Properly-scaled analog or physical models provide researchers and teachers with a powerful approach to understanding crustal deformation because deformation can be continuously and quantitatively documented under controlled conditions. Furthermore, physical experiments provide reliable benchmarks for numerical experiments. In a previous workshop with a similar format at the University of Massachusetts in 2015, the need for a platform for analog modelers became apparent. Although analog models contribute substantially to the development of new tectonic concepts, benchmarks of numerical models, and interactive teaching, the US analog modeling community is dispersed and small.

The aim of this second workshop is to once again bring together the analog modeling community to discuss exciting innovations in analog modeling research, authentic science curriculum materials and future directions for analog modeling. Furthermore we aim to strengthen the interaction and collaboration with numerical modelers.

The 2017 workshop will be held at the Bureau of Economic Geology at The University of Texas at Austin. The workshop will provide a forum for analog and numerical modelers to directly work together and learn ways to improve their experiments, as well as increasing networking between the groups. Discussion topics will include general modeling methodologies, monitoring techniques, boundary conditions, strain analysis, complex rheologies, innovative materials, force data collection and data archiving.

**Featured speakers**

Featured presentations will focus on a variety of analog and numerical modeling of tectonic processes at a wide range of crustal scales. Invited speakers include:

- Michele Cooke, University of Massachusetts, Amherst
- Eunseo Choi, University of Memphis
- Matty Mookerjee, Sonoma State University
- Roger Buck, Lamont-Doherty Earth Observatory, Columbia University
- Chris Paola, University of Minnesota
- Sarah Titus, Carlton College
- Oriol Ferrer, GRI, University of Barcelona, Spain
- Caroline Burberry, University of Nebraska-Lincoln
- Christoph von Hagke, RWTH, Aachen, Germany
- Giacomo Corti, CNR, IGG, Florence, Italy

**Travel Support**

Financial support for travel, housing and some meals is limited to 30 participants. Application is due by March 31, 2017. Preference for support (partial or full) will be given to students, post-docs, early career scientists, and those from under-represented groups. Participants must present research (analog or not) at the workshop in the form of a poster. Please visit the website for further details.

**Convenors:**
- Tim Dooley, Bureau of Economic Geology, The University of Texas at Austin
- Jacqueline Reber, Iowa State University
- Liz Logan, ICES, The University of Texas at Austin

**Web site:** [http://register.extension.iastate.edu/analogmodeling/about](http://register.extension.iastate.edu/analogmodeling/about)
### Analog Modeling of Tectonic Processes

**Agenda Workshop May 17-19**

**Wednesday 17 May**

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<td>Dilatant normal faulting in cohesive rocks – C. Von Hagke*, M. Kettermann, J. Urai</td>
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| 12.10 – 1.30 | Lunch – Room 1.116 Building 130  
Poster setup – Building 131/132 |
| 1.30 – 2.10 | Improving reproducibility of numerical tectonic models – E. Choi |
| 2.10 – 2.20 | Questions |
| 2.30 – 5.00 | Coffee  
Posters and experiments – Building 131/132 |
| 5.00 – 5.40 | Scale independence in small-world experiments: what do we know? – C. Paola, Building 130 |
| 5.40 – 5.50 | Questions |
| 6.00 – … | Beers at Lone star court  
Dinner individually |
Thursday 18 May

9.00 – 9.20 Recap from Wednesday – Building 130

9.20 – 10.00 Spatial and temporal variation in penetrative strain during compression: insights from analog models with varying mechanical stratigraphy – C. Burberry

10.00 -10.10 Questions

10.10 – 10.30 Coffee break

10.30 – 11.10 Analog modeling of fault asperity kinematics using a modified squeeze-box design and wax media – M. Mookerjee

11.10 – 11.20 Questions

11.20 – 12.00 Effects of pre-salt reliefs on suprasalt deformation in Mediterranean basins: Geology vs. physical models – O. Ferrer*, O. Gratacós, E. Roca, J. A. Muñoz

12.00 – 12.10 Questions

12.10 – 1.30 Lunch – Building 130

1.30 – 2.10 Physical models demonstrating concepts of mountain building and continental breakup – R. Buck

2.10 – 2.20 Questions

2.30 – 5.00 Coffee

Posters and experiments – Building 131/132

5.00 – 5.40 Analog models of a creeping strike-slip fault: application to the San Andreas fault system in central California – S. Titus*, Emily Ross, J. Reber

5.40 – 5.50 Questions

6.00 - … Conference dinner
Friday 19 May

9.00 – 12.00   Posters and teaching demonstrations with coffee
               Building 131/132

12.00 – 1.00   Final remarks
               End of the workshop
Talks will be held on the ground floor of the Bureau of Economic Geology – Building 130.

Poster sessions, workshops and modeling labs are in Buildings 131 and 132 (Core Research Center), a short walk from BEG.

The workshop hotel is the Home2Suites by Hilton.
Invited Speaker Abstracts
Centrifuge modeling of extensional tectonics, with applications to the evolution of the Main Ethiopian Rift, East Africa

Giacomo Corti
Consiglio Nazionale delle Ricerche (CNR), Istituto di Geoscienze e Georisorse, Firenze, Italia

The use of the centrifuge technique to perform experiments is based on the principle that the centrifugal force plays the same role in the models as does the force of gravity in natural geologic processes. Although this modeling has been applied to the analysis of deformation in different tectonic contexts, it has been proven to be very useful in extensional tectonics. Indeed, in the centrifuge, the models expand laterally and extend in response to the centrifugal body force field, allowing to avoid the use of velocity discontinuities that usually characterize natural-gravity models. By imposing a uniform stress field on the models, the distribution of deformation in the centrifuge models is only controlled by lateral variation in strength and rheology, providing a reasonable approximation for the natural process of extension of the continental lithosphere.

In this presentation I summarize the main findings obtained from analysis of lithospheric-scale centrifuge models reproducing continental rifting and will compare them with classical 1-g models with similar set-up. I will use modeling results and their comparison with examples from the Main Ethiopian Rift, in East Africa, to provide a general picture of the different evolutionary stages of continental rifting and the main parameters controlling it. These stages involve a first phase corresponding to the activation of few, large-offset boundary faults that accommodate basin subsidence. The plan-view geometry of these faults is primarily controlled by rift kinematics: orthogonal rifting gives rise to long, extension-orthogonal boundary faults with associated pronounced subsidence, whereas oblique rifting results in a general en-echelon arrangement of faults and basins with less subsidence. Progressive extension leads to a change in deformation style with deactivation of the large boundary faults and activation of dense swarms of extension-orthogonal faults -with limited vertical motions- at the rift axis. Models illustrate that the timing of migration of deformation and activation of internal structures is dependent on several parameters, including crustal thickness, rift kinematics, syn-rift sedimentation or rift width. In particular, rift kinematics seems to play a major role in controlling the timing of the process: model results suggest that the transition from the initial boundary faults stage to the later internal faults stage occur significantly more rapidly increasing obliquity. Therefore, the higher the obliquity the faster rifting evolves. This process is well exemplified in the MER where, according to model predictions, rifting is in an advanced stage in its Northern sector (where obliquity is moderate and deformation is almost entirely localized at the rift axis), in an intermediate stage in its Central sector (where obliquity is low and axial deformation is in an initial stage) and in an initial stage in its Southern sector (where extension is almost orthogonal and deformation is accommodated at the rift margins and axial deformation absent).
Physical experiments coupled with digital image correlation techniques provide direct observations of the evolution of fault networks. Together, these methods allow quantification of the spatial and temporal evolution in efficiency associated with both fault growth and abandonment. Within several suites of experiments, we test the hypothesis that fault systems evolve to become more efficient. Efficient systems accommodate the displacement applied to the system as slip along faults and consequently minimize off-fault deformation. One set of experiments explores the evolving efficiency at the onset of strike-slip fault development. Progressive strain localization evidenced by 1) the initiation of echelon faults segments, 2) their propagation, and 3) their coalescence into a through-going fault produce commensurate increases in kinematic efficiency. Once linked into a continuous surface, the fault will continue to slip without creating new segments, even though the kinematic efficiency is < 100%. This demonstrates how irregularities, such as stepovers, might persist within crustal fault zones. Relatively inefficient systems cannot meet the energetic requirements to grow new more efficient fault segments. This issue is also explored in another set of experiments that investigates the persistence of inefficient restraining bends along strike-slip faults. Gentle restraining bends can continue to accrue strike-slip, sometimes accompanied by reverse slip faults within slip-partitioned system, while strike-slip is abandoned within sharp restraining bends in favor of oblique slip faults. The development of slip-partitioning under oblique convergence seems to defy the principle of work minimization since developing a single active fault is more efficient than maintaining two active faults. A third set of experimental investigations of oblique convergence show temporally varying slip rates along slip-partitioned faults, suggesting that the faults continuously adjust to conditions produced by the other fault. The lack of steady state in the experiments suggests that slip-partitioned crustal systems may also evolve with alternating behavior rather than developing a single efficient active fault structure to accommodate oblique convergence.
Dilatant Normal Faulting in Cohesive Rocks

Christoph von Hagke, Michael Kettermann, Janos Urai

Close to the Earth's surface, cohesive rocks fail in extension, and normal faults in these rocks are commonly massively dilatant. Although near surface massively dilatant faults are common, their internal structure is poorly known, which makes structural and fluid flow predictions notoriously difficult. In an integrated project of scaled sandbox experiments, fieldwork and geomechanical modeling, we study near surface massively dilatant faults (MDF), to better predict their subsurface structure and understand their evolution.

Modeling dilatant faults in analogue experiments may be done using cohesive materials. We use hemihydrate (CaSO4 \( \times \) 0.5 H2O) powder because it has a well-known cohesion and tensile strength and can develop vertical walls. After sieving from a height > 30 cm, the powder has a density of 732 kg/m and a porosity of 75 %.

Using this material, we test the influence of mechanical stratigraphy on normal fault evolution. We implement cohesionless joints into the models and produce dilatant faults and open fractures (Figure 1). As the powder is very sensitive to compaction, it is important to form joints without damage to the surrounding material. Minimum disturbances were achieved by mounting thin low friction paper sheets in the box prior to sieving. Removing the paper after filling the box leaves cohesionless open (< 1 mm aperture) joints without compacting or fracturing the surrounding material, and furthermore guarantees consistent depth of the joint.

In a parameter study, we test the influence of the angle of preexisting joints with respect to a rigid basement fault, joint depth, as well as joint spacing. We use Particle Image Velocimetry (PIV) to measure displacements, rotations and strains. Results show that the general surface expression of MDF is different from non-dilatant faults and also different in experiments with and without pre-defined joints. We show that the damage zone width increases with increasing joint-fault angle, whereas the area fraction of open gaps remains more or less constant throughout the experiments. The angle between pre-existing joints and faults has a distinct effect on the network of open fractures mostly in terms of fracture surfaces and connectivity, while the volume of open space does not change dramatically. The most exciting results of the study is that also very shallow joints result in a similar fracture pattern as compared to deep-reaching joints. This is exciting as it implies that also small changes in mechanical stratigraphy govern fault geometry evolution. First experiments with different cohesions corroborate the importance of mechanical stratigraphy on normal fault evolution. We apply the results to different field areas, in particular Iceland and Canyonlands National Park.
Figure 1: Oblique view of an experiment showing deformation localizes at pre-existing joints and step-over structures. (b) Top-view photograph of the same experiment shows the typical zigzag shape formed by step-overs at the master fault.
Improving Reproducibility of Numerical Tectonic Models

Eunseo Choi

Numerical models are difficult to reproduce in general and numerical tectonic models are not an exception. Improving the reproducibility of numerical tectonic models would be one of the prerequisites for independently verifying and building on previous numerical results as well as for comparing analog and numerical models. This presentation discusses two main sources of tectonic models' poor reproducibility and their potential remedies. The first is the mesh dependence of the rate-independent strain-weakening plasticity. Widely used in tectonic modeling, this rheology can induce localization of plastic strain in the form of shear bands, which can represent faults. While capturing main features of faults, the strain localization induced by this rheology exhibits different width and orientation under different meshes. Several solutions proposed for this pathology include non-local and rate-dependent plasticity, controlling strain weakening rate with fault offset, and acoustic tensor- or energy-based computation of shear band orientations. The second source of poor reproducibility is the lack of protocol for reporting and archiving numerical experiments. While researchers do include details of numerical models in publications but peer reviews often fail to capture typos, errors or missing information necessary for reproducing the presented results. Broken reproducibility of a numerical experiment also stems from the complexity of existing software and systems, implicit dependencies, and compatibility of systems shifting over time. Among the proposed solutions is the automated creation of a self-contained metadata package that provides a complete description of all data elements associated with a computational experiment, including input files, parameter files, the model executable and any associated libraries, and all output files (results) produced. GeoTrust is an EarthCube-funded project to realize this idea into sandboxing-based systems and tools. An overview of GeoTrust and preliminary results from the application of this framework to some types of tectonic modeling will be presented.
Scale independence in small-world experiments: what do we know?

Chris Paola

A fundamental manifestation of scale independence in physical systems is common behavior across a wide range of governing dimensionless numbers, including asymptotic independence at large values. Given that independence of this sort is a more flexible basis for designing and interpreting ‘small-world’ experiments (i.e. experiments on Earth processes at drastically reduced scales), we explore what is known about asymptotic and other forms of independence of a suite dimensionless parameters relevant to designing such experiments.
Spatial and temporal variation in penetrative strain during compression: insights from analog models with varying mechanical stratigraphy

C. Burberry

Penetrative strain constitutes the proportion of the total shortening across an orogen that is not accommodated by the development of macroscale structures. It is widely considered to be an important process, but variation in the distribution of penetrative strain during a deformation sequence, or the proportion of shortening accommodated in this way is not well understood. This series of studies provide some first-order constraints on magnitude, and distribution of penetrative strain during deformation. Three series of experiments, one fully brittle, one with a ductile basal décollement and one with both a basal and an intermediate ductile décollement were systematically shortened. Within the limits of analog models, each initial configuration was geometrically similar, with mechanical variation introduced by the use of different materials. Model results indicate that penetrative strain is variable with depth, and the style of variation depends on the mechanical stratigraphy. The proportion of the total shortening accommodated by penetrative strain decreases as deformation progresses. Models also contain a foreland zone of penetrative strain, in which penetrative strain decreases exponentially away from the deformation front. These results are consistent with available field data and cross-sections, indicating that model results can be used to predict the penetrative strain and thus true total shortening across a deformed region. Estimates of this type may provide answers to the problem of “missing shortening” across orogens and the total amount of shortening experienced at collisional plate margins.
Analog modeling of fault asperity kinematics using a modified squeeze-box design and wax media

M. Mookerjee

Fault movement is strongly influenced by the physical characteristics of the fault surfaces. Fault surfaces are generally non-planar, and have a certain amount of roughness to them, which manifests as fault asperities. In order for a fault to continue moving along its preexisting surface, the asperities must either move past each other, which involve moving a large volume of rock around these obstacles, or create new fractures that “decapitate” and pulverize these asperities, ultimately leading to a smoother fault surface. We explore a new way to investigate fault asperity kinematics using a squeeze-box analog deformation rig. The more typical and classic squeeze-box model uses sand and/or clay to demonstrate fault and fold deformations. We have designed and built a new analog modeling rig that utilizes a dual-wax analog material. One constituent is white spherical wax particles that have been embedded in a lower-melting-temperature black matrix wax. Deformation of the analog material is facilitated by the addition of heating elements lining the underside and exterior walls of the squeeze-box reservoir. An aluminum asperity is secured to the floor of the reservoir. Additional overburden is simulated with lead shot that rest on the top surface of the wax block during deformation. Once the experiment is completed, the wax block can be finely sectioned, polished and scanned in preparation for analysis. Here, we present the first results from this new deformation rig where we were able to generate realistic looking deformation features at different strain rate conditions. The results of this type of modeling provide unique information about fault localization, the role of fluids, and fault asperity kinematics in a poly-phase system for modeling a variety of physical conditions within the Earth’s crust. These conditions are difficult to model with other analog or numerical techniques or to derive from field or seismic investigations.
Effect of pre-salt reliefs on supra-salt deformation in Mediterranean basins: Geology vs. physical models

Oriol Ferrer, Oscar Gratacós, Eduard Roca and Josep Anton Muñoz

Geomodels Research Institute, Departament de Ciències de la Terra i de l'Oceà, Facultat de Ciències de la Terra,
Universitat de Barcelona, Barcelona, Spain (joferrer@ub.edu)

The presence of a thick Messinian evaporite unit is a well-known feature of the Mediterranean basins. Whereas this unit is characterized by three sub-units in the Northwest Mediterranean, it is composed by a multilayered evaporite sequence in the Eastern Mediterranean. In the Western Mediterranean passive margins (e.g. Liguro-Provençal or Levant basins) salt acts as a regional detachment favoring the downslope gravitational failure of the overlying sediments in a thin-skinned deformation regime. These margins exhibit a three-domain structural zonation characterized by upslope extension, intermediate translation and downslope contraction. Nevertheless, the presence of pre-salt reliefs related to volcanic edifices is rather common in the translational domain of the Northwestern Mediterranean realm where they act as flow barriers hindering salt drainage and constraining supra-salt deformation. In contrast, the Eratosthenes seamount (Eastern Mediterranean) is characterized by a large scale submerged massif (ca. 120 km in size) that significantly influenced the structural evolution of the surrounding areas. This pre-salt relief acted as a buttress and deflected the Messinian salt flow (e.g. Levant Basin and Nile margin). In contrast, the Eratosthenes seamount also restrained the structural style of the allochthonous salt that was expelled during the development of the Cyprus subduction zone to the north.

Using an experimental approach (sandbox models) and new analysis techniques, in this presentation we will show salt and supra-salt deformation in response to two different types of pre-salt relief: 1) local seamounts during gravitational gliding (Western Mediterranean) and, 2) large regional reliefs during the emplacement of a thrust system (Eastern Mediterranean). The experimental results of the Western Mediterranean show that the height, the geometry (cylindrical or linear) and the orientation (orthogonal or oblique to the flow direction) of these reliefs are key factors during gravitational failure influencing supra-salt deformation. We will also show the preliminary results of some experiments focused on the Eastern Mediterranean were different responses are obtained along-strike as a consequence of shortening when modeling the huge Eratosthenes seamount. The presence of this seamount in the contractual domain, instead, initially enhanced salt inflation by buttressing and the subsequent development of salt sheets with the formation of an escarpment at the edge of the salt. The experimental results also provide geometrical constraints to bear in mind during interpretation of these structures and associated hydrocarbon plays, which are commonly poorly imaged in seismic data.
Physical Models Demonstrating Concepts of Mountain Building and Continental Breakup

W. Roger Buck, Lamont Doherty Earth Observatory of Columbia University

Analog models can be useful means of demonstrating concepts, particularly when those concepts are difficult to visualize. Here I discuss several simple physical models that maybe useful in showing how tectonic and magmatic processes work. Each of these can be or has been usefully extended using analytic and/or numerical approaches.

The first problem involves a novel mechanism of continental convergence. An aquarium is used to illustrate how variations in the thickness of shallow low-density mantle asthenosphere could produce crustal convergence. Analytic descriptions of the model indicate that the mechanism may explain the force needed to build the highest mountains on Earth with reasonable densities and thicknesses of a ‘plume-fed’ asthenosphere.

Next, a previously published model of viscous mountain building is discussed in light of the recent series of normal faulting earthquakes in the Apennines of Italy. A linear viscous ‘crust’ is driven to converge by the motion of underlying metal plates that are steadily pushed together. Surface extension occurs in the region of highest topography even while the regional deformation is contractional. Numerical models involving more realistic crustal realities are needed to demonstrate that this process is a viable explanation for normal faulting in the Apennines and other mountain ranges.

The last problem considered is the role of mantle plumes and related magmatic dike intrusions in promoting and localizing continental rifting. Most continental breakup events are accompanied by massive intrusion and extrusion of basaltic magma. Simple arguments about the stress needed for diking suggest that the force needed for ‘magma-assisted’ rifting of normal continental lithosphere can be an order of magnitude lower than needed for purely tectonic rifting. A simple demonstration of the facilitation of rifting by dike intrusion is done with a layer of gelatin taking the role of the lithosphere. The layer is put into extension, but the stress is not sufficient to cause the layer to split until water is injected into it. A water-filled ‘dike’ propagates from the center of intrusion and leads to the layer splitting into two ‘continents.’
Analog models of a creeping strike-slip fault: Application to the San Andreas fault system in central California

Sarah Titus, Emily Ross, Jacqueline Reber

The San Andreas fault changes from locked behavior along the Carrizo segment to aseismic creep in central California. The GPS velocity field shows distinct changes on either side of the transition from locked-to-creeping behavior, near Parkfield, a pattern that can be broadly matched by a simple elastic model. The velocity field can be used to infer local off-fault strain patterns, documenting local contraction NE of the transition and local extension to the SW. There are hints that this transition may also be recorded by long-term geologic structures in off-fault regions.

We use analog models to investigate the slip behavior transition by cutting and lubricating a fault above two moving plates (to simulate creeping behavior) and leaving the rest of the material intact (to simulate locked behavior). We test a variety of materials including silicone, silicone and sand, and silicone and kaolin. Particle image velocimetry and strain analysis software document a good match to both the velocity field and strain patterns observed NE of the San Andreas Fault. However, our analog models do not match patterns on the SW side of the fault.
Poster & Teaching Materials Abstracts
Modeling of brittle fracture with a phase field approach

Sanghyun Lee

This work presents phase field modeling approach of a brittle fracture in an elastic medium and of pressurized and fluid-filled fracture propagation in a poroe-elastic medium. Here lower-dimensional fracture surface is approximated by using the phase field function by treating the fracture surfaces as diffusive zones instead of as discontinuities. The phase-field model does not require consideration of unpredictable rock properties or stress inhomogeneities around crack tips.

The two-field displacement-phase-field system solves fully-coupled constrained minimization problem due to the crack irreversibility.

This constrained optimization problem is handled by using active set strategy. The pressure is obtained by using a diffraction equation where the phase-field variable serves as an indicator function that distinguishes between the fracture and the reservoir. Then the above system is coupled via a fixed-stress iteration.

The numerical discretization in space is based on Galerkin finite elements for displacements and phase-field, and an Enriched Galerkin method is applied to the pressure equation in order to obtain local mass conservation.

Numerical simulations including comparisons with a physical experiment using gelatin for a wing crack formation is presented.

It is shown by benchmarking the models with physical experiments that the numerical assumptions in the phase-field approach do not affect the final model predictions of wing crack nucleation and growth.

With this study, we demonstrate that it is feasible to implement the formation of wing cracks in large scale phase-field reservoir models.
Water released from the stagnant Laramide slab and the New Madrid Seismic Zone

Arushi Saxena, Eunseo Choi and Christine Powell

Center of Earthquake Research and Information The University of Memphis

New Madrid Seismic Zone (NMSZ), located in the Northern Mississipi Embayment, is one of the biggest source of intraplate earthquakes in the Central Eastern US. Although numerous geodynamic models have been proposed to explain the cause of this seismicity, new tomographic results continue to challenge the existing mechanisms. A recent high resolution tomography study by Nyamwandha et al.[1] (2016) for the NMSZ shows features at depths 100-250 km for which low Vp and Vs anomalies are both 3-5 %. Such a low velocity anomaly cannot be explained by high temperature alone and often requires the presence of melt or fluid[1]. Our goal is to explore the effects of the presence water in the mantle on the stress magnitude and distribution in the seismogenic upper crust of the region. We create finite element models using PyLith, an open source software for crustal dynamics[2]. We follow the modeling approach described in Zhan et al.[3] (2016). The model domain, 2665 x 2554 x 200 km, is divided into three layers corresponding to upper crust, lower crust and mantle. The viscosity of these layers are calculated by converting velocity anomalies for dry, damp (water solubility in Olivine ,is 50 ppm) and water saturated conditions as defined in Dixon et al. (2004)[4]. The estimated viscosity is used for computing stress fields under the kinematic boundary loadings for generating the observationally constrained regional stress. We present preliminary models and analyze the differential stresses beneath the NMSZ for the assumed conditions of fluid content. We also demonstrate that we can enhance the reproducibility of this type of rather complicated geodynamic models with GeoTrust, an EarthCube-funded project that aims to automate the creation of a self-contained metadata package that provides a complete description of all data elements associated with a computational experiment.

References


Effects of pre-existing structures on the seismicity of the Charlevoix Seismic Zone

Oluwaseun Fadugba, Eunseo Choi and Christine Powell

Center for Earthquake Research and Information, The University of Memphis, Tennessee, USA

The Charlevoix seismic zone (CSZ) is the most seismically active region in eastern Canada. It is located within the Cambro-Ordovician St. Lawrence rift zone in southeastern Quebec overlapping a Devonian impact crater. The crater was superimposed on three major rift faults trending N35°E and dipping at 70° to the southeast. The earthquakes in the CSZ are concentrated within the faulted volume bounded by the rift faults. Also, the regional stress data show that the maximum horizontal stress (SH) orientations inferred from the earthquake focal mechanisms are subparallel to the strike of the rift faults in the NW of the middle fault while oblique in the SE. Previous studies failed to provide explanations for this change in SH orientations. Motivated by a recent cluster analysis that better constrains the geometry of the rift faults, we aim to investigate whether the more realistic fault geometry can better explain the region’s seismicity and stress distributions. We use PyLith, an open-source finite element code for modeling dynamic and quasi-static tectonic deformation, to build models that incorporate three major faults and the damaged impact crater under the boundary loadings to generate a stress field similar to the broader-scale regional stress. We present preliminary model results and analyses on the spatial distribution of magnitudes and orientations of SH. We also demonstrate that we can enhance the reproducibility of complicated geodynamic models like ours with GeoTrust, a framework that aims to automate the creation of a self-contained metadata package that provides a complete description of all data elements associated with a computational experiment.
4D analogue modeling of transcurrent structures and interactions with thrust front: insights from SW Sicily and the Sicilian Channel

Jakub Fedorik¹, Frank Zwaan², Guido Schreurs², Giovanni Toscani¹, Lorenzo Bonini³, Emanuele Lodolo⁴, Dario Civile⁴, Silvio Seno¹

¹) University of Pavia, Department of Earth and Environmental Sciences, Pavia, Italy ²) University of Bern, Institute of Geological Science, Bern, Switzerland ³) University of Trieste, Department of Mathematics and Geosciences, Trieste, Italy ⁴) National Institute of Oceanography and Experimental Geophysics, Trieste, Italy jakub.fedorik01@universitadipavia.it

Analogue models were used to investigate the 4D evolution of a transcurrent structure and its interaction with a preexisting thrust front. An analysis of 7 models applying (i) pure strike-slip, (ii) transtension (10/20/30 degrees) and (iii) transpression (10/20/30 degrees) kinematics shows important structural variations in the area of transcurrent fault. Some models closely resemble the geometries of natural interaction observed between the transcurrent transfer zone of the Sicilian Channel (Italy) and the Maghrebian fold-and-thrust belt.

The experimental apparatus consists of a box with three independent rigid base plates. These plates were covered by a 4-cm-thick layer of quartz sand. During the first phase of deformation the thrust front was created as the upper plate was sliding on the fixed plate. In the second phase the lower plate was sliding under the fixed plate. The shape of the fixed plate permitted to build a transcurrent fault and at the same time the thrust front was reactivated. The analogue models were analyzed by X-Ray Computer Tomography (XRCT). This technique allows visualization of the interior of a model during deformation without destroying it (4D analysis).

In the area of SW Sicily and northern part of the Sicilian channel, two main structures, the Maghrebian fold-and-thrust belt and a transcurrent fault zone, interact. The most recent interaction was recorder during the Belice earthquake sequence in 1968 and the calculated focal mechanisms are compatible either with a pure E-W thrust plane or with a prevalently right-lateral movement on a NNW striking, WSW dipping plane. Analyses of multichannel seismic reflection profiles acquired in the northern part of the Sicilian Channel were used to analyze the Sciacca Fault which displays a positive flower structures. The outermost thrust sheet (bottom of Gela Nappe) is interpreted by many authors as a complex, imbricate wedge, involving the sequences of a foredeep basin. The Gela Nappe is well exposed along the southern coast of Sicily, where both Sciacca Fault and Gela Nappe can be observed.

The observations suggest that the SW of Sicily and the northern part of the Sicilian Channel were shaped by the occurrence of two tectonic processes, the Maghrebian fold-and-thrust belt emplacement and transcurrent fault acting simultaneously and overlapping each other. The interpretation of seismic reflection profiles, merged into a 3-D model together with the bathymetry, and its comparison with analogue models demonstrated a fair match between the models and natural case. Main equivalences are (i) the presence of well-developed flower structures along the transcurrent structure, (even within a transtensional experiment), (ii) rotation of the thrust front during deformation and (iii) segmentation of transcurrent structure in the area of the thrust front. Additionally, the results of 4D analyses of analogue models give a new perspective of fault development under different transcurrent regimes.
Inverted salt-detached ramp-syncline basins. A review of analog models and natural examples

M. Roma, O. Ferrer and J.A. Muñoz

GEOMODELS Research Institute, Earth and Ocean Dynamics Department, University of Barcelona (Spain).

The origin of extensional synclinal basins is currently a largely debated topic. These basins appear no-constrained by major faults and the main factors which control its development and kinematic are known to be related with: (i) the geometry variation of the basin-related basal fault, (ii) the salt evacuation or (iii) the combination of both mechanisms (i.e., salt-detached ramp-syncline basins). Moreover, synclinal basins were later inverted and the inherited basin architecture as well as the presence of salt are the main factors controlling the basin inversion.

A precise interpretation of its origin and its kinematic development it is sometimes difficult and complex due to the low quality of the seismic data and the complexity of the resulting geometries. The issue has been trying to be resolved over the past 20 years using analog modeling. From these great literatures we propose a review about the experimental studies of synclinal basins, as well as natural examples. Finally in order to complete the published research we present a new experimental program based on analog models and digital image processing tools which try to reproduce almost all factors that actually control the basin formation.
Numerical Modeling of Underwater Landslides

Gabriele Morra

Department of Physics, University of Louisiana at Lafayette

Underwater landslides are normally fed by fine-grained glacial or fluvial material and can reach thousands of cubic kilometers, due to the gentle gradient that characterizes the sea, and extraordinarily move to distances of hundreds of kilometers, despite the water drag resistance. Small environmental pressure variations are believed to be in relationship with their occurrence, suggested by the observation of small scale mud-slides in the Mississippi Delta area during hurricane passes.

I will show numerical models based on the Particles in Cell (PIC) technique and routines entirely developed in Python. PIC consists in calculating the solution of PDEs on a background lattice and projecting it on Lagrangian particles. Specifically I will present simulations with three components (bedrock, sediments, water), and investigate the mobility of the sediments, and the stability of the underlying bedrock.

My models show that some of the main features of underwater landslides such as morphology and speed, however others remain elusive. In particular understanding and reproducing the ability of landslides to remain mobile for large distances is particularly challenging. I propose specific numerical implementations of pore fluid pressure within the sedimentary layer that could unlock the secret of the motion on shallow slopes. Mechanisms for ruptures at the bottom of the sedimentary layer will be reviewed, and I will show how they may help landslide detection.

Numerical simulations of landslide can also complement laboratory models. For example granular flow experiments could help describing the details of the flow by using Particles Image Velocimeter (PIV), and the consequent acoustic wave propagation in water is still scarcely understood. Collaborations on all these aspects would certainly be very fruitful.
Experimental analysis of semi-brittle rheology: Implications for strain transients

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Mid-crustal rocks exhibit both brittle and ductile structures. The interaction and co-occurrence of these structures may induce a wide range of deformation dynamics ranging from stick-slip to creep. Understanding the role that complex, semi-brittle rheology plays in fracture interaction has the potential to impact the deformation dynamics in the middle crust. In the last decade, researchers have detected strain transients using geodesy and seismology. Strain transients are slip events that occur over time-scales much longer than that of earthquakes and may take several forms including aseismic slip, low-frequency earthquakes, and tremor. Previous studies have focused on frictional properties and fluid pressure as governing factors for strain transients but have yet to consider the mixed rheology that rocks exhibit at the pressure and temperature conditions of the middle crust. In our experiments, we deform Carbopol, an analog for rocks exhibiting both brittle and ductile rheologies, with a distributed simple shear apparatus. We measure shear displacement and force required to deform Carbopol. Mode I (extensional) fracturing in the Carbopol is related to slip events recorded in both force and displacement data. Mode II (shear) fractures are observed visually to bridge small distances (< 5 cm) between Mode I fractures. The interaction between the two fracture types can lead to strain transients in the experiments spanning form stick-slip to creep.
Effect of contrasting structural and compositional inheritances on the development of rifted margin: a modelling approach

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If progress has been achieved in the understanding of rifting processes, fundamentals questions remain on the role played by structural and compositional inheritances in the localization and development of rift structures. In a previous study, we performed lithospheric scale numerical experiments in extension with a bimineralic composition in the crust and the mantle to study the effect of compositional heterogeneities. We then demonstrated that bimineralic composition assimilated to heterogeneities succeed in explaining observations related to the formation of rifted margins such as: 1) the absence of a sharp brittle ductile transition, 2) the initiation of the rifting process as a wide delocalized rift system where multiple normal faults dipping in both directions; 3) the development of an anastomosing shear zone in the middle/lower crust and the upper lithospheric mantle similar to the crustal scale anastomosing pattern observed on the field or in seismic data; 4) the preservation of undeformed lenses of material leading to lithospheric scale boudinage structure and resulting in the formation of continental ribbons as observed along the Iberian-Newfoundland margin. In this new study, we explore the combined effect of the compositional and structural inheritances using a similar modeling approach. Instead of being randomly disseminated, heterogeneities are distributed according to a certain wavelength and orientation. By modifying the wavelength and orientation of the heterogeneities in the crust and the lithospheric mantle we can explore the effect of inherited crustal and mantellic fabrics in the localization and development of rift structures. We demonstrate that inherited fabric succeed in explaining 1) the distribution of the deformation during the initial phase of deformation (horst and graben versus tilted block), 2) the geometry of the necking domain (abrupt versus progressive). Results are finally compared with actual passive margins presenting contrasting geometry.
Rheological Effects on Fracture Pattern and Propagation

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Understanding fracture pattern and propagation is essential for an effective extraction of natural resources. Currently fracture models used for fracking and large scale carbon models are using an elasto-plastic rheology, ignoring the more complex rheology often observed in rocks. The aim of this study is to examine the effect of rheology on fracture patterns, fracture propagation speed, and pressure evolution by means of analog experiments. We test the impact of granular, elasto-plastic and visco-elasto-plastic rheology. To represent these systems we use flour, gelatin, and hydrous polymer (Carbopol) as rock analogs. The experiments are run in a Hele-Shaw cell that is filled with the respective material. The fractures are induced by injecting pressurized air allowing us to systematically change the overall pressure in the cell. The pressure evolution is recorded with six pressure sensors along the sides of the cell. Low pressures were required to propagate fractures in the granular system leading to one main fracture with smaller fractures branching off of the main fracture. In an elasto-plastic system, higher pressures are required for fracture propagation due to the yield-strength of the material. One single fracture initiates and propagates at a slower speed than in the granular system. In the visco-elasto-plastic system, we observe branched fractures that propagate at a speed similar to the elasto-plastic case. Our experiments show that the rheology has a significant impact not only on the fracture speed but also on the fracture patterns.
Analog modeling of semi-brittle deformation in introductory structural geology courses

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In spring, 2017, workshop convenor Jacqueline Reber and I developed and carried out an analog modeling laboratory exercise for students enrolled in an introductory level structural geology course. The exercise was done in week 6 of a 15 week semester, at which point students are comfortable describing and interpreting the products of brittle deformation processes and are ready to begin thinking about ductile deformation. The concepts surrounding ductile and mixed brittle-ductile deformation are naturally more difficult to grasp, as students are not used to thinking of rocks flowing in the solid state. This exercise makes use of two simple shear devices and a Hele-Shaw cell to produce semi-brittle deformation in a variety of materials. In doing so, students visualize the structures resulting from semi-brittle deformation, report force-displacement-time data, and make the leap from the experimental results to real rocks and seismic events.
The 2016-2017 Central Italy seismic sequence as a trigger for mud volcanoes eruption: a numerical modelling approach

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On 24th August 2016, and 26th and on the 30th October three medium-high magnitude earthquakes of Mw 6.0, 5.9 and 6.5 respectively hit central Italy. The seismic sequence persisted with a long series of moderate foreshocks and on the 18th January 2017, four seismic events with a Mw >5 (up to 5.5) hit again the area. In response to these seismic events was documented a wide range of coseismic effects (such as ground fracturing and rupturing, fault reactivation, sediment liquefaction, landslides, and rock falls ecc...). Moreover, after the main shocks a number of mud volcanoes along the Apennine foothills (Ascoli Piceno and Fermo provinces, Marche Region), erupted and showed a markedly increasing in their activity. Some of them were new features that formed some hours/days after the main seismic events. Our study will focus on the investigation of the role of this seismic sequence in the triggering of mud volcano eruptions, particularly on the evaluation of static/dynamic stress influence. To evaluate the role of static stresses in the triggering of mud volcanoes eruption we carried out a numerical modelling by means of the Coulomb 3.3 software, which is able to calculate the variation of normal stresses on a receiving fault/fracture created by the slip on a neighbouring seismogenic source fault. Using focal mechanisms calculated by different institutions (e.g. INGV and USGS) and our field data acquired before and immediately after mud eruptions, we evaluate if the normal stress change favoured or not the triggering of the eruptions. In particular, conditions favourable to eruption are when normal stress changes tend to open (unclamp) the feeder dike system of mud volcanoes. Numerical models addressed the potential effect on both reactivated and newly-formed mud volcanoes by normal stress changes produced by the main seismic events, which are located more than 40 km East of the main shocks. The modelling results indicate that static stresses associated with these earthquakes were relatively large but not suitably oriented to contribute to the triggering of the mud volcano eruptions (i.e., the static stresses clamped the inferred feeder dikes, or where sensibly smaller than the trigger threshold of 0.1 bar). Nonetheless, the temporal correlation among seismic events and eruptions is straightforward, in that mud volcanoes invariably responded hours to few days after the main earthquakes. Therefore, dynamic stresses associated with the passage of seismic wave are inferred to be the main triggering mechanism. In fact, Peak Ground Velocities (PGV) show values close to 8 cm/s (similar to the PGVs associated with other documented responses) in the area affected by mud volcanoes reactivation, when mud volcanoes did not respond to the seismic events where PGVs were smaller.
Analog Modeling in Teaching

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A simple analog modeling lab can be used to introduce structural geology students to the concepts of geometric, kinematic, and dynamic approaches to structures. I use an expandable workbench, metal sheets, and granular materials (garnet sandblasting sand, for example) to allow students to experiment with forming a thrust wedge, strike slip faults, or restraining and releasing bends. These simple models allow students to experiment with changing conditions (thickness of sand, width of model, original shape of the surface) without a lengthy set-up time. Students work only with surfaces (as opposed to cross-sections), to begin developing the concept of deforming surfaces. They sketch the results of their models (to practice using sketching to make observations) and sketch structural map symbols (bedding, fold hinges, and fault symbols) to begin thinking about geologic maps as a record of kinematic processes. They measure properties of their modeling materials, and use those properties to calculate the real-world scale that they have modeled. Lab discussions include separation observations from interpretations, the possible forces involved in driving the deformation that they see, and the variations amongst the different models. Each group’s experiment is recorded, allowing the class to go back and look at their models later in the semester, during more detailed discussion of the types of structures.
Analog experiments are the best way to study micromechanics of mudrocks and fault rocks

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Mudrocks and fault rocks share several microstructural qualities. Each comprise mixtures of “grains” and “matrix”, wherein the grains are generally non-reactive elastic particles in frictional contact, and matrix is more chemically and rheologically complex material. During deformation of such materials, whether during induced fracturing or tectonic faulting, the chemo-mechanical feedbacks between matrix, grains, and fluids (including aqueous species) make understanding natural materials very doable in terms of bulk-rock responses, but exceedingly difficult in terms the underlying micromechanics. Understanding micromechanics is, in turn, becoming increasingly important for evaluating how fractures liberate liquids for organic-matter-hosted porosity, and how clay minerals and interstitial fluids stabilize fault slip. Thus, for example, techniques that harness rock-mechanics experimentation, computerized tomography, nano-indentation, and high resolution scanning and transmission electron microscopy, all can show the range of possible behaviors in natural materials, and possibly be upscaled to field experiments. But it is difficult to isolate specific mechanical processes from the natural material. A mundane example of this is establishing when nano- and micro-scale fractures develop in an experiment, and how these are expressed relative to seismicity and fluid flow in a borehole experiment or at the field scale. One laboratory approach to understanding micromechanics is to use granular materials – such as acrylic or photoelastic grains – and an interstitial medium. Such granular experiments capture a great deal of the granular friction response to strain, but do not easily lend themselves to exploration of the evolution of the material (e.g., via comminution) and/or fracture. In contrast, polymers such as Carbopol allow an investigation of fracture, but we are only now understanding the micromechanics of such materials, which involve complex interactions between ionic forces and polymer-chain geometry. Thus, even though analog materials are the best way to study the micromechanics of mudrocks and fault rocks, they cannot be done in a vacuum, and require integration with numerical computational techniques, and integration with geological (both sample and field scale) efforts to be meaningful.
A significant portion of the deformation budget across irregular fault networks can be accommodated by permanent off-fault deformation that accumulates between earthquakes. This deformation may correspond to a reduction in the slip rates along the faults within these complex networks, which in turn may contribute to uncertainty when evaluating seismic hazards within southern California. We use well-validated 3D Boundary Element Method (BEM) models to investigate the irregular fault geometry through the San Gorgonio Pass. Within this region, ongoing debate centers on the activity level and geometry of the Mill Creek and Mission Creek strands of the San Andreas fault. Here we investigate five BEM models with varying geometries of active Mill Creek and Mission Creek strands. One alternate fault configuration consists of an active segment of the Mission Creek fault transferring slip to the Galena Peak fault. All models are run with a range of boundary conditions to account for epistemic uncertainty of tectonic loading, providing a range of slip rates and surface deformation. Each model results in fault slip rates that match several of the available geologic slip rates; however, there are two best-fit models to the geologic slip rates. The best-fit models produce significantly different uplift patterns of the region. These uplift patterns are compared to known exhumation rates and geodetic uplift rates to determine the most accurate fault geometry through the San Gorgonio Pass. Consequently, our assessment of seismic hazards in southern California may be improved due to increased characterization of the complex fault geometry within the San Gorgonio Pass.
Experimental analysis of the effect of grain size distribution on stick-slip and creep behavior

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Strike slip faults accommodate displacement through aseismic creep or earthquake-generating stick-slip events. The role, if any, of fault sediment in affecting fault behavior is not known. Field observations along the San Andreas Fault have shown that fault sediment in a locked section of the fault is dominated by small grains ~ 100 μm in diameter, while fault sediment at a creeping section of the fault has a wider distribution of grain sizes. Using elliptical acrylic disks of three sizes and a simple shear apparatus with a localized shear plane and energy conserving boundary conditions that do not prescribe the strain rate or the force, we test the effect of grain size distribution on fault behavior. Granular materials can flow, like sand in an hourglass, but can also geometrically lock up and then reorganize in stick-slip events. Early results indicate that a uniform grain size generates stick slip behavior, and that slip events scale with the diameter of the grains. We expect that aseismic creep can be achieved using a combination of large and small grains, as the small grains will flow between locked larger grains. Understanding how grain mechanics affect fault behavior will contribute to our overall understanding why faults do or do not generate earthquakes, and can give insight into the mixed behavior of the San Andreas Fault.
Stress modeling around the toe of an advancing salt sheet

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The sealing potential of tertiary salt welds depends in part on the amount and distribution of weld-adjacent deformation. The deformation may develop during salt sheet emplacement, during welding, or later, during reactivation of the weld. Although Heidari et al. (2016) conducted models of primary and tertiary welding process, little is known about the stress distribution near the toe of an advancing salt sheet, and how the traction on the base of salt sheet may affect the plastic deformation or brittle fracturing of underlying sediments.

Several finite element numerical models have been built to interpret the stress distribution and displacement around the toe of extrusive salt sheet during advance. In these models, the salt is considered as an visco-elastic material, and the sediment is considered as an elastic-plastic material. The flow of salt and deformation of sediment are examined under simple gravity loading and salt flow.

The modeling results show that the top of the spreading sheet moves faster than the base. The flow of salt generates a nonnegligible shear stress on the contact of salt base and underlying sediment. The magnitude of this shear stress is apparently independent of the effective viscosity of the salt, but dependent on the thickness of salt sheet. For a one order of magnitude difference of salt viscosity, the shear stress is nearly same. For a thickness of 400m, the salt flow can generate a maximum of ~4MPa of shear stress on the base, near to the toe of salt sheet. This highest shear stress is about a half of the vertical normal pressure on the salt base and is dependent on density and thickness of salt sheet. During allochthonous salt advance, the highest shear stress is always located at the base of salt sheet toe. With the continued advancing of the salt sheet, the vertical normal stress on the contact remains unchanged but the shear stress is gradually decreasing to about 15% of vertical pressure.

The flow of salt sheets under gravity loading also causes a changing of the stress field in the underlying sediments. The orientation of principal stresses in the sediment rotates during the advancing of salt sheet, primarily in the area around the toe. The flow of salt sheet causes a shallow horizontal contraction in the sediment immediately in front of the toe, and a strong traction under the toe. Under the toe of the salt sheet, a maximum upward extension occurs at an angle of 45°, and a maximum downward contraction at 45°. From the area in front of the toe, to the toe, and then the interior of salt sheet, the orientation of maximum principal stress within the underlying sediment changes from horizontal to a dip of 45°, and then to nearly vertical. These stresses near the base of the salt sheet may be strong enough to generate a shallow plastic deformation zone within the underlying sediments.
Scaled Physical Experiments of Salt Flow Subparallel to Basement-Involved Normal Faults

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Basement-involved normal faults influence the initial thickness and distribution of synrift salt. Deformation and deposition during and after rifting may cause highly ductile salt to flow; however, relatively few studies have examined the effects of a synrift ductile unit on subsequent deformation within a rift basin. We used scaled physical experiments to examine the secondary structures that develop in the sedimentary cover (wet clay) above synrift salt (silicone polymer) that flows subparallel to the strike of basement-involved faults (rigid blocks). In the experiments, two zones of deformation form within the sedimentary cover: 1) a shear zone with oblique-slip faults that overlies and trends (sub)parallel to the strike of the underlying preexisting fault; and 2) an extensional domain with normal faults that strike (sub)perpendicular to the flow direction of the ductile unit. With a thicker ductile unit broad domains of deformation form at the surface, whereas with a thin ductile unit narrow zones of deformation form directly above the underlying structures. When the flow of the ductile unit produces highly oblique extension at depth the extensional domain in the cover is broad, and the shear zone has a similar orientation to the underlying pre-existing fault. However, with highly oblique shortening at depth, the trend of the shear zone in the cover is not parallel to the strike of the underlying pre-existing fault, and secondary features in the extensional domain are muted. The latter suggests that the ductile unit subdues the expression of shortening and extension at the surface. The Jeanne d’Arc basin (offshore Newfoundland) is an example of a rift basin in which the initial thickness and distribution of synrift salt is fault-controlled. This modeling study suggests that the synrift Argo Salt in the Jeanne d’Arc basin flowed parallel to the basin’s long-axis. The salt flow produced secondary structures in the sedimentary cover above the salt including shear zones above basement-involved faults and trans-basin normal faults.
Design and performance of a deformation gear with two independently moving walls

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In order to complement the equipment of our structural lab we designed a sandbox with two independently moving walls which may be monitored through an automated system. Operations are controlled through an arduino-based software, which steers the movement of two stepper motors aligned along two steal zippers. Input parameters are propagation speeds, which are independently fixed for each wall, direction of movement and movement distance. Materials used are sand, spherules, clay and parafines. In order to determine velocity fields in granulated material, we added colored marker particles which, at a sufficiently low concentration (< 1%), do not alter the physical properties of the experiment. Tracking their incremental displacements allowed establishing movement paths for the span of an entire experimental run.

In order to test the reproducibility of our experimental array, we performed benchmark experiments considering the displacement of one wall, as established by Schreurs et al. (2006). Varying the displacement from 5 cm/h to 200 cm/h within a same experimental set-up, we noted a strain hardening, as expressed by an increased slope angle of the wedge and major fault dips.

In order to examine the effect of a pre-existing deformation we produced oppositely facing wedges during two successive deformation phases, moving each sandbox wall by an equal amount of distance. In these composite runs we allowed for a sufficient wedge spacing in order to avoid an interference of frontal faults. The two wedges displayed an equal number of faults, though less spaced and more inclined in the case of the second wedge. By its array, wedge two recorded a higher topographic angle, in analogy to wedges produced at higher strain rates. We tentatively conclude, that pre-existing deformations may induce strain hardening during an opposed shortening by imposing textural or structural anisotropies.

**Key words:** Sandbox with two moving walls, strain rate, wedge angles, deformation-induced strain hardening.
Imaging of dense particle suspension in fluid flow

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To explore the interstitial fluid motion through a freely evolving granular medium, we study the dynamics of dense suspensions of quasi-neutrally buoyant particles in a continuum fluid flow. Specifically, we consider the flow of a Newtonian liquid (water) laden with cm-sized particles (hydrogel spheres) at volume fractions 5%-30%. The choice of the material is dictated by the will of obtaining an unobstructed view of both phases. A paddle wheel circulate water in a racetrack-shaped flume. We illuminate a thin vertical slice using an infra-red laser, and measure the particle concentration and velocity by Particle Tracking Velocimetry (PTV) using a high speed CMOS camera. The fluid is also laden with microscopic silver-coated particles which do not affect the flow and behave as perfect tracers. Imaging of the tracers then allows the simultaneous measurements of the fluid flow at sub-millimeter resolution using Particle Image Velocimetry (PIV). With increasing particle volume fraction, the fluid flow boundary layer profile (which is fully turbulent in absence of particles) changes from a classic logarithmic shape to a linear-like shape. The particles have a similar velocity profile but systematically lag the fluid. The particle concentration profile has two peaks: one adjacent to the wall, corresponding to a layer of particles close to the packing limit, and a second one at a significant distance from the wall. The variety of phenomena at play suggests that the definition of macroscopic rheology for this class of flows would be non-trivial.

Figure: The flume powered by the paddle wheel (left) and particle suspensions at different volume fractions (right).
Stress concentration, Initiation and Propagation of fractures using Cheese

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* This class activity is inspired by an exercise developed by Dave Bice at Penn State Univ. (http://serc.carleton.edu/introgeo/demonstrations/examples/cheese.html). The current activity has been modified for the current class activity.

**Purpose:** The purpose of this demonstration is to show the concept of stress concentration, fracture initiation and fracture propagation in rocks.

**Materials:** Three different varieties of cheese (a) Yellow American Cheese, (b) Swiss Cheese with pre-existing holes, and (c) Pepper jack Cheese. The yellow homogenized American cheese represents homogenous rocks. The Swiss cheese with holes is used for represent idealized pre-existing cracks present in rocks. The holes are also used to study direction of propagation of fracture relative to the direction of applied stress. Pepper jack cheese contains small fragments of pepper in homogenized cheese. The fragments of pepper represent micro-cracks in real rocks.

**Activity 1:** Please recall the concepts discussed pertaining to initiation of fractures in rocks. Please take a slice of the yellow American cheese and apply a tensional stress slowly. Observe when any fractures open up. Note the direction of propagation of the fracture with the application of stress. Note the angle the long axis of the fracture makes with the edges of the square slice of cheese.

**Activity 2:** Please take a slice of the Swiss cheese and apply a tensional stress slowly. Observe where fractures open up. Why do the fractures initiate where they do? Note the direction of propagation of the fracture with the application of stress. Note the angle the long axis of the fracture makes with the edges of the square slice of cheese.

**Activity 3:** Please take a slice of the Pepper jack cheese and apply a tensional stress slowly. Observe where fractures open up. Why do the fractures initiate where they do? Note the direction of propagation of the fracture with the application of stress. Note the angle the long axis of the fracture makes with the edges of the square slice of cheese.

**Activity 4:** Please redo the activities 1-3 and indicate the type of fractures observed in the activities. As you redo the activities please not how different fractures that form during the deformation process interact. What is the angle between two interacting individual fractures.
The Microstructural Evolution of Quartzite During Gradually Increasing Stress

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Analysis of rock deformation experiments can be used to better inform studies of the stress history of geologic fault zones. While it is thought that most rocks experience a gradual increase in stress as they approach the brittle-ductile transition during exhumation, experiments simulating a stress increase during dislocation creep were not previously carried out. Figure 1 left panel is graphical representation of the general block diagram New Zealand's Alpine Fault and exhumation stress path depicted by the blue arrow. Recrystallized grain size in shear zones is often bimodally distributed. Figure 1 right panel is the EBSD map the typical New Zealand Alpine fault metachert from mylonite zone. We hypothesize that such distributions might form as a natural consequence of the gradual stress increase while rocks approaching brittle ductile transition.

We carried out several general-shear, Griggs rig experiments on quartzite annealed at 915°C and confining pressure of 1 GPa. Stress was increased in the experiments by gradually decreasing the temperature at various constant rates. Experimental design and mechanical data are presented along with discussion on grain growth and evolution. Preliminarily results showed that the technique is able to successfully simulate the exhumation stress path. Detailed study of the microstructure and grain statistics of experiments of this type has the potential to revolutionize the way that geologists interpret quartz microstructures. Evidence for widespread non steady state deformation at deep crustal levels demands a new series of experiments exploring the several exhumation stress histories. The results of the experiments can also be used to test grain size evolution theories such as the paleowattmeter.

Figure 1. Left panel depicts the long term steadily stress increase while rocks exhume towards the brittle-ductile transition (modified after Norris and Cooper, 2003). This hypothesis could be the main cause of forming quartz microstructure in mylonite zones. Right panel, is the EBSD map of the typical quartz microstructure from mylonitic metachert of New Zealand’s alpine fault. Color scale is quartz area (μm²).
Numerical modeling of large igneous wedges along volcanic rift margins

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Large igneous wedges along volcanic rift margins are identified globally from multi-channel seismic data as seismic reflectors. These reflectors that dip toward the ocean with a concave upward shape are called Seaward Dipping Reflectors (SDRs). The detailed geometry of the SDRs like the maximum depth and variations in dip angles are controlled by the thermal-mechanical evolution history of magmatism and tectonics. Thin elastic plate solution successfully shows that various structures can be reproduced merely by volcanic loading induced plate bending and that the result is very close to the two dimensional “pure elastic” numerical model result. The extra bulge off-axis produced from thin plate theory is suppressed when lava distribution is restricted to areas near the rift axis. Numerical models that can take into account the effects of plasticity with fixed thermal structure show minor difference to the “pure elastic” solution. However, when thermal evolution due to dike injection and downward advection of SDRs is calculated, plasticity plays a more important role in bending the plate and rapid subsidence of SDRs are reproduced.
How does the crust accommodate oblique-convergence?: Using physical experiments to investigate slip partitioning development along subduction zones.

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Slip partitioned systems, or fault systems that accommodate oblique convergence with different slip rake on two or more faults, are well documented in the crust (e.g. along subduction zones like the Great Sumatra Fault or Median Tectonic Line of Japan). Carefully scaled physical experiments using crustal analog materials inform our understanding of fault evolution because we can control the loading and directly observe the ensuing deformation. We simulate oblique convergence using blocks with 30° dipping contacts under wet kaolin clay where the overlying crust is obliquely thrust over the subducting slab. The non-zero cohesion of wet kaolin produces long-lived fault structures that easily reactivate. This long-lived behavior is particularly important for modeling the evolution of fault systems as the abandonment and reactivation of individual fault segments approximates the evolution of faults in the crust. Over eight experiments, we test convergence angles from 5˚ to 20˚ from margin parallel for experiments with and without a precut vertical fault in the clay. The precut experiments simulate a subduction system with a zone of pre-existing crustal weakness from intra-arc volcanism. We continuously document the development of slip partitioning with high-resolution stereo pair images. Digital image correlation from the images, combined with stereovision techniques, provides the incremental horizontal displacement and uplift fields. These state of the art methods provide complete slip vectors for the faults, constrain fault dip and provide strain fields surrounding the fault. The experiments reveal three styles of slip partitioning development—contingent upon convergence angle and the presence or absence of a pre-existing vertical fault. Across all experiments, the slip rates along slip-partitioned faults vary temporally suggesting that the faults continuously adjust to conditions produced by the other fault. The lack of steady state in the experiments suggests that slip-partitioned crustal systems may also evolve with oscillating behavior rather than developing a single efficient active fault structure to accommodate oblique convergence.