Abstracts

PyLith: A Finite-Element Code for Modeling Quasi-Static and Dynamic Crustal Deformation

We have developed open-source finite-element software for 2-D and 3-D dynamic and quasi-static modeling of crustal deformation. This software, PyLith (current release is version 1.9) can be used for quasi-static viscoelastic modeling, dynamic spontaneous rupture and/or ground-motion modeling. Unstructured and structured finite-element discretizations allow for spatial scales ranging from tens of meters to hundreds of kilometers with temporal scales in dynamic problems ranging from milliseconds to minutes and temporal scales in quasi-static problems ranging from minutes to thousands of years. PyLith development is part of the NSF funded Computational Infrastructure for Geodynamics (CIG) and the software runs on a wide variety of platforms (laptops, workstations, and Beowulf clusters). Binaries (Linux, Darwin, and Windows systems) and source code are available from geodynamics.org. PyLith uses a suite of general, parallel, graph data structures for storing and manipulating finite-element meshes. This permits use of a variety of 2-D and 3-D cell types including triangles, quadrilaterals, hexahedra, and tetrahedra. Current PyLith features include prescribed fault ruptures with multiple earthquakes and aseismic creep, spontaneous fault ruptures with a variety of fault constitutive models, time-dependent Dirichlet and Neumann boundary conditions, absorbing boundary conditions, time-dependent point forces, and gravitational body forces. PyLith supports infinitesimal and small strain formulations for linear elastic rheologies, linear and generalized Maxwell viscoelastic rheologies, power-law viscoelastic rheologies, and Drucker-Prager elastoplastic rheologies. Current software development focuses on coupling quasi-static and dynamic simulations to resolve multi-scale deformation across the entire seismic cycle and the coupling of elasticity to heat and/or fluid flow.

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Geodynamics of Mantle Plume Fluctuation and Termination

Mantle plumes play a significant role in plate tectonics and mantle convection; plume upwelling is the mantle's active counterpart to subduction zone downwelling of tectonic plates. Field observations and experimental and numerical modeling suggest possible processes for how mantle plumes initiate and persist. However, very little work examines the termination of mantle plumes despite several authors noting observations of 'dying' plumes in models and in observations. The objective of the study is to quantify the connections between variations in surface observables such as magma flux, the underlying mantle dynamics, and how these processes relate to mantle plume termination. In this study, we utilize a database of observable surface expressions along age-progressive hotspot island chains that includes erupted volcanic volumes, spacing between volcanic islands, and geochemical evolution along the tracks. These data will constrain numerical and laboratory models of plume dynamics and termination. Hypothesized mechanisms for fluctuation and termination include the entrainment of denser material from the source CMB, subducting plate interaction, solitary waves, and large-scale mantle flow. The results of the experimental and numerical modeling will be compared to the surface expressions to determine the connections between the Earth's surface and the deeper dynamics of mantle plume fluctuation and termination

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

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 themodel 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.

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CrusDe: A plug-in based simulation framework for composable CRUstal DEformation studies using Green's functions

CrusDe is a plug-in based simulation framework written in C/C++ for Linux platforms (installation information, download and test cases: http://www.grapenthin.org/crusde). It utilizes Green's functions for simulations of the Earth's response to changes in surface loads. Such changes could involve, for example, melting glaciers, oscillating snow loads, or lava flow emplacement. The focus in the simulation could be the response of the Earth's crust in terms of stress changes, changes in strain rates, or simply uplift or subsidence and the respective horizontal displacements of the crust (over time).

Rather than implementing a variety of specific models, CrusDe approaches crustal deformation problems from a general formulation in which model elements (Green's function, load function, relaxation function, load history), operators, pre- and postprocessors, as well as input and output routines are independent, exchangeable, and reusable on the basis of a plug-in approach (shared libraries loaded at runtime). We derive the general formulation CrusDe is based on, describe its architecture and use, and demonstrate its capabilities in a test case. With CrusDe users can: (1) dynamically select software components to participate in a simulation (through XML experiment definitions), (2) extend the framework independently with new software components and reuse existing ones, and (3) exchange software components and experiment definitions with other users. CrusDe's plug-in mechanism aims for straightforward extendability allowing modelers to add new Earth models / response function. Current Green's function implementations include surface displacements due to the elastic response, final relaxed response, and pure thick plate response for a flat Earth. These can be combined to express exponential decay from elastic to final relaxed response, displacement rates due to one or multiple disks, irregular loads, or a combination of these. Each load can have its own load history and crustal decay function.

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Melt migration, accumulation and lithosphere infiltration using the immersed boundary method

Receiver function studies in regions of melt generation such as hot spots [1,2,3] and rift zones [4] resolve strong gradients in shear wave velocity that may be related to melt distribution in the asthenosphere. In this study, we use a 2D geodynamic model of melt generation and migration to constrain the conditions required for decompacting and compacting boundary layers to give rise to the observed drop in seismic velocity at the lithosphere-asthenosphere boundary (LAB) as well as the increase in seismic velocity observed at depths consistent with the onset of melting.

The 2D geodynamic model solves the standard two-phase system of equations describing melt percolating through a viscously deforming solid matrix. The 1000°C isotherm is taken as the boundary above which melt percolating by porous flow freezes and we assume that this isotherm coincides with the LAB. The immersed boundary method is used to enforce boundary conditions on melt flux, temperature and solid velocity along the LAB. The boundary velocity, determined by a generalized Stefan jump condition, is used to calculate the boundary location through time.

Here, we present results that demonstrate the effectiveness of the immersed boundary method for treating sloping freezing boundaries in the asthenosphere. A test case with an impermeable LAB shows good agreement between the IBM and the near-zero melt fraction approach commonly used in melt migration models. Cases with non-zero flux imposed at the LAB due to dike propagation [5] cause local thinning of the lithosphere at appreciable rates of up to ~10 km/Myr and local thinning results in melt focusing up-slope. Finally, the asthenosphere melt fraction variations predicted by some simulations is sufficient to produce the shear wave velocity gradients required by receiver functions.

References: [1] Vinnik et al., GJI 2005. Seismic boundaries in the mantle beneath Iceland: a new constraint on temperature. [2] Rychert et al., Nature Geo. 2013. Seismic imaging of melt in a displaced Hawaiian plume. [3] Rychert et al., EPSL 2014. Receiver function imaging of lithospheric structure and the onset of melting beneath the Galapagos Archipelago. [4] Rychert et al., Nature Geo. 2012. Volcanism in the Afar Rift sustained by decompression melting with minimal plume influence. [5] Havlin et al., EPSL 2013, Dike propagation driven by melt accumulation at the lithosphere–asthenosphere boundary

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The role of heat on the styles and geometries of continental rupture

The evolution of strain during continental rupture can be quite complex, due to both changes in far-field stresses and/or the naturally evolving strength profile of the lithosphere. Here we use a 2-d finite element model to examine the evolution of rift systems and the relative impact of the initial thermal structure of the lithosphere. We begin with a model lithosphere mimicking the geometry of a paleo-orogen, with a welt of thickened crust. To model the impact of the initial thermal structure, we vary two parameters: the crustal heat production, and the thickness of the lithosphere. Model results indicate that the initial thermal structure of the lithosphere has first-order control on the rifting evolution and subsequent rupture. Two distinct locations of rupture are recognized; rupture in the center of the paleo-orogen, or rupture on the margin of the paleo-orogen. In addition, these locations of rupture can be associated with either a wide or narrow geometry. The location and geometry of the rupture are directly controlled by the initial thermal structure of the paleo-orogen. Modeled systems that rupture in the center of the paleo-orogen occur when the initial temperature of the upper mantle is relatively cool, while systems that rupture on the margin of the paleo-orogen occur when the initial temperature of the upper mantle is relatively warm. Given an initial temperature of the upper mantle (and thus, a known location of rupture), the geometry of the rupture (wide vs. narrow) is controlled by the relative contribution of heat conducted to the upper mantle from the asthenosphere versus the amount of heat generated within the crust. Wide geometries are predicted when significant heat is conducted from the asthenosphere, while narrow geometries are predicted when significant heat is generated within the crust. These results help to explain the variety of rupture styles and geometries observed, and indicate that extensional regions displaying complicated evolutions, such as the West Antarctic Rift System, may be the result of the natural evolution of the strength profile, and do not require external forcing such as changes in plate motions nor impingement of a thermal plume..

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Constraints on Lithospheric Deformation at Convergent Plate Margins from Observationally Based Three-dimensional Numerical Modeling

Flat slab subduction, continental scale faulting, and a non-linear rheology can exert a first order control on lithospheric deformation. I will present results from regional, observationally-based, 3D numerical models that investigate these processes in the eastern Alaska subduction-transform system. The models demonstrate that the location of intra-continental mountain building in the central Alaska Range, and the tallest mountain in North America, Mt. McKinley, can be produced by the modern flat slab configuration in Alaska combined with an intra-continental shear zone representative of the Denali fault. Furthermore, the combination of flat slab subduction and the intra-continental shear zone produce a semi-independent region in the overriding plate that becomes partially decoupled from the greater North American plate, forming an independently moving fore-arc sliver consistent with what has been observed in geologic and geodetic studies as the Wrangell block. I will also present results that focus on the influence of plate boundary coupling on the speed of the subducting plate as well as on the transfer of deformation into the overriding lithosphere, using examples from both the Alaska subduction zone and the Cocos-Nazca subduction system in Central and northern South America.

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NSF EarthCube: Earth Science Bridge – Towards a Model Coupling Cyberinfrastructure for Solid Earth Sciences

We present a large NSF EarthCube collaboration (led by Scott Peckham at CSDMS) to develop semantics and model interfaces that would allow for easier coupling of geodynamics, surface dynamics and landscape topography modeling tools. The grand idea behind the solid Earth component of the project is to enable a computational tool chain for multidisciplinary data assimilation / inversion. The immediate goal is to help link the CIG and CSDMS scientific tool chains, and the corresponding communities, through setting up an interoperability protocol between Pyre and the CSDMS model coupling approaches. We intend to define CSDMS standard names and example Basic Model Interfaces (BMI) for the components of the joint modeling approach that span geodynamic/tectonic modeling, along with synthetic tomography and electrical conductivity outputs, forming a computational "bridge" between these scientific approaches. In doing so, we hope to actively engage EarthScope/IRIS and CIG communities in the development of the semantic standards within CSDMS. The input of these communities will be critical to make the EarthCube cyberinfrastructure useful in practice.

A fully interdisciplinary model coupling framework would provide a pathway for an all-encompassing data assimilation in the solid Earth sciences, as it does with the coupled procedure employed for atmospheric research (e.g., at NCAR). In geophysics, the coupled models (and their variants required for data assimilation, known as adjoints) may be combined in such a way as to infer the true geodynamic processes in the deep Earth, constrained by the true, or measured/inferred, “data” obtained through EarthScope and related programs. While initial attempts to formally link geodynamic processes to seismology have been made (see also Simmons et al, 2006; Ritsema et al, 2007 and others), this is a highly challenging scientific, computational and technological problem requiring a highly multidisciplinary approach. A formal model coupling strategy (as is being addressed through the Earth Science Bridge collaboration) would provide advanced geodynamic data assimilation schemes such as Liu & Gurnis (2008), Spasojevich et al (2009) and Glisovic et al. (2012) with a full set of present-day constraints and a rich modeling toolbox for interdisciplinary transitions. In a truly coupled model, 3-D seismic tomography and magnetotelluric models of the Earth inferred from the data obtained at the Earth’s surface, as well as the actual observed landscape and geology, would all be used as a present-day constraint to infer the historic processes in the deep Earth: their past, present, and future. This would bring us as close as possible to the original goals and objectives of the EarthScope project, which is to explore the 4-dimensional structure and evolution of the North American continent and the processes that cause earthquakes and volcanic eruptions, and hopefully to gain a better understanding of the future of these processes.

SCHEME FOR MODEL COUPLING IN SOLID EARTH SCIENCES. (Refer to Illustration in original abstract)

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Three dimensional morphology and dynamics of ultra-low velocity zones

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 (McNamara et al., 2010). 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.

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Neotectonics of Java, Indonesia: toward understanding upper-plate deformation in orthogonal subduction systems

Refinements and discoveries of how subduction zones function are important to understand their complex dynamics and to develop methods of predicting and minimizing the dangers they pose. Deformation in subduction zones vary as a function of convergence rate, subducting plate geometry, age and morphology. Volcanic arcs are formed as consequence of subduction, but also preserve a record of deformation in the over-riding plate that can be used to infer subduction zones dynamics. Although we generally understand the processes that occur in the subduction zones, mechanisms of strain localization and partitioning are not fully understood. In this project, I use inverse problem methods by extracting upper lithospheric/crustal processes from deformation patterns. I chose Java Island in Indonesia to explore this problem because arc deformation is evident in Java. Java is part of a volcanic arc complex in the Sunda-Banda subduction system where the Indo-Australian oceanic plate moves northward and subducted beneath the India-Eurasian continental plate perpendicularly at an average rate of 6.7 mm/year. Geomorphic, geologic and geodetic evidence of arc deformation are observed in Java but there are few studies that have quantified active deformation. The limited mapping of the region has likely led to an underestimate of hazard in the region though the relatively low seismicity and lack of a continuous structure may indicate that the subduction zone is weakly mechanically coupled to the overlying plate. I use a combination of satellite and field-based mapping, fault kinematic analysis, volcano morphology analysis, and paleoseismic techniques to quantify the active deformation in Java and to develop Java structural model. Furthermore, we will incorporate parameters of the Java subduction system into both physical and numerical model to observe if there will be consistency or discrepancies of the model with our proposed structural model. This will be extremely important to understand the dynamic of subduction system with respect to Java as well as to justify our postulated structural model.

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Overview of Modeling Challenges in Lithospheric Dynamics

Before being on the road to exascale and petascale computations, we need to first be on the road to developing a reliable, robust, accurate, scalable and practical forward model which can used to further our understanding of three-dimensional lithospheric dynamics. To that end, the objective of this overview is to critically examine existing and emerging methodologies which are suitable for simulating lithospheric dynamics.

In this talk I will summarize a range of physical processes which are relevant for studying the dynamics of the lithosphere and highlight the challenges theses processes represent from a computational modeling perspective. This will entail a discussion of the major differences in modeling requirements between the mantle convection and lithospheric dynamics communities. An overview of existing computational strategies for studying lithospheric dynamics will be provided in order to clearly identify the relative strengths and weaknesses of each approach.

Additionally, I will also discuss several methodologies which have been developed within the fluid dynamics and solid mechanics communities, but have yet to be exploited by the computational geodynamics community. Here, purely speculative comments will be provided in regards to the applicability of such methods for studying lithospheric dynamics.

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Fabric evolution, localization, and strain-dependent strength profiles for the continental lithosphere

Plate boundaries must be in some sense weaker than plate interiors, but the origin of this weakness is still a matter of debate. Field observations suggest that the relevant weakening and localization processes in the middle to lower crust and the upper mantle involve grain size reduction and/or development of layers. Changes in deformation temperature or modal proportions have also been proposed. It possible to quantify the weakening associated with each of these phenomena thanks a localization potential developed by Montési (J. Struct. Geol., 2013) that predicts the increase in strain rate resulting from that change under constant stress conditions. According to this potential, the most efficient localization process in the middle crust invokes a structural transition whereby a weak phase in a rock forms interconnected layers. This process is efficient only if one phase is much weaker than the others or if the weakest phase has a highly non-linear rheology. Micas, melt, and fine-grained aggregates – unless dry rheologies are used – have the necessary characteristics. Grain size reduction can induce localization if it is allowed to proceed while a grain-size sensitive deformation mechanism dominates the rock rheology, i.e., when dislocation-accommodated grain boundary sliding (dis-GBS) is active.

These concepts lead to the definition of a strain-dependent strength profile for the continental lithosphere. At low strain (intact lithosphere or plate interior), we may assume fairly large grain size and little layering. The strength envelope of continental lithosphere features a maximum strength in the middle crust and in uppermost mantle, which is needed to form narrow rifts At this point the lithosphere strength profile may be classified as “jelly sandwich”. As the deforming region becomes more active and strain rate increases, strength increases everywhere due to the fundamental strain-rate hardening of ductile rheologies. However, fabric transitions in the middle crust (layering of phyllosilicates) and the upper mantle (grain size reduction and onset of dis-GBS) reduce the strength of these layers. These transitions likely do not take place in the lower crust, where phyllosilicates are unstable. Therefore, the lower crust becomes the strongest layer in active deformation zones and the strength profile evolves towards “crème brûlée”. Including fabric evolution into the evolution of strength envelopes for the lithosphere makes it possible to reconcile laboratory experiments that constrain rock rheologies with geophysical and geodetic observation of earthquake distribution and postseismic creep in active deformation zones. These changes can also stay as part of the lithosphere for long periods of time and facilitate reactivation of ancient plate boundaries.

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Mantle plume effects on oceanic transform evolution

Recent numerical studies of mid-ocean ridges (MORs) and oceanic transform faults (TFs) address whether TFs nucleate spontaneously or as a result of pre-existing lithospheric weaknesses and whether TFs are stable or transient structures. These studies have shown that TFs may nucleate spontaneously by MOR instability or by concentrating deformation at pre-existing weaknesses left by continental rifting processes. Transform stability is dependent on how weakly coupled the fault is relative to plate strength. Despite these new insights into TF dynamics, the impact of nearby mantle plumes on the development, evolution, and stability of TFs is unknown. The Galápagos transform fault (GTF) is a well-studied example of a plume-influenced TF; radiogenic isotope and trace element chemistry of intra-transform lavas is consistent with complex multi-stage melting dynamics and gravity anomalies indicate anomalously thin lithosphere surrounding the GTF. Using a numerical model with a visco-elastic-plastic rheology along with mantle melting, simplified melt transport, and tracking of geochemistry, we will explore the evolution of a TF at a plume-influenced MOR. Parameters to explore include differences in plate motion, transform obliquity, and parameters controlling plume dynamics (e.g., buoyancy flux). We will compare the results of our model to the Galápagos transform fault (GTF), a well-studied plume-influenced TF, and to global observations of the structure, magma flux, and intra-transform lava chemistry of TFs.

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Introducing HiPStER: a new PETSc-based finite-difference / marker-in-cell code for long-term geodynamic simulations

We introduce HiPStER (Highly-Parallel Stokes-solver with Exotic Rheologies), a new code for long-term geodynamic simulations. HiPStER solves for conservation of mass, momentum and energy in a 2D / 3D visco-elasto-plastic continuum using the finite-difference method. Non-linear viscosity and plasticity laws are incorporated directly in the discretized equations and solved with Newton's method using an approximate Jacobian matrix. This approach differs from that of most geodynamic codes, which rely on linear approximations of rheological parameters within Picard iterations. Markers handle advection of various material properties. HiPStER builds largely on the PETSc library, which allows efficient parallelization and offers a wide choice of numerical solvers for inverting the Jacobian. We present a range of 2D and 3D benchmarks aimed at validating the implementation of elasticity, plasticity (formation of localized shear bands), and viscosity (linear / non-linear Rayleigh-Taylor instabilities and Stokes sinker with large viscosity contrasts). In addition, we assess the performance of various solvers on multiple processors and discuss our approach to various challenging aspects of geodynamic simulations (e.g., implementing a free-surface, open boundary conditions, and material mixing).

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Mechanisms of Postseismic Deformation Following the 2010 El Mayor-Cucapah Earthquake

The Salton Trough is an ideal site in which to use postseismic deformation to study the rheology of the crust and upper mantle. In this region, lithospheric thinning has brought the low-viscosity asthenosphere up to within <50,km of the surface, high surface heat flow implies low viscosities throughout the lithosphere, and the transform component of relative plate motion produces large strike-slip earthquakes that impart large stress changes to this low-viscosity structure, likely inducing significant postseismic deformation. The 2010 Mw=7.2 El Mayor-Cucapah earthquake was the largest in the Salton Trough since at least 1892 and the postseismic deformation following this earthquake provides insights into rheology at depth that may be difficult to extract elsewehere. Following a strike-slip earthquake, the polarity of uplift and subsidence resulting from postseismic viscoelastic relaxation depends on the depth of the viscoelastic zone; we use elastic modeling of the 3D coseismic strain field to explain dynamically why this is so and apply it to the case of the El Mayor-Cucapah earthquake. Three-year postseismic displacement time series extracted at UNAVCO GPS stations show four key attributes: 1) the Imperial Valley experienced ~2,cm of uplift in both coseismic and postseismic deformation; 2) significant westward displacement occurred in the Peninsular Ranges, suggesting a deep, long-wavelength deformation mechanism; 3) near-field time series show rapid horizontal displacement in the first year after the mainshock; and 4) that rapid signal is followed by sustained horizontal displacement that is still ongoing at the time of writing. Forward modeling of stress-driven deformation reveals that the uplift in the Imperial Valley and the large displacements in the Peninsular Ranges are best fit to Newtonian viscoelastic relaxation in a low-viscosity asthenosphere with geometry matching the regional lithosphere-asthenosphere boundary inferred from receiver functions. The temporal signal in the near field can be fit to a variety of plausible mechanisms and rheologies but, among them, is well fit to a combination of afterslip on the deep extension of the rupture and Newtonian viscoelastic relaxation in a confined lower crustal zone aligned with shallow Moho, high heat flow and geothermal fields in the Salton Trough.

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DynEarthSol3D: An Efficient and Flexible Unstructured Finite Element Method to Study Long-Term Tectonic Deformation

Many tectonic problems treat the lithosphere as a compressible elastic material, which can also flow viscously or break in a brittle fashion depending on the stress level applied and the temperature conditions. We present a flexible methodology to address the resulting complex material response, which imposes severe challenges on the discretization and rheological models used. This robust, adaptive, multidimensional, finite element method solves the momentum balance and the heat equation in Lagrangian form with unstructured simplicial mesh (triangles in 2D and tetrahedra in 3D). The mesh-locking problem is avoided by using averaged volumetric strain rate to update the stress. The solver uses contingent mesh adaptivity in places where shear strain is focused (localization) during remeshing. A simple scheme of mesh coarsening is employed to prevent tiny elements during remeshing. Lagrangian markers are used to track multiple compositions of rocks. The code is parallelized via OpenMP with graph coloring. We detail the solver and verify it in a number of benchmark problems against analytic and numerical solutions from the literature.

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Is there a discrepancy between geological and geodetic slip rates along the San Andreas Fault System?

Several previous inversions for slip rate along the San Andreas Fault System SAFS), based on elastic half-space models, show a significant discrepancy between the geological and geodetic slip rates along a few major fault segments. In this study we use a more realistic model of an elastic plate over a viscoelastic half space to demonstrate that there is no significant discrepancy between long-term geologic and geodetic slip rates. The model includes ~50 major fault segments having steady slip from the base of the locked zone to the base of the elastic plate and episodic shallow slip based on known ruptures and estimated recurrence intervals to 1000 years before the present. The slip rates are constrained by 1989 present-day velocity measurements from EarthScope GPS and high-resolution interseismic velocity data from L-band InSAR onboard ALOS. Five models with different rheological properties, including an elastic half space, are tested in the slip-rate inversion. A model with a thick elastic plate (60 km) and half-space viscosity of 10^19 Pa s is preferred because it produces the smallest misfit to both the geodetic data and the geological slip rates. We find that the geodetic slip rates from the 60 km thick plate model agree to within the bounds of the geological slip rates, while the rates from the half-space model disagree on certain important fault segments such as the Mojave and the North Coast segment of the San Andreas Fault. In particular along the Mojave segment the recovered geodetic slip rate is 24.7 mm/yr for the half-space model but the result comes closer to the preferred geological rates of 34 mm/yr using a 60 km thick plate model (27.5 mm/yr) and a 30 km thin plate model (34.4 mm/yr). The plate models have generally higher slip rates than the half-space model because most of the faults along the SAFs are late in the earthquake cycle so today they are moving slower than the long-term cycle-averaged velocity as governed by the viscoelastic relaxation process.

Figure 1. Removing the earthquake cycle component from the observed present-day strain field reveals the permanent deformation along the San Andreas Fault System. The colored grid shows the areal strain rate (blue means contraction and red means extension). The vectors are the direction of the velocity field. Long-term tectonic processes might be investigated by this approach.

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Extensional collapse of orogens

Lithospheric extension commonly initiates in orogens either trailing or many eons after the end of orogeny. Using thermo-mechanical models constrained by geological and geophysical observations, we studied extensional collapse of orogens. Assuming a weak mid-crustal shear zone strengthens over time due to cooling and annealing, we showed that variable intensities of decoupling induced by the shear zone between upper and middle crust of variable strength can generate a wide range of extensional structures. Simulations of young orogens with weak to strong ductile middle crust predict three modes of extension dominated by middle crustal extrusion, detachment faults and metamorphic core complexes formation, and upper crustal thinning, respectively. Simulations of old orogens instead predict core complex, diffusive and localized rift mode. We found that core complexes and detachment faults are natural products of gravity driven middle crustal extrusion and exhumation and strong crustal decoupling along the preexisting shear zones in a favorable state of stress in collapsing orogens. Based on our numerical simulations and previous geological and geophysical observations, we categorized core complexes into four groups: i) massifs, ii) single large asymmetric core complex (classic core complex), iii) multiple less evolved core complexes, and iv) subsurface 'core complex'. We also recognized three types of detachment systems, each of which corresponds to unique styles of hanging wall normal faults as well as geological and geophysical conditions. Depth-dependent stretching, middle crustal flow and regional stress rotation are critical for the unique styles of extension in collapsing orogens and evolution of core complexes and detachment faults. Our models consistently predict diverse geological and geophysical observations in young Cenozoic/Mesozoic orogens such as US Cordillera, the Aegean, and Papua New Guinea as well as old Caledonian to Variscan orogens along the North Atlantic margins.

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A 3-D Geodynamic Model of Strain Partitioning in Southern California

In southern California, strain resulting from the relative motion between the Pacific and the North American plates is partitioned in a complex system of transcurrent, transcompressional, and transtensional faults. High-precision GPS measurements in this region have enabled kinematic modeling of the present-day strain partitioning between major faults in southern California. However, geodynamic models are needed to understand the cause of strain partitioning and to determine strain in regions where faults are blind or diffuse. We have developed a regional-scale geodynamic model of strain partitioning in southern California. This 3-D viscoelasto-plastic finite element model incorporates first-order fault geometry of the major active faults in the region. The model domain includes an elastoplastic upper crust on top of a viscoelastic lower lithospheric layer. Deformation is driven by the relative motion between the Pacific and the North American plates, imposed as a displacement boundary condition. Plastic deformation both within the fault zones and in the unfaulted surrounding crust is calculated. Our results show that the Big Bend of the San Andreas Fault, and other geometric complexity of faults in southern California, plays a major role in strain partitioning. The observed variations of strain portioning in southern California can be explained by the geometric configuration of fault systems relative to the relative plate motion, without appealing to basal traction of a flowing lower lithosphere. The model predicts concentrated plastic strain under the reverse fault systems in the Transverse Ranges and the young and diffuse faults in the Eastern California Shear Zone across the Mojave Desert, where a number of damaging earthquakes occurred in the past decades.

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