' using the methodology outlined by van Heck and Tackley [4], decaying radiogenic heat sources, and a cooling core boundary condition. Even with advances in computing power, it is unlikely that solving the set of conservation equations will replace thermal history models any time soon. The goal is to assess whether given the same parameters these two formulations will produce a similar temperature history.

[1] Schubert, Turcotte & Olsen (2001) *Mantle Convection in the Earth and Planets*, Ch 13.

[2] Gurnis (1989) *GRL* 16, 179-182.

[3] Solomatov (1995) *Phys. Fluids* 7, 266-274.

[4] van Heck & Tackley (2008) *GRL* 35, L19312.

Controls on Long-wavelength Mantle Structure and Plate Motions and Their Implications for Evolution of the Earth's Mantle Structure since the Early Paleozoic

Xi Liu, Max Rudolph, and Shijie Zhong

Department of Physics, University of Colorado, Boulder, Colorado 80309, USA,
szhong@colorado.edu

Arguably two most important observations about the Earth's dynamics are the present-day degree-2 mantle structure (i.e., two major seismically slow anomalies under Africa and central Pacific that are separated by circum-Pacific seismically fast anomalies) and supercontinent Pangea's assembly and breakup in the last 500 Ma. These observations raise some important questions. What are the mechanisms that control Pangea's assembly and breakup and are responsible for formation of long-wavelength mantle structure? Do we expect degree-2 mantle structure during Pangea time? Mantle convection calculations including plate motion history for the last 120 Ma suggest that these degree-2 structures result from plate subduction history (e.g., McNamara and Zhong, 2005). Mantle convection models with free-slip boundary conditions demonstrate that lithospheric viscosity together with a viscosity increase across the upper mantle may control the formation of the long-wavelength mantle structure (Zhong et al., 2007). Particularly, commonly accepted lithospheric viscosity and upper-lower mantle viscosity increase lead to degree-1 structure formation that may play an important role in supercontinent assembly. This led to suggestion that the Earth's mantle structure may alternate between degree-1 and degree-2 structure, modulated by supercontinent cycle, and that the present-day's degree-2 structure represents a snapshot of this structure evolution following the Pangea breakup (Zhong et al., 2007). This scenario was largely confirmed by models of mantle convection with plate motion history for the last 500 Ma (Zhang et al., 2010).

We have recently expanded these model calculations with both free-slip and imposed plate motion boundary conditions. We found that for Rayleigh numbers and buoyancy numbers that are similar to the Earth's mantle in thermochemical convection models with free-slip boundary conditions, lithospheric viscosity remains the most important control on the long-wavelength structure formation, while the buoyancy number does not affect the results significantly (Liu and Zhong, 2013). In particular, the thermochemical piles appear passive in responding to downwelling flow. There is always significant entrainment for the thermochemical piles in models with buoyancy numbers leading to the piles. Together with other observational constraints such as the geoid, this raises the question whether the piles consist of primordial or dynamically replenished /recycled materials. We also found that three different plate motion history models (Zhang et al., 2010; Lithgow-Bertelloni and Richards, 1998; Muller et al., 2008; Seton et al., 2012) produce nearly identical mantle structure for the present-day (Rudolph and Zhong, 2014). These plate motion models, in their chosen reference frames, include significantly larger net lithospheric rotations prior to 50 Ma than the present-day, that is difficult to be explained in geodynamic models. This suggests that either some new dynamic mechanism is needed to account for the net lithospheric rotation or plate motion history models need to consider better for the effects of true-polar wander and reference frames.

Paleozoic Plate Motion History and the Longevity of Deep Mantle Heterogeneities

A. L. Aller¹, M. Domeier¹, T. H. Torsvik¹⁻³

¹ Centre for Earth Evolution and Dynamics (CEED), University of Oslo, 0316 Oslo, Norway. a.l.bull@fys.uio.no, mathew.domeier@fys.uio.no, t.h.torsvik@geo.uio.no

² Geodynamics, Geological Survey of Norway, 7491 Trondheim, Norway.

³ School of Geosciences, Witwatersrand University, WITS 2050 Johannesburg, South Africa.

ABSTRACT

Numerical studies of mantle convection have attempted to explain tomographic observations that reveal a lower mantle dominated by broad regional areas of lower-than-average shear-wave speeds beneath Africa and the Central Pacific. The anomalous regions, termed LLSVPs (“large low shear velocity provinces”), are inferred to be thermochemical structures encircled by regions of higher-than-average shear-wave speeds associated with Mesozoic and Cenozoic subduction zones. The origin and long-term evolution of the LLSVPs remains enigmatic. It has been proposed that the LLSVP beneath Africa was not present before 200 Ma (i.e. before and during most of the life-time of Pangea), prior to which time the lower mantle was dominated by a degree-1 convection pattern with a major upwelling centred close to the present-day Pacific LLSVP and subduction concentrated mainly in the antipodal hemisphere. The African LLSVP would thus have formed during the time-frame of the supercontinent Pangea as a result of return flow in the mantle due to circum-Pacific subduction. An opposing hypothesis, which propounds a more long-term stability for both the African and Pacific LLSVPs, is suggested by recent palaeomagnetic plate motion models that propose a geographic correlation between the surface eruption sites of Phanerozoic kimberlites, major hotspots and Large Igneous Provinces to deep regions of the mantle termed “Plume Generation Zones” (PGZs), which lie at the margins of the LLSVPs. If the surface volcanism was sourced from the PGZs, such a link would suggest that both LLSVPs may have remained stationary for at least the age of the volcanics. i.e., 540 Myr. To investigate these competing hypotheses for the evolution of LLSVPs in Earth's mantle, we integrate plate tectonic histories and numerical models of mantle dynamics and perform a series of 3D spherical thermochemical convection calculations with Earth-like boundary conditions. We improve upon previous studies by employing a new global plate motion model to impose surface velocity boundary conditions for a time interval that spans the amalgamation and subsequent break-up of Pangea. Our results are distinct from those of previous studies in several important ways: our plate model explicitly includes (i) absolute longitudinal reconstructions and (ii) TPW-correction, and (iii) our model extends back to the mid-Paleozoic (410 Ma). We find that, were only the Pacific LLSVP to exist prior to the formation of Pangea, the African LLSVP would not have been created within the lifetime of the supercontinent. We also find that, were the mantle to be dominated by two antipodal LLSVP-like structures prior to the formation of Pangea, the structures would remain relatively unchanged to the present day and would be insensitive to the formation and break-up of the supercontinent. Our results suggest that both the African and Pacific LLSVPs have remained close to their present-day positions for at least the past 410 Myr.

Dynamic Linkages Between the Transition Zone & Surface Plate Motion in 2D Models of Subduction

K. Arredondo¹, M.I. Billen²

¹University of California, Davis, Dept. of Earth and Physical Sciences, karredondo@ucdavis.edu

²University of California, Davis, Dept. of Earth and Physical Sciences, mibillen@ucdavis.edu

ABSTRACT

The mechanisms for slab stagnation near depths of 660 km and subsequent sinking into the lower mantle remain enigmatic. Possible explanations include the complex mineral physics within the transition zone such as the olivine phase transitions at 410 and 660 km depth and metastable olivine within the cold slab. While laboratory experiments do not support the presence of the latter, they indicate the definite presence of several more phase transitions aside from the two major olivine phase transition that are commonly modeled (e.g., Weidner and Wang, 2000). Other phase transitions are also seismically observed near and within subduction zones (e.g. Thomas and Billen, 2009). The eight major composition-dependent phase transitions for pyrolite, harzburgite and eclogite, may be an important influence on subducting slab dynamics due to the additional forces that are dependent on depth and compositional layering within the slab (e.g., Ricard et al., 2005). Our numerical models test the importance of various factors on slab behavior: compositional layering, the composition-dependent phase transitions, explicit plate speeds versus dynamically evolving plate and trench velocities, the viscosity structure, and the presence of shear, adiabatic and latent heating. Preliminary results indicate possible feedback between different factors, such as large slab folding with the combination of both latent heat and phase transitions. Dynamic models with all the composition-dependent phase transitions are very sensitive to model parameters such as the geometry and viscosity of the plate boundary shear zone. Small variations in these parameters cause large relative changes in plate speeds and in some cases cause slab detachment. This extreme sensitivity stresses the importance of an accurate understanding of phase transitions in the transition zone, where basic parameters such as the Clapeyron slope remain debatable for some mineral transitions. Feedback between a compositionally layered slab and dynamic trench may produce behavior not seen in previous studies and improve our understanding of subducting plate behavior at the surface and within the upper and lower mantle.

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Dynamic Topography and Sea Level above Stable Antipodal Mantle Upwellings

C.P. Conrad^{1*}, B. Steinberger^{2,3}, T.H. Torsvik^{3,4,5}

¹ Dept. Geology and Geophysics, SOEST, Univ. of Hawaii at Manoa, Honolulu, HI 96822, USA

² Helmholtz Cen. Potsdam, GFZ German Res. Cen. for Geoscience, 14473 Potsdam, Germany

³ Centre for Earth Evolution and Dynamics (CEED), University of Oslo, 0316 Oslo, Norway

⁴ Geodynamics, Geological Survey of Norway, NO-7491, Trondheim, Norway

⁵ School of Geosciences, University of Witwatersrand, WITS 2050, South Africa

ABSTRACT

Although convection within Earth's mantle ultimately drives much of Earth's geological evolution, constraints on the history of mantle flow are difficult to obtain because the geometries and magnitudes of past driving forces are difficult to estimate. However, plate tectonic reconstructions, which are becoming increasingly well-constrained, should contain information about the underlying mantle flow that drove plate motions in the past. Although the motions of individual plates can be affected by the specific details of individual plate forces, which can vary significantly in both space and time, long-wavelength forcings on plates may be reflected in patterns of plate motions occurring over length scales longer than those of individual plates. To test this, we measured the dipole and quadrupole moments of present-day plate motions and compared their orientations to the analogous moments of basal tractions exerted on plates in a mantle flow model driven by tomographically-inferred mantle density heterogeneity. We found that both plate motions and net tractions converged in a net sense toward a dipole located in Asia. Similarly, both vector fields indicate quadrupole divergence in both Africa and the equatorial Pacific and quadrupole convergence in southeast Asia and eastern South America. These similarities in dipole and quadrupole orientations indicate that the net characteristics of surface plate motions are reflective of global mantle flow patterns. To constrain temporal variations in mantle flow patterns, we measured the dipole and quadrupole moments of surface plate tectonics as a function of time for three different plate tectonic reconstructions dating as far back as 250 Ma. In all three, we found remarkable stability in the orientations of both the dipole moment and the divergence component of the quadrupole moment, indicating that the locations of net upwelling flow in the Earth's mantle have remained relatively fixed, at least throughout the Cenozoic and Mesozoic.

If these active upwellings are indeed stable, they should support long-wavelength dynamic topography at the Earth's surface. The motions of the continents above this background pattern of dynamic topography should produce changes in sea level as the average dynamic deflection of the seafloor changes with time. We estimate that dispersal of the Pangean supercontinent away from the African upwelling may have exposed the seafloor to an increasingly large area of positive dynamic topography since the early Cretaceous. This trend should cause ~50-100 m of sea level rise during this time period. This component of sea level change helps to balance observations of Cretaceous and Cenozoic sea level change with an estimated total sea level budget that includes concurrent tectonic and climatic influences that produce sea level up to ~250 m of drop.

Influences on the positioning of mantle plumes following supercontinent formation

P.J. Heron¹, J.P. Lowman^{2,1}, C. Stein³

¹University of Toronto, Department of Physics, pjheron@physics.utoronto.ca

²University of Toronto Scarborough, Dept. of Phys. & Env. Sci., lowman@utsc.utoronto.ca

³University of Munster, Institut fur Geophysik, stein@earth.uni-muenster.de

ABSTRACT

Several processes unfold during the supercontinent cycle, more than one of which might result in an elevation in subcontinental mantle temperatures through the generation of mantle plumes. Geodynamic modeling motivated by paleogeographic plate reconstructions have indicated that subcontinental mantle upwellings appear below large continents that are extensively ringed by subduction zones. Moreover, several numerical simulations of supercontinent formation and dispersal show that the genesis of subcontinental plumes follows the formation of subduction zones on the edges of the supercontinent, rather than resulting from continental thermal insulation. However, the influence of the location of mantle downwellings on the position of subcontinental plumes has received little attention.

Using numerical mantle convection models, we examine the evolution of mantle dynamics after supercontinent accretion at a subduction zone (as occurred during the formation of Pangea) considering a range of continental coverage. We present 2D and 3D Cartesian geometry mantle convection simulations, featuring geotherm- and pressure- dependent viscosity profiles with thermally and mechanically distinct oceanic and continental plates. Through changing the size of the supercontinent we are able to analyze the factors involved in the generation of mantle plumes considering purely thermal convection. We also change the upper and lower mantle viscosity contrast to determine its relation to plume formation in simulations of vigorous mantle convection. In additional 3D models, the influence of continental thermal insulation and global subduction zone evolution on the thermal evolution of the subcontinental mantle is also investigated.

Investigating Mechanisms of South American Flat Subduction

Jiashun Hu (jhu16@illinois.edu), Armando Hermosillo, Lijun Liu

Department of Geology, University of Illinois at Urbana Champaign, Champaign, IL

ABSTRACT

Flat-slab subduction is a pronounced tectonic phenomenon occurring at 10% of the convergence plate boundaries today. Causes of flat-slab formation remain debated, where proposed mechanisms include subduction of buoyancy anomalies such as oceanic plateaus and aseismic ridges, dynamic suction from thickened overriding plate, and enhanced subduction speed and reduced seafloor ages. South America represents an ideal place to test these hypotheses, with ongoing flat subduction as well as possible flat-slab scenarios during the geological past. Here, we use geodynamic models with plate kinematics and seafloor ages as boundary conditions to reproduce the history of South American subduction since the Late Cretaceous, during which we attempt to investigate the dynamic causes and impacts of flat subduction. The modeling results will be compared to present-day upper mantle slab geometry through *slab 1.0* [Hayes et al, 2012] and lower mantle structures in several tomography models including *GyPSuM* [Simmons et al, 2010] and S20RTS [Ritsema et al. 1999]. We will present the model setup and some preliminary results.

Three dimensional morphology and dynamics of ultra-low velocity zones

M. Li¹, A.K. McNamara^{2*}, and E.J. Garnero³

¹Arizona State University, School of Earth and Space Exploration, mingming.li@asu.edu

²Arizona State University, School of Earth and Space Exploration, allen.mcnamara@asu.edu

³Arizona State University, School of Earth and Space Exploration, garnero@asu.edu

* Presenting author: A.K. McNamara

ABSTRACT

Seismic tomography results have revealed two large low shear velocity provinces (LLSVPs) in the lowermost mantle beneath the central Pacific and Africa that have been hypothesized to be caused by the presence of long-lived compositional reservoirs. Results from forward waveform modeling also reveal the presence of much smaller ultra-low velocity zones (ULVZs) on the core mantle boundary, with increased density (~10%) and significant drop of seismic velocity. The ULVZs are roughly located near the margins of LLSVPs, with a height in the range of about 5-40 km. ULVZs may be caused by a small volume of high density compositional heterogeneity that may include partial melt. Previous two-dimensional thermochemical geodynamical studies have shown that convection can dynamically support small scale accumulations of ULVZ materials along the margins of larger compositional reservoirs). However, in a three-dimensional geometry it is uncertain whether ULVZs should be uniformly located along the edges of LLSVPs or accumulate into discontinuous patches. Here, we performed 3D high resolution calculations to further explore the morphology and dynamics of ULVZs. We found that ULVZs tend to distribute into discontinuous patches on the core mantle boundary. Both small and large patches of ULVZs are found in our models. While most of ULVZs locate at the edges of LLSVPs, some may stay at the center of LLSVPs temporary because of changing patterns of convection.

Influence of Chemical Piles on Convective Structure and the Geoid from 3D Spherical Mantle Convection Models

Xi Liu¹ and Shijie Zhong²

¹Department of Physics, University of Colorado, Boulder, Colorado 80309, xi.liu@colorado.edu

²Department of Physics, University of Colorado, Boulder, Colorado 80309, shijie.zhong@colorado.edu

ABSTRACT

Classic mantle dynamic models for the Earth's geoid are mostly based on whole mantle convection and constrain that the upper mantle is significantly weaker than the lower mantle. Whole mantle convection models with such mantle viscosity structure have successfully explained the long-wavelength structure in the mantle. However, with increasing consensus on the existence of chemically distinct piles above the core mantle boundary (CMB) (also known as large low shear velocity provinces or LLSVPs), questions arise as to what extent the chemical piles influence the Earth's geoid and long-wavelength mantle convection. Some recent studies suggested that the chemical piles have a controlling effect on the Earth's degree two mantle structure, geoid, and true polar wander, although the chemical piles are estimated to be of small volume (~2% of the whole mantle) by seismic studies.

We have formulated dynamically consistent 3D mantle convection models using CitcomS and studied how the chemical piles above CMB influence the long-wavelength convective structure and geoid. The models have free slip boundary conditions and temperature dependent viscosity. By comparing thermochemical models with purely thermal convection models, we found that the long wavelength convective structure is not sensitive to the presence of the chemical piles. In purely thermal convection, the contribution to the geoid from the bottom layer of the mantle always has the same sign with the total geoid. However, in the thermochemical convection, the bottom layer with overall negatively buoyant chemical piles gives rise to the geoid that has opposite sign with the total geoid, which would be cancelled out by the positive geoid contribution from the layer right above chemical piles. Thus, the geoid from a bottom part of the mantle would give a net contribution of ~0 to the total geoid. The 'compensated bottom mantle' is two to three times as thick as the chemical piles. It indicates that for mantle convection with heavy primordial chemical piles, the geoid is only contributed from upper part of the mantle. In this case, the seismic velocity and density anomalies scaling needs to be reconsidered so that the observed geoid could be accounted for by the upper mantle structure. Our model with two primordial chemical piles yields two geoid highs over the piles, which is consistent with the Earth scenario of geoid highs over Africa and Pacific chemical piles.

Modeling laboratory plumes with numerical techniques: validation, verification and the determination of specific heat

Ross Maguire¹, Peter E. van Keken¹, Madeline Dibble¹, Anne Davaille²,

¹Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI 48109, USA, romaguir@umich.edu

²Laboratoire FAST, UMR 7609, Université Pierre et Marie Curie, Université Paris-Sud XI, CNRS, F-91405 Orsay, France.

Numerical modeling has been used to gain insight into many geodynamic processes, including mantle plume behavior, subduction zone dynamics, and the thermal evolution of the Earth. However, in order to confidently apply numerical modeling techniques to the Earth's interior dynamics, we must seek validation of the methods through comparison between models and physical observations. Direct comparison between numerical and analog experiments provide an important approach to validation since the numerical methods can be tested for problems in the discretization and solution of the governing equations, while laboratory models can be tested for issues in model setup, measurement accuracy, and the determination of approximate form of the constitutive equations.

Here we will discuss numerical simulations of thermal plumes generated in near isoviscous silicon oil and a sugar solution that has a strongly temperature dependent viscosity. This modeling follows the study by *Vatteville et al.* (2009). In this work using silicon oils, a generally good agreement between isotherms and velocity profiles was demonstrated. It was shown that the numerically derived velocities needed to be filtered using an averaging window to mimic the averaging performed in the Particle-Image-Velocimetry technique used to determine velocities in the laboratory fluid. However even with this averaging, the numerical models tend to be systematically faster (see figure below).

In our work we provide a further detailed comparison between laboratory models and high-resolution finite element models that mimic the laboratory set up as closely as possible. We demonstrate that small variations in the constitutive equations significantly influence the plume evolution. We also demonstrate that small variations in specific heat can lead to moderate changes in plume evolution and can explain the differences in timing shown in the figure. We extend this further to sugar solutions where the temperature-dependence of viscosity is significantly higher.

In general the determination of specific heat and its temperature-dependence for laboratory fluids is less precise than that of viscosity, conductivity and density. We provide a systematic study of how variations in specific heat influence the evolution of the numerical plume and we perform a simple Monte Carlo inversion to determine the best fit for specific heat. This suggests that we can use numerical simulations of laboratory plumes to determine fluid properties that are difficult to determine by traditional techniques.

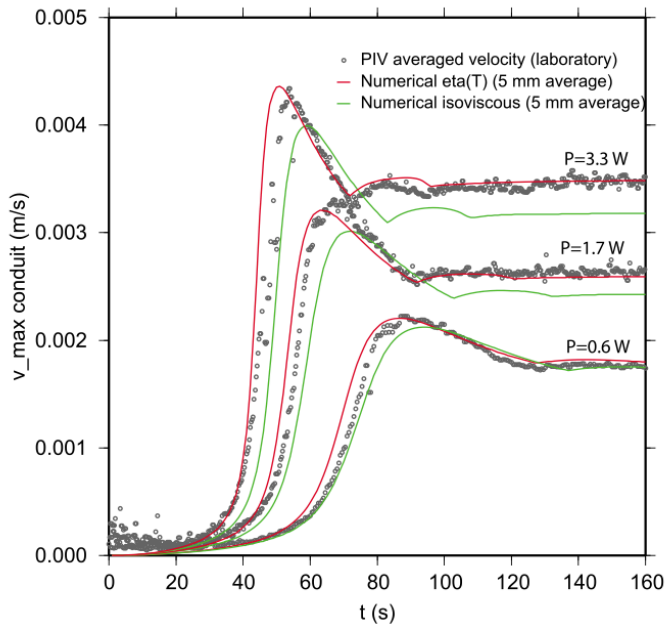


Figure 1: Maximum velocity in plume conduit for numerical and laboratory experiments. In the stage of transient plume development, the numerical models consistently over predict velocity.

*I would prefer a poster presentation for this workshop

Deep mantle structures and CMB heat flux derived from surface plate motions

T. Nakagawa¹, L. Bello², N. Coltice², P. J. Tackley³

¹Department of Mathematical Science and Advanced Technology, Japan Agency for Marine-Earth Science and Technology, Japan, ntakashi@jamstec.go.jp

²Laboratoire de géologie de Lyon, CNRS UMR 5276, Ecole Normale Supérieure de Lyon, Université Claude Bernard Lyon 1, France, lea.bello@ens-lyon.fr, nicolas.coltrice@univ-lyon1.fr

³Institute of Geophysics, Department of Earth Sciences, ETH Zurich, Switzerland, ptackley@ethz.ch

ABSTRACT

We hereby investigate structure and dynamics in the deep mantle and its influence to heterogeneity of heat flux across the core-mantle boundary (CMB) with an extended version of STAGYY [Tackley, 2008] on numerical thermo-chemical mantle convection incorporating into the plate reconstruction database (GPlate) [Bello et al., 2013]. In our previous studies on investigating such topics, we have just assumed the pseudo-plastic rheology or simplified rheology without any geological data in thermo-chemical mantle convection simulations [Nakagawa and Tackley, 2008; Nakagawa et al., 2010]. With those, we could discuss some characteristics of physics and chemistry occurring in the deep mantle but not fully discuss deep Earth's dynamics and structures at the present time. Trying to fully discuss deep Earth's interior at the present time, we use an extended version of STAGYY, that is, the surface velocity from the plate reconstruction database at the present time is imposed into thermo-chemical mantle convection simulations with the simplified phase transition systems or realistic mineral phase diagrams calculated from free energy minimization. Two types of compositional anomalies are assumed here: 1. Initially layered at the base of mantle or surface of mantle and 2. Initially uniform composition but the melt-induced differentiation can generate the oceanic crust. To compare with those cases, isochemical case is also examined here.

The preliminary results suggested that the large-scale heterogeneous anomalies would be likely obtained for thermo-chemical cases but not for isochemical cases, that is, the smaller-scale structure would be dominated. In order to compare with tomographic images, we operated simple resolution filtering for our preliminary results. These filtered anomalies was not very different from those found from full resolution results.

Regarding the scaling relationship between seismic anomalies and CMB heat flux, the post-perovskite effects would be dominated to generate the non-linearity of scaling relationship. The compositional anomalies might work for generating uncertainties to determine the scaling relationship. This may be consistent with cases without imposing surface plate motion provided from the plate reconstruction database [Nakagawa and Tackley, 2008]. More interesting results will be provided in the presentation.

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Thermal structure in large lower mantle viscosity convection models

Keely A. O'Farrell¹, Julian P. Lowman^{2, 1} & Hans-Peter Bunge³

¹ Dept. of Physics, University of Toronto, 60 St. George St., Toronto, Ontario, M5S 1A7, Canada,
Phone: 416-737-0221, Email: ofarrell@physics.utoronto.ca

² Dept. of Physical and Environmental Sciences, University of Toronto Scarborough, 1265
Military Trail, Toronto, Ontario, M1C 1A4, Canada Phone: 416-208-4880;
Fax: 416-287-7279, Email: lowman@utsc.utoronto.ca

³ Dept. of Earth and Environmental Sciences, Ludwig-Maximilian University, Munich University,
Theresienstr. 41, 80333, Munich, Germany, Phone: +49 (89) 2180-4225,
Fax: +49 (89) 2180-4205, Email: bunge@lmu.de
A. Rovelli¹, Y. Ben-Zion², etc. Times New Roman 12 pts plain text centered

ABSTRACT

Plane-layer convection models remain a useful tool for modeling mantle convection in studies featuring large Rayleigh numbers. However, these plane-layer models feature larger mean temperatures than spherical shell systems. It is possible to derive a single equation for predicting mean temperature in uniform property fluids in both plane-layer and spherical shell models. This equation can be used to correctly adjust the plane-layer systems to model the cooler mean temperatures and geotherms observed in spherical shell models. With the inclusion of a depth-dependent viscosity, a single parameterization for mean temperature is not possible in the more complicated systems. A system of parameterizations can be developed for a given depth-dependent viscosity profile in the different geometries. By analyzing the mean temperature of over 100 spherical shell and plane-layer models with a viscosity contrast of 30 and 100 across the mantle, systems of equations for predicting mean temperature are determined. An effective Rayleigh number is defined based on the average viscosity of the mantle, Ra_{η} . The parameterizations for mean temperature, θ , depend on the effective Rayleigh number, Ra_{η} , and internal heating rate, H , and are able to predict mean temperatures to an accuracy of a few percent or better. These systems of equations can be used to derive the correct heating parameters in plane-layer systems to obtain the thermal structure observed in spherical shell models. Increasing the lower mantle viscosity results in a larger difference in mean temperature between the two system geometries. Incorporating the correct heating rate in plane-layer geometry systems is especially important in systems featuring temperature-dependent parameters.

The role of non-Newtonian rheology on the thermal evolution of stagnant-lid bodies

A. Plesa¹, C. Huettig¹, N. Tosi¹ and D. Breuer¹

¹German Aerospace Center (DLR) Berlin, ana.pl;esa@dlr.de

ABSTRACT

Deformation in the mantle of terrestrial bodies is accommodated by diffusion and dislocation creep. While the former likely plays a dominant role at high temperatures and pressures, the latter is thought to be important at relatively low pressures, as inferred by seismic anisotropy of the Earth's upper mantle.

From a numerical point of view, dislocation creep is more challenging to handle than diffusion creep. Being a non-Newtonian mechanism, it renders the viscosity strain-rate dependent, thereby introducing a strong non-linearity that requires much longer computational times. To circumvent this additional complexity, a Newtonian rheology (i.e. diffusion creep) with reduced activation parameters is often used to mimic non-Newtonian behavior. Nevertheless, although this approximation is widely used to model convection in stagnant-lid bodies, it was originally derived for bodies in mobile-lid regime. Furthermore, it implicitly assumes that the entire mantle deforms via dislocation creep, even though both dislocation and diffusion creep are expected to be at play in dependence of local conditions of temperature, pressure and strain-rate (Figure 1).

We perform a series of simulations in 2-D cylindrical and 3-D spherical geometry using our mantle convection code GAIA. We focus on modelling the interior of Mercury, Mars and the Moon as prototypes of stagnant-lid bodies whose mantle covers a relatively limited pressure range over which dislocation creep is generally expected to be dominating. By comparing the coupled thermal evolution of the mantle and core of these three bodies assuming a purely Newtonian, purely non-Newtonian or mixed-rheology, we describe the consequences and assess the limits of validity of the above approximation.

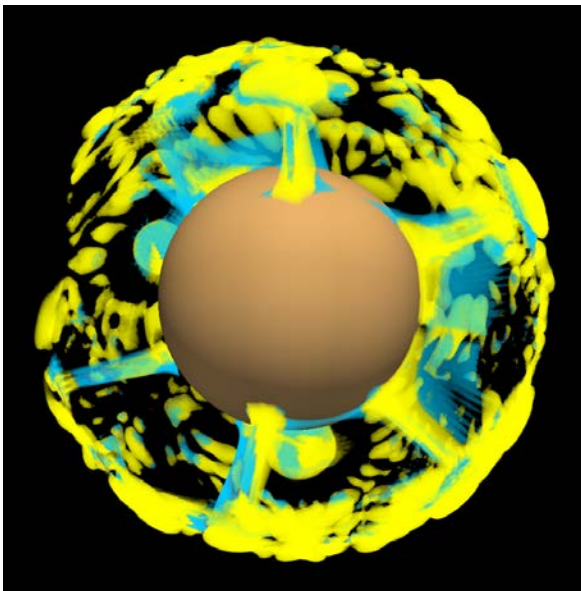


Figure 1: Thermal evolution snapshot using Mars-like parameters and a mixed Newtonian - non-Newtonian rheology. Yellow shows regions where the rheology is dominated by dislocation creep, while areas dominated by diffusion creep are depicted in blue.

Three-Dimensional Thermal Structure of the Central America Subduction Zone

Juan Carlos Rosas¹, Claire Currie², Jiangheng He³

¹ Department of Physics, University of Alberta, Edmonton, AB, T6G2E1
Email: jrosas@physics.ualberta.ca

² Department of Physics, University of Alberta, Edmonton, AB, T6G2E1
Email: claire.currie@ualberta.ca

³ Pacific Geosciences Centre, Canadian Geological Survey, Sydney, BC, 9860 West Saach Road
Email: jiangheng.he@nrcan-rncan.gc.ca

One of the key parameters controlling the thermal structure of a subduction zones is the flow pattern of the mantle wedge. In the context of fluid mechanics, the flow in the wedge is modeled as corner flow, in which the downward motion of the descending oceanic slab drags down the mantle by viscous coupling and sets up a two-dimensional forced-convection flow pattern. However, it is known that variations in the along-strike geometry of the subducting slab can induce a three-dimensional flow that departs from the classic 2D corner flow. Evidence for this three-dimensional flow field comes from seismic anisotropy observations, which have revealed an along-strike flow component in a variety of subduction zones, such as the Central America Subduction Zone. Variations in arc geochemistry along the volcanic arc of Central America further support the existence of a lateral flow.

In this study, we present an analysis of the mantle wedge flow field and thermal structure for the Central America Subduction Zone, extending from South Costa Rica to North Nicaragua. We use 3D numerical models that consist of kinematically-defined subducting and overriding plates, and a flowing mantle wedge driven by drag exerted by the subducting plate. The finite-element code PGCtherm-3D is used to solve the steady-state governing equations for mantle wedge flow and the 3D thermal structure of the subduction zone. Our models employ the most up-to-date subducting slab geometry, which incorporates changes in the dip from approximately 45 degrees offshore the Nicoya Peninsula to 70 degrees in Nicaragua. Using an isoviscous mantle wedge, variations in the geometry of the subducting slab induce a lateral flow with a maximum magnitude of 3.5 cm/yr, nearly 40% of the plate convergence rate (8.5 cm/yr). This lateral flow produces changes in the thermal structure with respect to 2D models, with a difference in temperature exceeding the 100° C in the mantle below the volcanic arc. This change is important, as it might change the degree of melting of the mantle wedge depending on the amount of water released by the subducting slab. Our models also incorporate a three-dimensional oceanic geotherm for the subducting slab that fits the abrupt transition in the thermal structure of the oceanic plate associated with a change from crust generated at the East Pacific Rise and crust generated at the Cocos Nazca Spreading Center. Future models will explore a non-Newtonian, temperature-dependent mantle wedge rheology. The combined effect of a 3D oceanic geotherm and temperature-dependent flow in the wedge is expected to have a strong impact on metamorphic reactions within the oceanic plate, such as the transformation of oceanic basalt into eclogite, as well as the width of megathrust earthquake seismogenic zone.

Effect of continental lithosphere and deep mantle compositional heterogeneities on the surface mobility of terrestrial planets

S.J. Trim¹ and J.P. Lowman²

¹University of Toronto, Department of Physics, strim@physics.utoronto.ca

²University of Toronto Scarborough, Department of Physical and Environmental Science, lowman@utsc.utoronto.ca

ABSTRACT

The surface mobility of terrestrial planets is driven by mantle convection. Consequently, factors affecting mantle flow, such as compositional variations, can impact surface mobility. In the Earth's mantle, there is evidence of deep reservoirs of compositionally enriched material that is denser than the ambient silicates. If compositional heterogeneities exist in the Earth, it is also likely that they exist in other terrestrial mantles.

We have found in previous numerical experiments that for a compositionally heterogeneous mantle, surface mobility is more likely to be maintained if the enriched material is either completely entrained or organized into distinct provinces or piles. Vigorous downwellings tend to sweep enriched material into chemical piles. However, we find it difficult to maintain multiple downwellings if the lithosphere is completely oceanic.

Here, we investigate the interaction between continental lithosphere and compositionally enriched material using numerical models of mantle convection. Composition is tracked using the tracer ratio method. Flow velocities and temperatures are calculated using a hybrid spectral finite difference scheme. Tectonic plates are modeled using the force-balance method. The lithosphere is comprised of both oceanic and continental components. Continental material cannot be consumed at convergent margins, and differs in strength from oceanic lithosphere. In the event of two continental segments colliding, the segments are sutured together to form a single continent. Suture zones have a lower yield stress than ambient continental material.

Continental lithosphere has the potential to affect surface mobility. Continental material is preserved at convergent plate boundaries, which may increase the number of mantle downwellings, leading to the formation of chemical piles and enhanced surface mobility. However, plates can also be consumed more rapidly due to the increased number of convergent margins leading to a decrease in mobility. Results examining the differences in surface mobility in thermochemical calculations with and without continental lithosphere will be described.

Generating 3D Models for the Alaska-Aleutian Subduction System

K.E. Volk¹ & P.E. van Keken²

^{1,2}Dept. of Earth and Environmental Sciences, University of Michigan, Ann Arbor, Michigan

¹Email: kevolk@umich.edu

²Email: keken@umich.edu

It is well established that young, warm subduction zones have shallow earthquakes while old, cold subduction zones experience much deeper earthquakes. There is also strong evidence that intermediate depth seismicity is linked to dehydration reactions within the slab (Schmidt and Poli, EPLS 1998; Hacker et al., JGR 2003; van Keken et al., JGR 2011). However there are still many questions regarding the exact location of dehydration reactions with respects to earthquakes and how well 2D models can represent the dynamics of a 3D subduction zone, especially in situations of oblique subduction. Of particular interest is the Alaska-Aleutian Arc, which is produced as the Pacific Plate subducts beneath North America at roughly 55 mm/yr (DeMets et al., GRL 1994). In Alaska, convergence is nearly trench normal, but trends towards greater obliquity in the western Aleutians. Along much of the Alaska-Aleutian Arc trench parallel splitting is observed, regardless of trench normal or oblique convergence (Yang and Fischer, JGR 1995; Christensen and Abers, JGR 2010). Also there are sudden changes in the distance between the volcanic arc and top of the subducting slab, from ~130 km at the island of Bogoslof, to just ~65 km a short distance west at Seguam island. Understanding the characteristics of the Alaska-Aleutian subduction zone system requires accurate dynamic models. However, with 2D models it is unclear if cross-sections of the subduction zone should be taken perpendicular to the trench or parallel to the convergence direction. 2D models show that temperatures at the top of the subducting slab can vary up ~20°C at a given depth in the western Aleutians depending on the chosen cross-section. The difference is even great at the subducting slab's Moho, ~7 km depth, varying up ~50°C. It is apparent that understanding where dehydration reactions occur in the slab and relating dehydration to intermediate depth seismicity is sensitive to the chosen cross-section. We therefore confirm the conclusions from Bengtson and van Keken, (JGR, 2012) that for subduction zones with oblique convergence we need full 3D models. 3D modeling may also resolve whether toroidal flow occurs in the Aleutian-Alaska subduction system, which has been suggested to be related to the trench parallel shear wave splitting patterns and changes in the slab arc distance. I am working on creating workable 3D finite element meshes for the Alaska-Aleutian Arc using the interactive meshing software Cubit. These models should allow us to resolve the thermal and velocity structure of the Alaska-Aleutian Arc and how 3D flow may occur as convergence trends towards greater obliquity. This work is a part of the GeoPRISMS implementation plan for the Alaska-Aleutian Arc and is funded by that community.

Presentation Preference: Prefer poster presentation

Proposed Session: Solid Earth Session S5

Oceanic asthenosphere subduction and intraplate volcanism

Quan Zhou (qzhou11@illinois.edu), Lijun Liu

University of Illinois at Urbana-Champaign, Department of Geology

ABSTRACT

We investigate the evolution of oceanic asthenosphere during subduction by exploring plausible values of asthenosphere viscosity and density. By comparing with multiple observations, we find that oceanic asthenosphere viscosity is between 2×10^{19} Pa s and 5×10^{19} Pa s. In order to allow slabs to subduct into the deep upper mantle, a maximum oceanic asthenosphere density reduction relative to the underlying mantle should be no larger than 0.7%, assuming a 200-km-thick asthenosphere channel. An important result is that a significant amount (>100 km thick) of oceanic asthenosphere is easily entrained in the underlying mantle beneath the down-going slab, in contrast to an earlier suggestion that negligible amount (<30 km thick) of asthenosphere could get subducted. The recycling of a hot and buoyant asthenosphere thus provides a novel mechanism for the formation of slow seismic anomalies within the deep mantle. This, in turn, questions the commonly believed deep mantle plume origin of intra-plate volcanism, with a typical example being the Yellowstone volcanic system. Our current results suggest that a buoyant asthenosphere can be dragged down into the lower mantle and then moves upward due to its buoyancy when the overlying slab barrier is removed. To further test our hypothesis, we construct a 4D subduction model for western North America during the Cenozoic. We use data assimilation techniques to incorporate plate kinematics and sea floor ages as boundary conditions, and seismic anomalies converted density structure as internal buoyancy source. The subduction history is calibrated through a hybrid of forward and adjoint simulations satisfying multiple observational constraints. Some preliminary results will be presented and implications discussed.

Geodynamics of lithosphere evolution: Numerical models and observational constraints

Numerical modeling has become an important tool for investigating lithosphere dynamics over geological timescales (10^4 - 10^9 years) and for aiding in the interpretation of geophysical and geological observations of lithosphere structure. Advanced models include coupled thermal-mechanical calculations, non-linear rheologies and deformation at a range of spatial scales. Many challenges remain, such as the need to model processes at higher resolution and incorporate surface processes and multiphysics (e.g., two-phase flow). In addition, the relationship between numerical model predictions and observational data is often complex. This session will address the advances and challenges in understanding lithosphere structure and evolution. We welcome contributions that examine lithosphere dynamics from plate margins to plate interiors, as well as studies that explore linkages between lithosphere dynamics, surface erosion/sedimentation, and mantle convection.

The roles of magmatism, fault strength and crustal flow in lithospheric extension

W. R. Buck

Lamont-Doherty Earth Observatory of Columbia University, buck@ldeo.columbia.edu

Continental extension occurs in a variety of ways that produce distinct structures ranging in scale from microscopic fault fabrics up to the ~1000 km width of the Basin and Range Province. The origin of these different structures is quite controversial. Recently collected data and improved numerical models have resolved some of these controversies and brought others into sharper focus. This talk touches on three areas that are not well understood.

The first concerns the role of magma in rifting. One question is why most rifts are magma rich while a few are magma poor? It appears that the breakup of continents is accompanied by massive outpouring of basalt and even large fluxes of intrusives. This may relate to the force needed to tectonically extend normal continental lithosphere (i.e. in the absence of magma) that may be as high as 50 TN/m. The force needed to open dikes cutting through such lithosphere can be an order of magnitude lower and more in line with the estimated magnitude of plate driving forces. The heat emplaced by the dikes eventually weakens the lithosphere so that extension can continue even without additional magma. Numerical models indicate that the amount of magma required for this transition to tectonic stretching is much less than the amount of magma extruded in large igneous provinces. It appears that active mantle plumes or even plume heads are needed to provide the pulse of magmatism to initiate rifting. However, the great volumes of magma emplaced along volcanic passive margins may result from a second stage of melting produced by the passive upwelling of hot mantle as lithospheric stretching occurs.

Another area of recent work focuses on the strength of faults. New data from oceanic core complexes indicates that the related large offset normal faults formed at high dip angles and only the abandoned up-dip section of the faults are rotated to low dips. This means the some so-called low-angle normal faults may not be anomalously weak. New high resolution models of extensional faulting reproduce the blocks of hangingwall that are carried as 'rider blocks' on top of the footwall of a large offset fault. These structures, seen in continental and oceanic core complexes, put narrow bounds on fault strength that are quantified by the numerical models.

New data on the patterns of ductile deformation in metamorphic core complexes has renewed the debate over the roles of local crustal buoyancy versus regional extension to drive core complex formation. Mapping of a radial pattern of crustal flow-related foliation in the D'Entrecasteaux Islands, the youngest known continental core complexes, suggests a role of crustal diapirs rising from a subduction zone. In contrast the foliation pattern in some core complexes in the Aegean Sea indicate compression occurred normal to the extension direction. In both cases 2D and 3D numerical models are shedding light on how these structures form.

Continental subduction and (ultra)high-pressure rock exhumation: contrasting numerical models based on the Alps and Caledonides

J.P. Butler, C. Beaumont, R.A. Jamieson

Departments of Oceanography and Earth Sciences, Dalhousie University, Halifax, NS

ABSTRACT

(Ultra)high-pressure metamorphic ((U)HP) terranes that record the subduction of continental crust to mantle depths (~100 km) are found in many Phanerozoic orogens. Recently, new conceptual tectonic models have been advanced to explain how these terranes were buried to such extreme depths and subsequently exhumed. Our research aims to test these and more traditional models by comparing specific case histories with quantitative predictions from numerical geodynamic models.

Here we use 2D upper-mantle-scale thermal-mechanical finite-element models to explore and compare the dynamics of oceanic and continental subduction and (U)HP terrane exhumation in simplified ‘Alpine-’ and ‘Caledonian-type’ orogens. The requirement for a successful model is that it replicates key constraints on (U)HP terrane exhumation and general orogen-scale evolution from either the Western Alps or Norwegian Caledonides, our case examples. Throughout we show how these ‘working’ model results inform interpretation of geophysical and geological observations concerning the lithosphere-scale evolution of these orogens.

The model results show how differences in the strength of the subducting crust, the duration and scale of orogeny, and driving plate motions can lead to marked contrasts in the nature of burial and subsequent exhumation-related extension. Most differences in the size, pressure-temperature history, and structural evolution of the Alpine and Caledonian (U)HP terranes can be explained by these factors. In the Western Alps, rapid (1-3 cm yr⁻¹) exhumation of small, relatively cold (~500-650°C) (U)HP terranes took place during the early stages of collision, and was accomplished by localized crustal extension during continued orogen-scale shortening. The model results show that this style of syn-orogenic extension and rapid exhumation can be driven by the rapid ascent of buoyant crust from the subduction channel. By comparison, the more voluminous Western Gneiss Region (WGR) (Norwegian Caledonides) underwent high-temperature (~700-800°C) (U)HP metamorphism near the end of the Caledonian orogeny, followed by slow exhumation (~0.5-1 cm yr⁻¹) during orogen-scale extension. These features are explained by a model in which crustal subduction occurs beneath an already hot orogenic wedge, followed by protracted residence at (U)HP conditions. Subsequent slow exhumation of a large (U)HP terrane results from orogen-scale extension driven by gravitational spreading during slowing of convergence and later plate divergence.

These examples can be viewed as end-members in which (U)HP terranes were exhumed at very different times during orogeny by contrasting modes of crustal extension. Observations from other orogens should also be compared with the model predictions. Exhumation by buoyancy-driven flow may apply to other ‘early-orogenic’ (U)HP terranes, whereas large, ‘late-orogenic’ (U)HP terranes may only appear where orogeny was followed by considerable lithosphere-scale extension.

Implication of flow in the lower crust on strain localization across time and length scales

L. Le Pourhiet¹

¹Institut des Sciences de la Terre Paris Univ. Pierre et Marie Curie, laetitia.le_pourhiet@upmc.fr

ABSTRACT

The classical inter-seismic mechanical models of the lithosphere assume that the earth lithosphere is a horizontally layered media with homogeneous rheological properties at a given depth. Recently, less classical models have been proposed in order to include lateral variation of the viscosity underneath fault zone. These models have been shown to be as, and sometimes more, effective at reproducing the geodetic data during the seismic cycle than the simple laterally homogeneous stratified models.

These new models have in common to require a finite width low viscosity zone underneath the fault zone. Proposed explanations for the formation of these localized low viscosity zone includes grain size reduction, shear heating and localized presence of fluids. All these mechanisms are valid in order to locally weaken an initially strong lower crust, however they are not efficient to localize strain across strike slip faults in post-orogenic setting when the lower crust is weak.

I will present results of 3D numerical modelling studies run with GALE, which show that metamorphic core complex are exhumed under transtensional structure in post orogenic setting. Using a parametric approach, I will show that the smaller the width of the step over and the thicker the low viscosity channel in the lower crust is initially, the strongest is the localization. Using a second round of experiment, I will demonstrate that transtensional boundary conditions are sufficient to triggers long lasting weakening of the crust through the exhumation of lower crustal material in post orogenic setting. In both case, the long-term tectonic re-structuration of the crust obtained over long time scale results into localized low viscosity weak zones that develop self consistently beneath strike slip fault zone within the aseismic part of the crust. So that long-term model appear compatible with short-term ones and imply that strain localization in a jelly sandwich lithosphere leads self-consistently to the formation of a "banana split" type rheological structure.

All models, which predict weak material within the fault zone produce long-term secular lateral gradient in surface velocity even with an elastic lid representing the inter-seismic brittle crust placed at the top of the model. This secular gradient still remains even when transients from the last earthquake have vanished from the signal. Trying to interpret this secular gradient as a visco-elastic transient with an inappropriate simplistic model might result in wrong interpretations, including wrong estimates of the viscosity structure of the lithospheric mantle. An Earth's lithosphere rheological model based on some simple physics which is equally valid at all time scale from inter-seismic to orogeny is a good reason to use more complex rheology and geometrical assumptions when modelling short time scale observations, because it is the key of deeper understanding of the state of stress acting on faults.

3-D geodynamic models of the India-Eurasia collision zone: investigating the role of lithospheric strength variation

Sarah Bischoff¹ and Lucy Flesch¹

¹Department of Earth, Atmospheric and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907

ABSTRACT

The India-Eurasia collision zone is the largest zone of continental deformation on the Earth's surface. A proliferation of geodetic, seismic, and geologic data across the zone provides a unique opportunity for constraining geodynamic models and increasing our understanding of mountain building and plateau growth. We present a 3-D, spherical, Stokes flow, finite volume, geodynamic model of the India-Eurasia collision. Lithospheric volume is constrained by seismic data. Continuous surface velocities, inferred from GPS and Quaternary fault slip data, are used to approximate velocity boundary conditions. We assume a stress-free surface, and free-slip along the base. Model viscosity varies with depth and is calculated assuming the laterally-varying, depth-averaged viscosities of Flesch et al. (2001) and a cratonic Indian plate. Laterally the model extends from the southern tip of India northward to the Tian Shan, and from the Pamir Mountains eastward to the South China block. Vertically the model volume extends to a depth of 100 km, and is divided into three layers: upper crust, lower crust, and upper-lithospheric mantle. We use COMSOL Multiphysics (www.comsol.com) to investigate the role of vertical viscosity variation on surface deformation by holding the dynamics constant, adjusting the viscosity substructure, and determining the resultant stress and velocity fields. Solved model surface velocities are compared to the observed surface velocities inferred from GPS and Quaternary fault slip rates. A two-layer model employing laterally-variant viscosity estimates throughout the crust and mantle is ineffective at replicating the observed force balance. The weak crustal viscosities necessary for attaining the observed clockwise rotation around the eastern Himalayan syntaxis also result in erroneous southward velocities in southern Tibet, driven by excessive gravitational collapse. Strengthening crustal viscosities balances the boundary/body forces and allows for accommodation of Indian plate motion across Tibet, but no longer produces clockwise rotation around the eastern syntaxis. The best-fit velocity magnitude and rotation solution is achieved by a full three-layer model incorporating an upper crust of intermediate strength, a weaker lower crust, and a stronger upper mantle. Our three-layer model achieves rotation around the indenter without excessive gravitational collapse. Model and observed velocities diverge slightly in the Tarim Basin, the southern Gobi, and the northern South China block. Model velocities in the Tarim Basin are shifted in an easterly direction; possibly indicating a weaker than previously assumed Altyn Tagh fault, while Gobi and South China model velocities are shifted to the north; suggesting the presence of an additional level of complexity.

Seafloor subsidence and mantle dynamics

C. Adam¹, S. King¹, M. Rabinowicz², V. Vidal³, and A. Jalobeanu⁴

¹Department of Geosciences, Virginia Tech., Blacksburg, VA, USA, ca3@vt.edu, sdk@vt.edu

²GET, Observatoire Midi-Pyrénées, Toulouse, France, Michel.Rabinowicz@irap.omp.eu

³Laboratoire de Physique, ENS Lyon, France, Valerie.Vidal@ens-lyon.fr

⁴ARL UT Austin, USA, ajalobea@nps.edu

ABSTRACT

The subsidence of seafloor is generally considered as a passive phenomenon related to the conductive cooling of the lithosphere since its creation at mid-oceanic ridges. Recent alternative theories suggest that the mantle dynamics plays an important role in the structure and depth of the oceanic lithosphere. However, the link between mantle dynamics and seafloor subsidence has still to be quantitatively assessed. Here we provide a statistic study of the subsidence parameters (subsidence rate and ridge depth) for all the oceans. These parameters are retrieved through the positive outliers method, a classical method used in signal processing. We also model the mantle convection pattern from the S4ORTS tomography model. The density anomalies derived from this model are used to compute the instantaneous flow in a global 3D spherical geometry, and the induced dynamic topography.

The variations of the mid-oceanic ridge depths are well recovered by the modeled dynamic topography. Moreover, the dynamic topography perfectly matches the subsidence trend away from mid-oceanic ridges. The systematic fit of the bathymetry allows the recovery of the subsidence rate, from which we derive the effective thermal conductivity, k_{eff} . This parameter ranges between 1 and 7 $\text{Wm}^{-1}\text{K}^{-1}$. We show that departures from the $k_{eff}=3 \text{ Wm}^{-1}\text{K}^{-1}$ standard value are systematically related to mantle convection and not to the lithospheric structure. Regions characterized by $k_{eff}>3 \text{ Wm}^{-1}\text{K}^{-1}$ are associated with the uplift of mantle plumes. Regions characterized by $k_{eff}<3 \text{ Wm}^{-1}\text{K}^{-1}$ are related to large scale mantle downwellings such as the Australia-Antarctic Discordance (ADD) or the return flow from the South Pacific Superswell to the East Pacific rise. This demonstrates that the mantle dynamics plays a major role in the shaping of the oceanic seafloor. In particular, the parameters generally considered to quantify the lithosphere structure, such as the thermal conductivity, are not only representative of this structure but also incorporate signals from the mantle convection occurring beneath the lithosphere.

Incorporating elastic and plastic work rates into energy balance for long-term tectonic modeling

Sabber Ahamed¹ and Eunseo Choi¹

¹Center for Earthquake Research and Information, University of Memphis,
msahamed@memphis.edu

ABSTRACT

Deformation-related energy budget is usually considered in the simplest form or even completely omitted from the energy balance equation. We derive an energy balance equation that accounts not only for heat energy but also for elastic and plastic work. Such a general description of the energy balance principle will be useful for modeling complicated interactions between geodynamic processes such as thermoelasticity, thermoplasticity and mechanical consequences of metamorphism. Following the theory of large deformation plasticity, we start from the assumption that Gibbs free energy (g) is a function of temperature (T), the second Piola-Kirchhoff stress (\mathbf{S}), density (ρ) and internal variables ($q_j, j=1\dots n$). In this formulation, new terms are derived, which are related to the energy dissipated through plastic work and the elastically stored energy that are not seen in the usual form of the energy balance equation used in geodynamics. We then simplify the generic equation to one involving more familiar quantities such as Cauchy stress and material density assuming that the small deformation formulation holds for our applications. The simplified equation is implemented in DyanEarthSol3D, an unstructured finite element solver for long-term tectonic deformation. Aiming to systematically investigate the sensitivity of temperature field on each of the newly derived terms, we will present preliminary results about the effects of plastic dissipation on the evolution of a large offset normal fault.

Gravitational removal of magmatic arc roots in Cordilleran orogens

C. Currie¹, M. Ducea², P. DeCelles³, and C. Beaumont⁴

¹Department of Physics, University of Alberta, claire.currie@ualberta.ca

²Department of Geosciences, University of Arizona, ducea@email.arizona.edu

³Department of Geosciences, University of Arizona, decelles@email.arizona.edu

⁴Department of Oceanography, Dalhousie University, chris.beaumont@dal.ca

ABSTRACT

Cordilleran orogens, such as those in western North and South America, form where upper plate shortening creates a continental mountain belt above an active subduction zone. Two key observations are: (1) the orogenic lithosphere is generally thin (50-80 km), despite significant crustal shortening (there are local areas of thicker lithosphere), and (2) orogenesis is accompanied by magmatism which produces an andesitic-dacitic volcanic arc and thick (>30 km) granitoid batholiths. These compositions require a multi-stage model of magmatism, whereby mafic magmas generated through subduction-related flux-melting of the mantle wedge stagnate within the continental lithosphere, and subsequent partial melting of lithosphere and magmatic differentiation result in felsic melts that rise upward through the crust. This leaves a high density pyroxenite root in the deep lithosphere that is gravitationally unstable. Removal of this root may then provide a way to thin the orogenic lithosphere (observation 1).

Here, we study the growth and removal of the pyroxenite root using two-dimensional thermal-mechanical numerical models of subduction below a continent. Our goal is to address the dynamics at the scale of the root (1's to 10's of km) and thus we use a two-step proxy model to grow the batholith-root complex during model evolution. First, the position of the volcanic arc is dynamically determined based on subduction zone thermal structure. Second, batholith and root formation is simulated by changing the density of the arc lithosphere at a prescribed rate based on the magmatic flux observed at subduction zones. For the model lithosphere structure, magmatic roots with even a small density increase are readily removed for a wide range of root strengths and subduction rates. The dynamics of removal depend on the relative rates of downward gravitational growth and lateral shearing by subduction-induced mantle flow. Gravitational growth dominates for high root densification rates, high root viscosities and low subduction rates, leading to drip-like removal as a single downwelling over 1-2.5 Myr. At lower growth rates, the root is removed over >3 Myr through shear entrainment, as it is carried sideways by mantle flow and then subducted. In all models, >80% of the root is removed, making this an effective way to thin orogenic mantle lithosphere and (at least partially) resolve the mass problem in Cordilleran orogens.

Evolution of multiple décollements in a thrust system: A numerical approach

Lian Feng¹, Eunseo Choi², Mervin J. Bartholomew³

¹University of Memphis, Department of Earth Sciences, lfeng@memphis.edu

²University of Memphis, Center for Earthquake Research and Information, echoi2@memphis.edu

³University of Memphis, Department of Earth Sciences, jbrthlm1@memphis.edu

Various structures associated with thrust ramps are commonly found in thrust systems of different scales and have received much attention in the southern Appalachian fold-and-thrust belt. Understanding major factors that control formation and evolution of thrust-related structures is important for inferring the original geometry of subsurface structures which, in turn, is useful for balancing cross sections. We employ a novel finite element code for long-term tectonic simulations, DynEarthSol2D (available at <http://bitbucket.org/tan2/dyneearthsol2>), to construct numerical models with two layer-parallel décollements. We quantitatively examine effects of initial geometric configuration on deformation styles of décollements. A 30×15km model domain represents rock in which décollements are embedded and is assumed to be a strain-weakening Mohr-Coulomb plastic material. The décollement is a ~500m-thick zone of a lower cohesion and friction angle than its surrounding rocks. The rock above the lower level décollement, is pushed at 1.6 cm/yr. on the right boundary. Our preliminary model results show that initial spatial arrangements of décollements control a) the timing, b) site of initiation of upward ramping, and c) various styles of fault-related folds. Thrust evolution also exhibits sensitivity to the strain weakening rate: 1) higher rate of strain weakening promotes the formation of a thrust fault with uniform orientation; 2) lower rate of strain weakening promotes lateral propagation of the thrust fault. We further explore a possible spectrum of structures in a thrust ramp both from our model results and previous fieldwork in the southern Appalachian Mountains.

Marie Green
University of Utah
CEMI student

INTERPRETATION OF EARTHSCOPE MAGNETOTELLURIC DATA FOR NORTHWESTERN UNITED STATES

We present the results of large-scale three dimensional magnetotelluric (MT) inversion, based on the nonlinear conjugate gradient algorithm and the contraction integral equation forward modeling method, applied to data collected in Northwestern United States for part of the EarthScope project. The most noteworthy anomalies within the inverse geoelectrical model are resistive structures associated with oceanic lithosphere and cratons, and conductive features associated with mantle upwelling. Density estimations from seismic data analysis show upwelling phenomena in the upper mantle where Yellowstone is the present day surface expression of the deep heat source. Comparison of MT results to approximately 400 km depth have reasonable correlation with P-wave and S-wave velocity models obtained from seismic tomography. Strong resistive zones line up along the northwest coast correlating to recent seismic interpretations of old oceanic slabs at 100 km depth believed to be remnants of the Farrallon oceanic plate. Access to multiple physical properties within the subsurface increases our ability to understand complexities in geological interpretations resulting from the interplay of transforming quanta at differing pressure and temperature regimes with depth. EarthScope is proving true to the founding philosophy that the bold, new experiment will fundamentally change our view of the planet.

Mantle flow and overriding plate stress state in 3-D models of thermo-mechanical subduction

A. Adam F. Holt¹, Thorsten W. Becker¹

¹University of Southern California, Department of Earth Sciences, adamholt@usc.edu

ABSTRACT

The formation of back-arc basins is a fundamental component of plate tectonics, yet the mechanism for their formation, and whether an individual mechanism is dominant over different tectonic settings, is not entirely clear. On top of the classic mechanism of extension being driven by basal tractions due to poloidal return flow, recent studies have indicated that, for slabs with finite widths, toroidal return flow around slab edges plays an important role. We investigate the relative contribution of poloidal and toroidal flow field components to back-arc extension by examining the overriding plate stress regime in conjunction with the flow field for various model setups. We characterize the velocity field by decomposing it into toroidal and poloidal components at various stages of subduction, and calculating the ratio of the toroidal to poloidal RMS velocities (TPR).

Models are carried out using a thermo-mechanical setup of the finite element code, CitcomCU. Fixing the position of either the subducting (SP) or overriding plate (OP) causes the amplitude of back-arc extension to be greater than that for the case when both plates are free. This occurs because, for the OP models, all of the slab rollback is forced to occur at the expense of OP thinning, and for the fixed SP models, increased rollback causes heightened toroidal flow. For models with significant slab rollback, the poloidal RMS velocity is maximum in the very upper and lower portions of the model whereas toroidal flow is maximum at mid-domain depths due to return flow around slab edges, indicating that slab rollback-induced toroidal flow is focused at sub-lithospheric depths, where it has the potential to contribute to back-arc extension. Models with vary narrow plates have vastly reduced slab rollback velocities, yet elevated back-arc extension that is focused closer to the trench. In such models, toroidal flow magnitude is approximately constant throughout the domain, and yet the magnitude of OP extensional stress is large, suggesting an alternate control on back-arc extension for models with near-stationary trenches.

Moving towards heightened realism, we investigate the effect that Byerlee plasticity and laterally confining side plate has on both OP stress state and the TPR. A side plate does not modify the slab dynamics and OP stress state, yet significantly reduces the toroidal RMS velocity component throughout the model, while retaining the systematic variation, which results in a uniformly reduced TPR throughout the domain. The inclusion of plasticity, intended to approximate brittle failure at shallow depths, gives rise to elevated forearc compression, due to increased plate convergence, and reduced backarc extension.

Farallon Plate subduction dynamics and the Laramide orogeny: Numerical models of flat subduction

Sibiao Liu¹, Claire A. Currie²

¹University of Alberta, Department of Physics, sibiao@ualberta.ca

²University of Alberta, Department of Physics, claire.currie@ualberta.ca

ABSTRACT

The Laramide orogeny (~80-50 Ma) in the western United States was contemporaneous with subduction of the Farallon Plate beneath western North America. Most studies conclude that the angle of this subduction was abnormally shallow or even flat during late Cretaceous - Paleocene time, such that the horizontal compressive stress from the low-angle slab produced thick-skinned deformation in Rocky Mountain foreland, more than 1000 km inboard of the plate boundary. However, it is uncertain what factors caused the low-angle subduction during pre-Laramide and Laramide time, or how stress was transmitted to the continental interior. Several mechanisms have been proposed for triggering low-angle or flat subduction: (1) an increase in westward (trenchward) motion of North American plate; (2) an increased slab suction force in the mantle wedge; (3) subduction of a buoyant oceanic plateau; and (4) break-off of oceanic Farallon plate during subduction. In this study, we apply numerical models to investigate these mechanisms, using a model geometry that is analogous to the western United States. The first purpose is to assess the factors needed to dynamically develop low-angle subduction. We find that the main control is the continental velocity, with enhanced slab shallowing as the continental velocity increases. In order to create a section of horizontal subduction beneath the continent, break-off of the deep part of the oceanic plate is needed. A further requirement is the presence of an oceanic plateau with thick non-eclogitic oceanic crust and/or a low-density harzburgite layer. The slab suction force is less efficient at creating a flat slab than the other factors. An analysis of the density structure of the models indicates that the subducting slab can be flattened or overflattened when its average density is at least 17 km/m^3 less than that of the surrounding mantle. Future work will examine variations in the strength of both the continental plate and the interface between the continent and oceanic plate during flat subduction, in order to explore the stress transmission from the flat slab to the Rocky Mountain foreland and determine if this is a viable mechanism for generating Laramide-style deformation.

Lithospheric structure of northwest Africa: Insights into the tectonic history and influence of mantle flow on large-scale deformation

M.S. Miller¹ and T.W. Becker¹

¹University of Southern California, Department of Earth Sciences, msmiller@usc.edu and twb@usc.edu

ABSTRACT

Northwest Africa is affected by late stage convergence of Africa with Eurasia, the Canary Island hotspot, and bounded by the Proterozoic-age West African craton. We present seismological evidence from receiver functions and shear-wave splitting along with geodynamic modeling to show how the interactions of these tectonic features resulted in dramatic deformation of the lithosphere. We interpret seismic discontinuities from the receiver functions and find evidence for localized, near vertical-offset deformation of both crust-mantle and lithosphere-asthenosphere interfaces at the flanks of the High Atlas. These offsets coincide with the locations of Jurassic-aged normal faults that have been reactivated during the Cenozoic, further suggesting that inherited, lithospheric-scale zones of weakness were involved in the formation of the Atlas. Another significant step in lithospheric thickness is inferred within the Middle Atlas. Its location corresponds to the source of regional Quaternary alkali volcanism, where the influx of melt induced by the shallow asthenosphere appears restricted to a lithospheric-scale fault on the northern side of the mountain belt. Inferred stretching axes from shear-wave splitting are aligned with the topographic grain in the High Atlas, suggesting along-strike asthenospheric shearing in a mantle channel guided by the lithospheric topography. Isostatic modeling based on our improved lithospheric constraints indicates that lithospheric thinning alone does not explain the anomalous Atlas topography. Instead, a mantle upwelling induced by a hot asthenospheric anomaly appears required, likely guided by the West African craton and perhaps sucked northward by subducted lithosphere beneath the Alboran. This dynamic support scenario for the Atlas also suggests that the timing of uplift is contemporaneous with the recent volcanism in the Middle Atlas.

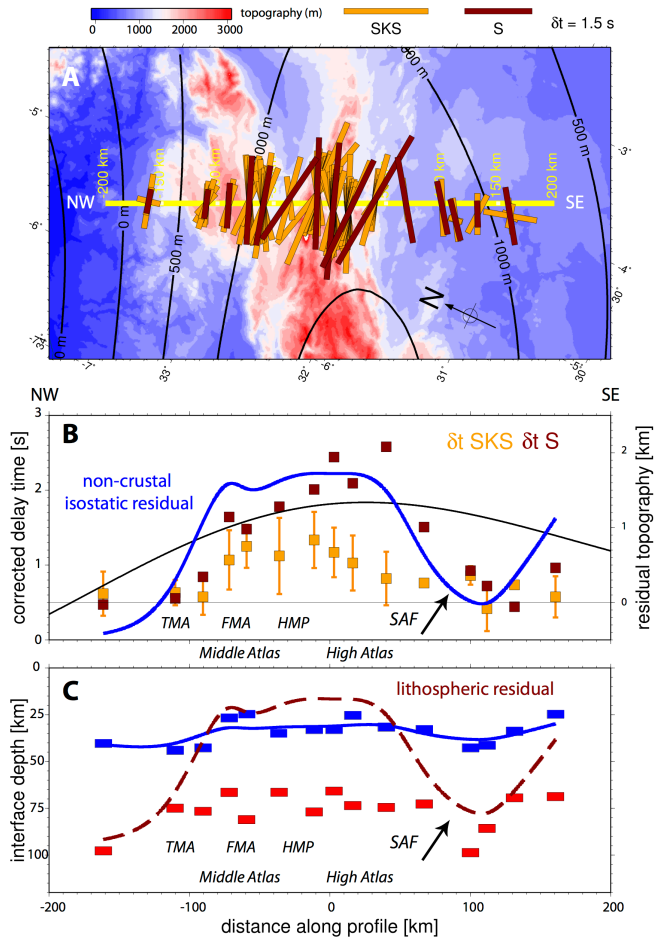


FIGURE: Lithospheric structure and topography across the Atlas. (A) Map of stations (oblique Mercator projection across the Atlas) with $SK(K)S$ splitting in orange and local S splitting in dark red (Miller et al., 2013). Fast polarization orientations and delay times are denoted by stick orientation and length as in legend. Background shading is actual topography and black contour lines show gravity-inferred residual topography and the yellow line indicates the position of the profile in (B) and (C). (B) Above 410 km path-length corrected delay times from splitting measurements along the profile. The black line shows the free-air gravity inferred residual topography along the profile, and blue line denotes residual topography obtained by subtracting a crustal isostatic model from smoothed actual topography. (C) Picks for the Moho (blue dashes) and LAB depths (red dashes) from the S receiver functions (Fig. 2) along the profile. The blue line is a smoothed fit to the Moho depth and used for the crustal residual in (B). Dark red dashed line shows inferred lithospheric thickness from isostasy assuming zero mantle-induced dynamic contribution to the residual topography in (B). The approximate location of the South Atlas Fault (SAF) is shown with an arrow and the tectonic domains along the profile are labeled following the convention in the text and Fig. 1. All spatial smoothing applies a 150 km 6σ width Gaussian filter to reduce the effect of elastic flexure.

What Resists Orogenic Shortening: Topography or Mantle Lithosphere?

Huilin Wang¹ & Claire A. Currie²

¹Department of Physics, University of Alberta, huilin1@ualberta.ca

²Department of Physics, University of Alberta, claire.currie@ualberta.ca

ABSTRACT

Orogens are built by compressional forces which shorten the crust and uplift the surface. Assuming the compressional force (e.g. slab pull or ridge push) is constant, an orogen should not grow infinitely; instead the shortening should slow down or migrate to boundaries of the orogen. Two resistive forces within an orogen have been postulated to balance the external compressional force: topography and mantle lithosphere. As the orogen grows, the higher topography exerts a greater gravitational stress, counteracting further growth. This may cause deformation to move to the low elevation orogen edges, which are areas of lower resistance. The second force comes from lithospheric viscous stresses; as the lithosphere thickens during shortening, it will become progressively more difficult to continue to thicken it. Previous work has shown that both of these factors affect orogen growth. However a third factor that has not been widely studied is the resistive force associated with crustal metamorphism. The formation of dense eclogite in thickened lower crust can reduce surface topography and may trigger foundering of the deep lithosphere, and therefore the overall resistive force will be affected.

Here, 2D numerical models are used to investigate the source of the resistive force and the effects of metamorphic eclogite on orogen growth. We monitor the horizontal force when the upper plate is shortened during orogenesis. First, we focus on the feedback between the resistive force and topography/mantle lithosphere without eclogite formation. Results show: (1) the resistive force is proportional to topography; (2) a strong and thick mantle lithosphere provides a constant resistive force; and (3) the total resistive force depends on both topography and strength of mantle lithosphere. Second, we test the effects of eclogite formation. We find: (1) before lithospheric foundering, formation of eclogite reduces the resistive force by an amount proportional to the negative buoyancy of the eclogite; and (2) after removal of eclogite through foundering, the surface uplifts rapidly. As a result, the orogen experiences an increase in the internal resistive force that can balance or overbalance the compressive force, which causes shortening to localize at the orogen boundaries. For the Tibetan orogen, the collision rate between the Indian and Eurasia plate has slowed over time, implying a nearly constant resistive force. Our results show that this is consistent with the combined effects of rising topography, lithosphere thickening, and formation of dense eclogite. In contrast, shortening in the central Andes orogen has increased over time and migrated from the high plateau to its eastern boundary at 10 Ma. In this case, rapid surface uplift following lithosphere foundering may have increased resistance in the orogen interior, causing shortening to localize on the plateau edge.

The origin of core complexes in the US Cordillera and the Aegean

G. Wu, L.L. Lavier

Jackson School of Geosciences, University of Texas at Austin, glwu@utexas.edu

ABSTRACT

Core complexes are regionally observed in the US Cordillera and the Aegean. Despite significant progresses and many models proposed, a unified view on their formation does not exist. We devised thermomechanical simulations on a representative orogenic belt that has initial topography, Moho relief, and a preexisting mid-crustal shear zone. We recognized four major types of core complexes characterized by massifs, core complexes, multiple consecutive core complexes, and large subsurface low angle detachment fault, respectively. All the core complexes generated have their counterparts in the US Cordillera and the Aegean. We found that the strength of deeper crust, and the existence and strength of a shear zone significantly affect the formation and evolution of core complexes. Topographic loading and buoyancy forces drive a regional crust flow from the highland towards the lowland. The crust flow extrudes at the lowland where intensive faulting induces strong unloading. The detachment fault is a decoupling zone that accommodates large displacement and accumulates sustained shear strain between upper and deeper crust in several Ma. The shear strain in the detachment fault is predominantly simple shear. Thermal history of the exhumed shallow shear zones suggests rapid exhumation in less than 1 Ma for some core complexes to relatively slow exhumation in more than 10 Ma for some others. Our new models provide a unified view on how core complexes form and evolve.