T42F MC: 308 Thursday 1330h

Viscoelastic Deformation of the Earth: Observations and Models II

(joint with G, S, DI, MR)

Presiding: **J X Mitrovica,** University of Toronto**; S Zhong,** University of Colorado

T42F-01 1330h

Anelastic Modeling of Upper Mantle Seismic Observations: Explaining Rocky Mountain Isostacy and Constraining Rheological Uncertainty

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Utilizing tomographic models of attenuation and velocity derived using the Rocky Mountain Front (RMF) broadband seismic dataset acquired in 1992, this study models the relationships of attenuation to velocity to identify regions of elevated temperature and anomalous rheology. Studies of the area include P, S and surface wave velocity tomography and all indicate slow upper mantle velocities below the Rocky Mountain region. Recent attenuation measurements exhibit a similar trend. The coupling of attenuation and velocity measurements provides an indication of the change in temperature (Karato, 1993). A more vigorous examination of the relationships between attenuation and velocity can provide insight into the rheological parameters of the mantle.

The theoretical basis of the modeling is the complex modulus of the standard anelastic solid under the influence of a thermally activated process (Nowick and Berry, 1972). An activation energy of 500 kJ/mol, the diffusion of oxygen through olivine, is assumed. An integral part of the modeling is the assumption that the thermally activated process has a normal distribution of activation energies. A greater variance of this distribution is an indication of the materials inability to equilibrate differential stress.

Relationships between attenuation and velocity suggest elevated temperatures up to 300 K 100 to 150 km beneath the Colorado Rocky Mountains. This temperature difference is enough to cause density changes partly responsible for isostacy of the mountains. Additional findings include a significant reduction in variance of the activation energies in the upper mantle coincident with the region of elevated temperature. This is due to a softening of the mantle material and may imply the existence of partial melt.

URL: http://ucsu.colorado.edu/~oliverb/AnMod.html

T42F-02 1345h INVITED

Resolving 3D Anelastic Structure of the Upper Mantle

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Through the mapping of 3D variations in elastic velocities and attenuation, global seismic tomography gives us access to key physical parameters for the understanding of global mantle composition and dynamics. With elastic velocities alone, it is difficult to distinguish unambiguously whether the heterogeneity is in temperature, composition or both. Attenuation tomography should provide independent constraints, particularly since Q has a very strong dependence on temperature. Inversion for elastic structure uses the information in the waveform phase/travel times, which are relatively free of effects such as focusing and scattering. On the other hand, in the amplitudes, used for Q inversion, these factors are both strong and difficult to estimate accurately, due to our imperfect knowledge of elastic structure gradients, as well as computational limitations. Our approach for the study of upper mantle 3D Q, in the last ten years, has been to develop rigorous data selection methods in order to minimize, rather than directly correct for, unwanted elastic effects in the amplitudes of long period surface waves. A spectral domain approach allows to do so readily (Romanowicz, 1994; 1995), but is restricted to fundamental modes and therefore limits depth resolution.

Recently, we have developed a time-domain waveform inversion method, which iteratively solves for elastic and anelastic 3D structure and thus holds the promise of resolving Q structure below the transition zone, by combining fundamental and higher mode surface waves as well as body waveforms. So far, we have obtained a stable degree 8 model of Q in the uppermantle by inverting a global dataset of carefully selected three component data. This model confirms the correlation of Q with tectonic features in the first 200 km of the upper-mantle, with high Q signature of shields and low Q along mid-ocean ridges and in back arcs. In this depth range, a low Q region is present in the Pacific, joining Hawai to the Pacific superswell. At greater depths (200-400 km) the connection to tectonics and the Hawai signature fade out, and is replaced by two prominent Q minima, one in the south Pacific and the other under Africa, correlated in their position with the lowermost mantle "superplumes", and encompassing most of the hotspots.

T42F-03 1405h

Superelastic Softening of Perovskites at Seismic Frequencies

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Recent experimental and theoretical studies agree that the lower mantle is significantly anelastic (i.e. there is a time-dependence of the elastic strain, causing attenuation of seismic waves). The origin of this anelasticity is still debated, however. A possible cause is the viscous motion of transformation twin walls. Here we use dynamical mechanical analysis (DMA) to study the effect of transformation twinning on the seismic-frequency elastic properties of perovskites at high temperature. We apply the technique to (Ca, Sr)TiO3, a close structural analogue of the MgSiO3 perovskite phase believed to make up more than 70% of the Earths lower mantle. We demonstrate that superelastic behaviour associated with the motion of transformation twin walls dominates the elastic response over a temperature range spanning several hundred degrees. This is accompanied by a factor-of-two decrease in the Youngs modulus below the cubic to tetragonal phase transition and a rapid increase in attenuation. Freezing of twin domain walls at lower temperatures leads to elastic stiffening and a broad peak in attenuation ($\tan\delta > 0.1$ at 200 °C and 1 Hz). The observations confirm transformation twinning as a possible source of anelasticity and rheological weakening in the lower mantle.

T42F-04 1420h INVITED

Accelerated Buildup of Stresses on the Southern San Andreas Fault and Surrounding Regions due to Post-Landers Viscous Flow

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The San Bernardino Mountain segment of the Southern San Andreas Fault has not ruptured in 190 years and is capable of producing major quakes with magnitudes greater than 7.5. We calculate that coseismic slip associated with the 1992 M=6.1 Joshua Tree, M=7.3 Landers, and M=6.3 Big Bear quakes have raised Coulomb stress on the San Bernardino Mountain segment by 1.5-2 bars. Using viscoelastic parameters that reproduce the observed post-Landers horizontal surface deformation, we calculate that viscoelastic flow in a lower crustal or upper mantle lowviscosity layer may have further added 1-1.5 bars of postseismic stress to the San Bernardino Mountain segment during 1992-2001, while the 1999 M=7.1 Hector Mine quake added yet another 0.2-0.3 bars of coseismic stress. Most importantly, model calculations predict that viscoelastic flow will continuously add stresses to the San Bernardino Mountain segment for a couple of decades to come, with combined coseismic and postseismic stress changes approaching 3.5-5 bars from 1992 to year 2020. These accelerated stress accumulations may hasten the occurrence of a major earthquake on this part of the Southern San Andreas Fault. These results further imply that the Landers and Hector Mine quakes have generated a zone of increased stress that is predicted to migrate toward the Los Angeles Basin as the lower crust and upper mantle relax. Thus stress buildup is also predicted to occur on major portions of the San Jacinto and Elsinore faults in the years to come, bringing these fault zones closer to failure. To the north of the Landers region, near Barstow, viscous flow is calculated to increase stresses on the Calico fault. The San Jacinto and Calico faults may be showing signs of being close to rupture as numerous aftershocks continue to occur in these fault zones. This pattern of observed aftershock clustering and calculated Coulomb stress build-up is similar to that noticed in the Hector Mine region prior to the 1999 M=7.1 quake.

T42F-05 1440h INVITED

Inelastic Behavior of the Lithosphere as Inferred From InSAR Observations

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Constraining the visco-elastic structure of the lithosphere relies on observations of the time-dependent response of the Earth's surface to large perturbations. These perturbations include volcanic intrusions and earthquakes. Models of the inelastic response benefit from a good model of the perturbing process as well as spatially and temporally dense observations of deformation. Interferometric Synthetic Aperture Radar (InSAR) can provide a complete spatial map of the deformation field. We can detect displacement rates of a few millimeters per year by combining many independent interferograms. We can resolve both horizontal and vertical components of the deformation field by combining interferograms from different viewing geometries. This ability to resolve both horizontal and vertical deformation is critical to discriminating between different rheological models.

We demonstrate the use of InSAR to constrain the perturbing process, by considering the co-seismic deformation field associated with the 1999 M_w 7.1 Hector Mine earthquake. The spatial coverage of the InSAR data for this event permits us to not only develop a detailed model of co-seismic slip including the fault geometry, but also provides a sensitivity to the presence of elastic layering and may also suggests the need to incorporate inelastic yielding during or soon after the earthquake.

We illustrate the ability to detect small-scale deformation using InSAR observations of the lithospheric response to the 1975-1985 rifting episode in the Krafla segment of the Northern Volcanic Zone in Iceland. This region experienced a maximum total opening of about 5 to 8 m. Our observations span the time period from 1992-2000, many years after the perturbing event. We use interferograms from several satellite line-of-sight (LOS) directions including two ascending orbital tracks and one descending orbital track. Each track has multiple independent interferograms. Where available, we compare our InSAR observations with ground-based measurements. The LOS relative displacement fields form an asymmetric butterfly pattern, with the asymmetry dependent on the LOS direction. Peak relative displacements rates are between 3 and 4 cm/year. Preliminary analysis suggests that the combination of InSAR and GPS observations will challenge simple models that incorporate only a layered rheological structure.

T42F-06 1520h

The Observed Eigenfrequency of the Chandler Wobble

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In the absence of excitation, the amplitude of the Chandler wobble would freely decay due to dissipation. Mantle anelasticity is one possible dissipation process of the Chandler wobble and is also responsible for the decay of both seismic waves and the Earth's normal modes. Assuming that a single absorption band extends from the Chandler frequency to seismic frequencies, then the observed values for the period and quality factor Q of the Chandler wobble can be used to estimate the frequency dependence of the dissipation. In the past, estimating the period and Q of the Chandler wobble has been hampered by not knowing its excitation mechanism(s). However, it has been recently demonstrated that the Chandler wobble is excited by a combination of atmospheric and oceanic processes, with ocean-bottom pressure fluctuations being the dominant excitation mechanism. Here, products of atmospheric and oceanic general circulation models are used to model the excitation of the Chandler wobble when estimating its period and Q. Implications for mantle anelasticity of this newly determined value for the eigenfrequency of the Chandler wobble are discussed.

T42F-07 1535h

Bonneville, Lahontan, and Minchin: New estimates of crust and upper mantle viscosity and density structure from large lake loads

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Sufficiently large paleolakes are useful probes of crust and upper mantle strength. Each of the shorelines formed by the lakes was horizontal when they formed, but are now found at higher elevations near the basin center, due to isostatic response to the removal of the water load represented by the former lake. Improvements in the input data and in the modeling strategy for three significant paleolakes are reported.

At their maximum extents, lakes Bonneville, Lahontan, and Minchin respectively occupied areas of (49, 22, 56) 10^3 km^2, and water volumes of (8.9, 2.0, 4.5) 10^3 km^3 in western Utah, western Nevada, and western Bolivia, all at nearly the same time. Peak elevations in each case occurred 14-15 kyr BP.

In order to use the shoreline elevation pattern of a paleolake to provide constraints on Earth structure, several ingredients are necessary. In most cases, the easiest to obtain is the spatial pattern of shoreline elevations, and the most difficult to obtain is the temporal pattern of lake surface elevation variations.

In previous analyses of these three basins, the elastic structure (density, rigidity, and bulk modulus) has been held fixed at seismically determined values, and only the viscosity has been adjusted to match the observed rebound pattern. In the present analyses, viscosity and density were both varied in each layer. Small changes in density structure removed long wavelength residuals which were present in the previous analyses.

The Bonneville data set includes slight revisions in loading history, and incorporates elevations from the Bonneville (1550 m), Provo (1440 m), Stansbury (1350) and Gilbert (1300 m) shorelines. Previous analyses have not used the Stansbury data.

The Lahontan data set includes minor revisions to loading history, and incorporates 180 elevations from the highest (Sehoo) shoreline.

The Minchin data set includes substantial recent revisions to the previously used loading history, and corrects a misidentified elevation at one of the survey sites. This error had lead to the suggestion of a basin-wide tilt signal, which is now seen to be spurious.

T42F-08 1550h INVITED

Modeling GPS Observations of the 3D Crustal Deformation Field in Fennoscandia

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Observations of 3-D crustal motion in Fennoscandia obtained via Project BIFROST (Baseline Inferences for Fennoscandian Rebound Observations, Sea Level and Tectonics) show a pattern that is clearly related to the on-going glacial isostatic adjustment (GIA) of the region. To predict the deformation field we adopt a GIA forward model comprised of a spherically symmetric, self-gravitating, compressible, viscoelastic earth model; a number of recent models of the Fennoscandian ice history; and an ocean load computed by solving a recently improved form of the sea-level equation. The contribution to the deformation field from GIA-induced perturbations in the model earth's rotation vector is also incorporated in the predictions. Comparison between the GIA predictions and the GPS-derived observations show a strong correlation, verifying that GIA is by far the dominant contributor to the observed deformation pattern. A series of forward predictions that sample an extensive range of viscosity parameter space yield models that are compatible with those inferred from recent analyses of Fennoscandian relative sea-level data. For example, the viscosity model preferred by this exercise is characterized by a 120 km elastic lithosphere, upper mantle viscosities in the range 5 x 10^{20} to 10^{21} Pa s, and lower mantle viscosities in the range 5 x 10^{21} to 5 x 10^{22} Pa s. We compute a residual deformation pattern by subtracting a best-fitting GIA model prediction from the observed rates. The residual field suggests that that non-GIA processes, such as neotectonics, produce motions of magnitude around 1 mm/yr (in the rsm sense) or less in the region.

T42F-09 1605h

Effects of Laterally Varying Mantle Viscosity on Post-Glacial Rebound from Spherical Finite Element Models

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Observations of isostatic adjustment of the earth's surface due to transient loading provide important constraints on the mantle viscosity structure. However, most studies of this response have assumed a spherically symmetric earth. Seismic observations indicate that the visco-elastic properties of the mantle may include significant lateral variations. Therefore, it is important to study the sensitivity of surface uplift to lateral variations in viscosity structure. To study such effects, we have used 2-D and 3-D spherical finite element software CitcomSVE [Zhong, 2001]. For earth models with spherically symmetric viscosity structure, we were able to test the reliability of the finite element results by comparing against the traditional analytic method for models with a realistic (in space and time) glacitaion-deglacitation model, similar to the history of the Laurentide ice sheet. Having determined that, for sufficiently high space and time resolution, these two methods yielded surface responses that agreed to within 0.5%, we have explored the effects of the size of the updating time-step and self-gravitation in the finite element calculations. We have found that the largest permissible time-step size is $\sim 0.3\eta/\mu$ (where η and μ are the viscosity and shear modulus for the lower mantle) for models with either an isoviscous mantle or a radially stratified mantle where the upper mantle's viscosity is 10 times smaller. The effects of self-gravity are examined with calculations that include different numbers of spherical harmonic degrees in the perturbed gravitational potential (from $l_{max} = 0$ for no self-gravitation, to $l_{max} = 10$, 20, and 32). While self-gravitation has relatively small ($< 2\%$) effects on the vertical motion at the center of the ice disk, its effects at the peripheral bulge are rather significant. The relative difference between the finite element and exact models at the bulge is 15% and 9% for $l_{max} = 2$ and 10, respectively. However, we found that $l_{max} = 20$ seems to be sufficient to represent the self-gravitation. We will use the results of this model to discuss the effects of lateral variations in viscosity on surface response, particularly the sensitivity of the response to the distribution of viscosity anomalies.

T42F-10 1620h

Modeling the Response of a Three-Dimensional, Viscoelastic Earth

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We describe a finite-element numerical scheme for modeling the response of a viscoelastic Earth. The scheme has been developed to consider problems on either global or regional scales and thus has application to both post-glacial rebound and post-seismic relaxation. The method provides a time-domain, fully three-dimensional solution which honors both seismic discontinuities and lateral variations in the viscoelasticity of the mantle and lithosphere.

At each time step, the numerical procedure simultaneously solves for material displacements and the perturbed gravitational potential. Our preliminary calculations adopt the Cowling approximation for the perturbed gravity and assume a Maxwell viscoelastic rheology. We have developed a special tetrahedral grid for regional problems that allows for the treatment of explicit PREM-like discontinuities. The discretization is based on a finite volume approach, combined with a standard linear interpolation within each grid element. This combination results in a fast assembly and an efficiently designed system matrix. The resulting algebraic system is solved based upon an ILU-preconditioned, generalized minimal residual method.

We review the theoretical aspects of the scheme and discuss the results of a series of benchmarks.

T42F-11 1635h

Tectonic Plate Coupling and Elastic Thickness Using a Viscoelastic Model of Crustal Deformation in Southern North Island, New Zealand

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The crustal deformation in the Wellington region of North Island, New Zealand has been studied by inverting GPS-derived crustal velocities using a steady-state viscoelastic model of oblique plate convergence. The deformation is driven by pseudo-backslip on the locked Pacific-Australia plate interface. Finite element techniques are used to calculate effective Green functions for the slip elements and slip velocities are determined from a weighted least squares analysis. The parameters of the model are the depth-dependent backslip velocities, v(z), (or equivalently the coupling between the plates, a = abs[v/V] where V is the relative plate velocity), the elastic plate thicknesses, and the elastic moduli. Seismic data indicate that Young's modulus of the Australian crust is about half that of the Pacific plate. In this case, the model best fits the data when the Pacific plate elastic thickness is 40-60 km and the Australia plate elastic thickness is 100-150 km. These elastic thicknesses are greater than those derived from seamount loading data suggesting that the elastic thickness on the geodetic time scale (decades to centuries) is greater than that on a tectonic time scale (millions of years). The elastic thicknesses increase as the modulus contrast is reduced, but decrease if the modulus contrast is greater than that suggested by seismic observations. The elastic thickness estimates are derived by minimizing the reduced chi-squared misfit between the model predictions and observations. We find that there is a broad range of statistically acceptable elastic thicknesses distributed about the optimal value. However, the coupling distribution is more tightly constrained with strong coupling (a= 0.8-1.0) occurring to depths of more than 20 km. We further find that the fit of the viscoelastic model to the data is marginally better than the fit of the "best" elastic model. Finally we note that most of the information for discriminating between models comes from the trench-normal rather than the trench-parallel components of the horizontal velocities.

T42G MC: 309 Thursday 1330h

Initiation of Subduction: Constraints From the Field and From Modeling II

(joint with OS)

Presiding: **J Encarnacion,** Saint Louis University; **M A House,** California Institute of Technology

T42G-01 1330h INVITED

Spontaneous Nucleation of Subduction Zones in the Western Pacific During Middle Eocene Time: Evidence From the IBM Forearc Ophiolite

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Subduction zones nucleate in two fundamentally different ways. Induced nucleation is a response to continuing plate convergence following a collision event and requires the lithosphere to fail under compression; no change in plate motion is expected. Spontaneous nucleation of a subduction zone (SNSZ) manifests failure of old lithosphere due to gravitation instability. SNSZ doesnt require plate convergence to occur but major changes in plate motion are expected. SNSZ is possible where old oceanic lithosphere is unusually dense (old continental margins) or weak (along fracture zones). The western edge of the Pacific plate spontaneously reorganized as a convergent margin during Middle Eocene time (∼50-42 Ma) and is the best known example of SNSZ. The unusual nature of this episode is preserved