EUG XI

Symposium MS08

Mantle Convection and Lithosphere Deformation

Convenors

Yuri Podladchikov
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MS08
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MS08 : WEpm25 : F6
Super-Zed Pattern; the Pattern when Very Large Fracture Zones adjust to New Spreading Directions

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Menard and Atwater (Nature, 1968) looked at fracture zone and magnetic anomaly data in the northeast Pacific and showed that when changes in spreading direction between the Pacific and Farallon plates occurred, the orientation of fracture zones and rise crests between fracture zones changed direction accordingly in a pattern they named the 'Zed-pattern'. This topic was revisited by Hey, Menard, Atwater, and Caress (JGR, 1988); propagating rift 'sweeps' re-align the rise crest segments to become perpendicular to the new orientation of the fracture zones, a modification of the original 'Zed-pattern'. We look at the very large offset fracture zones (the Mendocino, Murray, Molokai, Clipperton, etc.) which have another variation on this pattern. The more recent part of the Mendocino Fracture Zone is a single strand oriented east-west. At an earlier time (~45 Ma), the Pacific-Farallon relative motion was more northeast-southwest oriented, and the (single) large-offset Mendocino was instead several smaller fracture zones oriented with this different relative-spreading direction. At an even earlier time (~70 Ma), the Pacific-Farallon relative spreading was near east-west and the many small-offset fracture zones were combined in a single strand. The Murray Fracture Zone has the opposite sense of offset than the Mendocino. Here, during the 70-45 Ma interval when the Mendocino has multiple strands, the Murray has only one; older than 70 Ma and younger than 45 Ma, it has many. The Molokai Fracture Zone, which has the same offset as the Mendocino, is multiple-single at the same times as the Mendocino; the Clipperton, which has the same offset as the Murray, has the Murray's multiple-single pattern. Some of these changes in morphology of the great fracture zone single-strand/multiple-strand patterns occur in the Cretaceous quiet zone; this change in pattern can be used to assign concurrent ages to these different places in the Pacific basin. Small offset fracture zones (i.e., Pioneer) don't have the single/multiple strand behavior (they behave as described in the Menard and Atwater paper); these fracture zones are the best to use when finding the finite rotations needed to define the history of a plate-pair.

MS08 : WEpm27 : F6
An Elastic Layer in the Mantle-Lithosphere Boundary can Make the Difference in the Modelling of Lithosphere Deformation

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The critical taper theory has been widely used in the understanding of the mechanics of formation of mountain belts. This theory is particularly fit to study the mechanics of development of accretionary wedges and thin skinned tectonics. For the brittle upper crust, exact and approximate solutions have been derived for two-dimensional deformation of thrust wedges having constant surface slopes. This theory predicts that wedges attain critical angles of taper depending on the internal and basal coefficients of friction. Conversely, when reasoning at the scale of the entire lithosphere, we question about the effects of the presence of an elastic layer(s) during contraction as a result of plate convergence. The answer to this question is the aim of this work. Fully three-dimensional problems are less amenable to exact solution, and thus we have chosen experimental modelling as an alternative approach. Our experiments were designed to investigate the role of an elastic layer in the mantle-lithosphere boundary (or in a ductile/brittle boundary within the lithosphere) on the deformation of the lithosphere and on the topography created during shortening due to plate convergence. We also investigated what instabilities and lateral heterogeneities in that boundary could be responsible for the progressive development of arcuate thrust belts. Experiments were conducted on sandpacks overlying ductile PDMS (poly-dimetil-syloxane) with an intervening thin film of elastic material. The test model was contained in a rectangular box and was shortened by a straight rigid piston with width equal to the width of the box. The most critical result is that the thin elastic film forces the upper surface of the ductile PDMS layer to buckle. The geometry of this deformation is dependent on elastic layer thickness, thickness distribution and strain rate. The shortened surface of the PDMS/elastic layer pack resembles that of mountain ranges, with periclinal antiforms and synforms that witness heterogeneous noncylindrical folding.

MS08 : WEpm29 : F6
Behaviour of the Lithosphere and Upper Mantle during a Young Continental Collision: Numerical Modeling and Observation

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The nature of deformation of the lithosphere and upper mantle during continental plate collision still remains unresolved. It has often been proposed that the mantle lithosphere is removed mainly by a process of Rayleigh-Taylor type instability of a thickened lithospheric (viscous) root. Our recent work, however, suggests that significant portions of convergent mantle lithosphere may also behave in a distinctly plate-like manner and essentially undergo subduction. To consider further this issue we model the thermochemical evolution of the lithosphere-mantle system using arbitrary Lagrangian-Eulerian (ALE) finite element techniques. We incorporate a mix of viscous (thermally activated power-law creep) and plastic (frictional Coulomb with strain softening) rheologies in the numerical experiments to treat disparate composition in the crust, mantle lithosphere and asthenosphere. A range of rheological and mechanical parameters is explored to determine controls on the style of deformation. In models with a dry olivine mantle, for example, we find that convergence is accommodated by subduction as the mantle lithosphere behaves predominantly in a plate-like fashion and descends as a coherent slab. With a wet olivine rheology, approximately the upper half of the mantle lithosphere continues to subduct, but the lower portion develops as a Rayleigh-Taylor viscous `drip' and is removed as a mantle downwelling. In an alternate series of experiments the mantle lithosphere tends completely toward this dripping instability when the crust is doubled in thickness and the associated higher temperatures result in a low viscosity mantle lithosphere. These modeling results are interpreted in the context of observed deformation across South Island, New Zealand. Recent geological and geophysical evidence there provides some insight into the nature of deformation during active, young continent-continent collision. We reconcile the models with these observations and suggest that the lithosphere may be undergoing a combined slab-like subduction and viscous gravitational instability.

MS08 : WEpm30 : F6
Plate Reorganization Events Triggered by Radiogenic Mantle Heating

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Plate reorganizations (changes in plate motion direction) are a poorly understood phenomena of plate tectonics. The most well known reorganization occurred at approximately 43 million years ago and was recorded by the bend in the Hawaiian-Emperor seamount chain, although plate reorganizations have also been documented in the Paleozoic based on continental paleomagnetic evidence. We have documented a mode of convection in 3D Cartesian mantle convection models with strong dynamic plates, where the direction and magnitude of plate motion driven by changing convection patterns, changes over a short interval of time. Changes in plate motion occur in nearly periodic to random time intervals depending on the size of the plates, the amount of internal heating, and other parameters. We find that internal heating in the mantle plays a critical role in this behaviour because plate reorganizations in the models are driven by the growth of a hot, buoyant, region of fluid in the relatively isolated core of the plate-scale flow pattern. These hot regions result from internal heating and drive flow opposing the plate-scale flow. Flow driven by the hot region decreases the shear traction aligned with the direction of plate motion and results in a decrease in plate velocity. Eventually, the plate scale flow is weakened by tractions on the base of the plate that result from the flow generated by the hot buoyant region, leading to a reorganization event. The time scale of the process is on the order of 200 million years. Our analysis shows that plate motions vary in magnitude but are uniform in direction until the onset of a plate reorganization event. During these events, plate motion changes dramatically over a period of a few million years. Subsequently, plate motions settle back into a steady period in which the plate velocities become nearly fixed in direction until the start of a new reorganization event. Because this behavior is controlled by the growth of a hot region of fluid near the downwelling flow, we predict that there will be an increase in heat flow and shallowing of the ocean floor near downwellings before a plate reorganization occurs.

MS08 : WEpm33 : F6
Thermo-Mechanical Models of Orogenic Collision Stage

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The thermo-mechanical development of orogenic belts during continent-continent collision stage are modelled by upper mantle convection models. The numerical calculations are carried out with the 2-D convection code FDCON by H. Schmeling (Schmeling & Bussod 1996). Thermal and compositional convection is included in the models which provide conservation of mass, momentum and energy. To take dynamic interaction between crust and mantle during orogenic evolution into account, the models cover convection in the upper mantle, i.e. a scaling depth of 670 km. Crustal and mantle rheologies are assumed to be temperature- and stress-dependent. Lithospheric Mantle and asthenospere are selfconsistently defined by their properties and the evolving physical state. Thermal boundary conditions are 0° C at the surface and a constant heat flux from the lower mantle of 20 mW/m^2. Together with radiogenic heatproduction within cust and mantle these assumptions lead to a surface heat flux of about 53 mW/m^2. The potential mantle temperature is 1200°C. Mechanical decoupling of the continents is realised by a pre-described weak zone "cutting" the lithospheric mantle. Plate motions are pre-described by 2 cm/a velocity on the lithospheric mantle of one of the continents. The models show complex crustal development as "crocodile" structures, entrainment of the lower crust into the mantle and transport of slices of lithospheric mantle into mid-crustal levels. From the physical point of view the models govern transition from "plate-kinematic" collision stage to "self-dynamic" orogenic evolution. Model observables are synthetic PTt-paths, thermal and mechanical properties during orogeny and resulting surface heat flux. The models show that crustal root formation strongly depends on the choice of rheology and the (pre)existence of weak zones in the lithosphere (Arnold et al., 2000). Numerical models for lithospheric root detachment developed by B. Schott (Schott and Schmeling 1998)show similar results, i.e. regions with rheological weakening within the orogen are explicitly required for root detachment. 2D thermo-mechanical models for uplift history of metamorphic core complexes with tectonic inversion of E. Sebazungu (Willner et. al. 2000) have shown the significance of geometrical and rheological features of these weak zones, too.

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Wednesday PM Session

MS08 : WEpm34 : F6
Folding of Layered Rocks: Analytical and Numerical Models

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Analytical and numerical models to investigate the mechanics of folding of layered rocks are presented. First, folding of a viscoelastic layer embedded in a viscous matrix is studied analytically using two viscoelastic rheological models: The Maxwell and the Kelvin model. The layer deformation behaviour approximates the viscous or elastic limits depending on the single parameter, R, which is proportional to the viscosity contrast and the ratio of layer-parallel stress to shear modulus. A layer with Maxwell rheology approximates this limit that generates the fastest amplification whereas a layer with Kelvin rheology approximates the slowest limit. For R<1 the viscous limit is fastest whereas for R>1 the elastic limit is fastest. The Kelvin rheology is suitable to describe the effective flexural response of a lithospheric plate consisting of an elastic layer overlying a viscous layer, since the Kelvin rheology yields an identical bending moment. A critical elastic layer thickness, $R^2H/3$ (H=lithospheric thickness), is derived at which the deformation behaviour of the lithospheric plate changes from quasi-viscous to quasi-elastic. Second, an analytical expression for the amplification rate during folding under gravity of a ductile (power-law) layer resting on a viscous matrix of finite thickness is derived. A dimensionless parameter, S, combines the effective viscosity contrast between layer and matrix and the Argand number, the ratio of stress caused by gravity to stress caused by shortening. S enables calculating the critical layer thickness for which gravity becomes significant. Calculations show that large-scale, gravity-controlled folding can only take place for a certain range of Argand numbers. Third, a numerical algorithm is presented that simulates large deformations of heterogeneous, viscoelastic materials in 2D. The algorithm is based on a spectral/finite-difference method and uses the Eulerian formulation including objective derivatives of the stress tensor in the rheological equations. The derivatives in the direction of periodicity are approximated by spectral expansions whereas the derivatives in the direction orthogonal to the periodicity are approximated by finite-differences. The performance of the numerical code is demonstrated by calculation of the pressure field evolution during folding of viscoelastic multi-layers. The algorithm is stable for viscosity contrasts up to 500000, which demonstrates that spectral methods can be used to simulate dynamical systems involving large material heterogeneities.

MS08 : WEpm35 : F6
Thin-Sheet Dynamics of Subduction

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The mechanisms that control the geometry of subducted slabs and the state of stress within them remains poorly understood, especially in realistic three-dimensional configurations. I present a model in which the slab is regarded as a thin viscous sheet whose shape is described at each point by a metric tensor $a\alpha\beta$ and a curvature tensor $b\alpha\beta$. By performing asymptotic expansions of the viscous flow equations in powers of the sheet's 'slenderness' ε, I derive a set of two-dimensional equations that describe the sheet's instantaneous response to arbitrary body or surface loading. The model is completed by a set of kinematic equations describing the time evolution of the sheet's thickness and shape. An analytical solution of the equations in the ``shallow-sheet'' limit shows that the sheet responds to loads by a combination of stretching and bending, in a proportion that depends on the sheet's principal curvatures k_1 and k_2 and the characteristic wavelength L of the applied load. In general, large local values of the dimensionless curvature $L(k_1^2 + k_2^2)^{1/2}/\varepsilon$ favor stretching ('membrane' response), whereas small values favor bending. Both responses are important in subduction dynamics. I illustrate these ideas using numerical solutions of the thin-sheet equations for two idealized model problems: (1) a flat viscous sheet extruded horizontally at speed U_0 (the 'plate speed') and deforming under its own weight. The sheet's hinge point migrates in the direction opposite to the plate speed, which may explain the phenomenon of 'trench roll-back'. (2) A viscous sheet initially in the form of a spherical cap which sinks along an arc-shaped trench. The dynamics of the sheet are controlled by folding/buckling instabilities of a basic membrane state, a result with important implications for the distribution of stress in subducting slabs.

MS08 : WEpm36 : F6
Plate Equilibrium over the Rotating Earth

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The location of the spreading and subduction sources of the plate motion is permanently modified because the evolution of rigid plates tends to scatter the spreading sources and to bring closer the subduction sources. It results in a lithospheric twist along a great circle that presently runs along the San Andreas fault and the SW Indian ridge, and can be traced back through geological times. Plate tectonics rules a permanent upward and downward mass exchange between the lithosphere and the astenosphere. Considering the Earth's rotation, the conservation of the cinetic momentum of the exchanged masses imparts a retrograde rotation of the lithosphere. The centrifugal force keeps its centre of mass in the equatorial plane. Singular cases excepted, the twist motion pushes the centre of mass away from the equatorial plane. This perturbation of the Earth's gyroscope is immediatly corrected by the rotation of the twist great circle around the second axis of inertia of the Earth. The great circle is thus attached to this equatorial axis of the inertia reference frame. During its retrograde rotation, the centre of mass of the lithosphere moves from one side of the great circle to the other. Accordingly, the renewal rate of the lithosphere, which replaces an old, heavy oceanic lithosphere by a young, light one, is alternately maximum at one and at the other side. Hence, the two upwelling columns of the lower mantle, presently below the Pacific and Africa, are alternately prompted. With reference to the plate history, this dual engine appears to have ruled the opening, then closure, of the Tethys ocean, and, in a general way, the gathering, then dispersal, of continents, at a 350-400 Ma period.

MS08 : WEpm37 : F6
Seafloor Spreading: A Way towards the Coupling between the Lithosphere and the Upwelling Mantle

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The development of a quantitative theory of plate tectonics should clearly show how the thermo-mechanics of the lithosphere and the flow of the underlying mantle are connected. With this end in view, we study the asymptotic structure suggested by the existence of two length scales arising from the advection-diffusion of temperature. To illustrate how it works, the much-studied problem of seafloor spreading is revisited assuming an incompressible plastic/viscoplastic constitutive model. It is shown that the steady two-dimensional dynamics of the oceanic lithosphere is controlled by the horizontal velocity at the spreading ridge and the temperature of the upwelling mantle beneath the ridge. Futhermore, if the mantle is hot enough, the lithosphere sustains a state of horizontal tension balancing the friction of the mantle acting on the overlying lithosphere. The upwelling of the mantle is then driven by motion of the plate, which, in turn, results from a horizontal force pulling on the lithosphere far from the ridge. The magnitude of the lithospheric tension determines the depth of brittle/ductile transition, while the horizontal strain rate then follows from continuity of stress at transition. The strain rate is found to be small, implying that the horizontal velocity is nearly constant in the lithosphere. Thus, above a 'critical temperature' of the upwelling mantle, the concept of the oceanic lithosphere as a thermal boundary layer moving with constant horizontal velocity is upheld. This indicates that the appropriate boundary condition for mantle convection is a constant horizontal surface velocity although this may cease to be true at lower upwelling temperature.

MS08 : WEpm38 : F6
Mantle Advection and Geological Structures: Origin and Evolution

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The origin and evolution of geological structures could be a clue forunderstanding of crust-mantle interaction. For simulation of geological processes and geological structures evolution in connection withdeep mantle movements all possible geological-geophysical data werecombined and analysed and the mechanical-mathematical models of different rheology were used. Mantle activity of different scale can be reflected in surface dynamics. So on the basement of super plume can arise instability of smaller scale (diapirs). As plume is responsible for whole Alpine belt activization as diapirs are connected with evolution of the belt sedimentary basins and rifts.

Investigation of deep structure and geodynamic regimes of the lithosphere on the base of deep drilling and geotransects are extreamely important for fundamental Earth sciences development and interpretation of petrological, geological, geothermal and geophysical data. At present time the next scientific deep and superdeep boreholes are drilled in Russia: Kola SG-3 (12261 m), Vorotilov (5374 m), Ural (4950 m), Tyrnyauz (4001 m), Colva (7057 m), Tyman-Pechora (6904 m), Tumen (7500 m), Kuban (4000 m), Tujmazinskaya (3845 m), Minnibaevskaya (5099 m), Novoyelkhovskaya 20009 (5500 m). The drilling is continuing now in Novoyelkhovskaya 20009, Ural and Tumen wells. The Kola superdeep borehole works as geolaboratory and deep observatory for long-term geological and geophysical investigations.

Modelling gives possibility to calculate P-T parameters distribution in the layers of lithosphere and asthenosphere in the process of the evolution. Some geological effects can be explained by mantle dynamics. The existing of stretching zones in back arc basins can be explained by upwelling of mantle diapirs as a result of geothermal effect and raising of asthenosphere in the process of collision of deep mantle flows.

In analitical decision it is possible to find critical parameters of the problem, connecting the form of diapir, its depth and velocity with structure of the Earth's surface. Defining boundary conditions on the basement surface we can get some conclusions about deep mooving in asthenosphere. Mantle upwelling can be evaluated by geothermal-gravity data. The results of modelling are investigated on the example of the Pre-Caspian Depression, Russian Platform, Baikal rift, sedimentary basins of Brazil, Pacific and Alpine belts geological structures and give good agreement with geological-geophysical data.