to the tip of the corner flow. These synthetic experiments shed light on a real data set collected in Kamchatka. Directions of fast propagation (and thus mantle flow) inferred from teleseismic shear waves parallel the Kamchatka trench, perpendicular to the expected trench-normal corner flow. The puzzle is resolved with local S waves, which are sensitive only to the supra-slab wedge. Local S reveal a different fast-polarization pattern, which agrees with corner flow in some regions, but trends away from expectations close to the edge of the Kamchatka slab. Thus mantle deformation beneath the slab appears to dominate long-wavelength teleseismic *S* waves, while local *S* phases sense a different fabric above the slab. Better agreement with theoretical predictions is seen in teleseismic shear waves from Adak Island in the Aleutian Arc. Fast shear polarization aligns well at Adak with the direction of oblique plate convergence, consistent with slab-driven wedge flow. From the Kamchatka example one must be concerned, however, about the depth of the detected fabric. Observations of birefringent shear waves are a good tool to study mantle dynamics, but their relation to the mantle flow at depth has significant complications that need to be considered.

T23A-04 1415h INVITED

Surface Topography and Stress-State in Non-Newtonian Models of Slab Dynamics

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Previous studies of subduction zones, using instantaneous dynamic flow models, predict that a region of low viscosity in the shallow mantle wedge, which decouples the slab flow from the overriding plate, is necessary to reproduce surface observations of topography, gravity, and stress-state[1]. However, the lateral extent of the low viscosity region and magnitude of viscosity reduction are only partially constrained by surface observations. Time-dependent models, which also test the consistency of the viscosity structure with the dynamic evolution and thermal structure of the slab and the source region of island-arc magmas, are required to further constrain the wedge viscosity structure and the weakening mechanism(s). We present 2-D, time-dependent, finite element models of thermal convection exploring the dependence of slab dynamics on the viscosity structure in the upper mantle. The viscosity structure evolves in time and is defined by a composite rheology, including both diffusion (Newtonian) and dislocation (non-Newtonian) flow laws and a yield criterion at low temperatures. Subduction with slab dip, varying in time, between 30° and 90° occurs for models that include strain-rate dependence and a high yield strength for the cold interior of the slab. Two low viscosity regions, which overlap in the mantle wedge corner, form in response to high strain-rates: the first lies below the overriding plate where mantle flow is drawn into the wedge corner, and the second occupies a narrow zone above the slab interface to depths of 200–250 km. As in the instantaneous flow models, the development of these low viscosity regions influences the surface topography and stress-state of the overriding plate, in addition to affecting the evolution of the slab thermal structure and thermal erosion of the sub-arc mantle.

1. Billen, M. I., M. Gurnis and M. Simons, Multiscale Dynamic Models of the Tonga-Kermadec Subduction Zone, Geophys. J. Int., 153, 359-388, 2003

T23A-05 1430h INVITED

Dynamic Topography of Oceans and Continents

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The large contrasts in surface topography are one of the most striking features of our planet. Contributions to topography range from short-wavelength uncompensated features due to tectonic activity, to variations in crustal thickness and density structure and long-wavelength deflections of the lithosphere caused by mantle dynamics. Upwelling or downwelling flow in Earth's mantle can elevate or depress the earth's surface even if the sources of buoyancy are deep in the mantle. However, direct observation of this "dynamic topography" has been elusive, because it is obscured by the isostatic contribution due to crustal and lithospheric structure. Any potential confirmation of the role of dynamic topography, sheds light not only on the impact of mantle dynamics on surface processes, but also on the nature of mantle dynamics itself. For example, we expect dramatically different topographic signals from layered vs. whole mantle convection. We have learned a great deal about the consequences of dynamic topography for continental flooding and the formation of large sedimentary basins since the pioneering work of Mitrovica et al. [1989] and Gurnis [1990]. Recently, unequivocal signals of dynamically supported topography have been found in both continents (Africa [Lithgow-Bertelloni and Silver, 1998] and Arabia [Daradich et al., 2004]) and oceanic basins (North-Atlantic [Conrad et al., 2004]). In all three cases, the identifiable dynamic topography signal results from upwelling mantle. In regions associated with downwellings considerable controversy remains [e.g. Wheeler and White, 2002]. There is a hint in this result that relates to the ability of slabs to penetrate into the lower mantle and of upwellings to reach the surface from great depth. We review in this talk the evidence for dynamic topography in continents and oceans, and present some speculations related to the nature of layering in mantle convection.

T23A-06 1445h INVITED

Mantle heat flow beneath the cratons

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Heat flow and heat production data from different cratons are now sufficient to provide information on the boundary conditions at the base of the lithosphere and thus a constraint for models of mantle convection.
In order to determine the heat flow from the convecting mantle, one must determine the crustal heat production. Using the data sets from the Canadian Shield and the Appalachians, we have used different methods to estimate the crustal heat production and the heat flow from the mantle. All these estimates for mantle heat flow range between 11 and 15 mW m^{-2}. On the scale of the Canadian Shield, variations in mantle heat flow do not exceed $\pm$2mW m^{-2}, i.e. the magnitude of the error on these estimates.
In several other cratons where heat flow and heat production distributions are well documented, the mantle heat flow values are close to those in the Canadian Shield, with mantle heat flow estimates slightly lower ($<$ 12mW m^{-2}) for the Baltic and Siberian Shield than for Canada, in the same range ($11 - 17$mW m^{-2}) for India as for Canada, but higher ($15 - 22$mW m^{-2}) in South Africa than in Canada. Thickness of the lithosphere beneath the craton could vary by 40km with Moho temperature (i.e. crustal heat production). For all the cratons, estimates of lithospheric thickness exceed 200km. Heat production in the lithospheric mantle is not included in the budget and would it result in even lower heat flow from the convecting mantle.

T24A CC: 516 D Tuesday 1530h

Mantle Dynamics and Surface Observables II *(joint with G, GP, P, S, SEDI)*

Presiding: **R Pysklywec,** University of Toronto**; S L Butler,** University of Saskatchewan

T24A-01 1530h

Observational (NUVEL) Euler Poles Have the

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Large sets (up to 54,000,000) of arbitrary configurations of Rayleigh-Benard mantle convection polygons were constructed by spherical Voronoi tessellations from random global configurations of fixed numbers (6 to 50) of mantle upwelling centers; collectively (within each large set) the upwelling centers proved to be uniformly distributed on the globe. Using the convection-induced basal shear tractions to drive the full complement (14) of major lithospheric plates, the computed Euler poles of individual plate motions show global patterns of preferred locations. Thus, plates of elongated aspect show a strong preference for their Euler pole to occur on (or near) plate-center, its antipode, or 90 degrees from plate-center in the direction of its major axis; circular plates strongly prefer their Euler pole near 90 degrees from plate center (i.e. on the plate co-centric equator); the strength of preference is greatest for small plates (e.g. the global max / min preference ratio = 380 for the Juan de Fuca plate). Plates which closely satisfy these preference criteria include Juan de Fuca and Philippine (Euler pole located near plate-antipode), Cocos and Arab (near plate), Australia, Pacific, Antarctic and Caribbean (near 90 degrees from plate center). As a second result, when the arbitrary Benard cell configurations are screened (selected) to retainonly those which simultaneously yield the computed Euler poles within circular neighborhoods of the corresponding HS2-NUVEL1 model poles, and reject all other configurations of the set, the results reveal a virtually unique global distribution of upwelling centers; the surviving upwelling centers occur in a small number of clusters centered on (or very near to) Hawaii, Iceland, Reunion, Easter Island, Cap Verde / Canary Islands, Tristan da Cunha, and the Tasman Sea region; the tightness of the clusters is inversely related to the radius of the circular pole-constraint; the remaining global surface is virtually devoid of screened upwelling centers. Earlier work [Pure appl. geophys. v.159, p. 2585 (2002)] has shown that optimization of the Benard cell distribution for the full complement of HS2-NUVEL1 model poles (13 of 14 poles), yields the same upwelling centers, although somewhat displaced, and all poles (except Eurasia) within their error ellipses; the five most accurately known poles (Australia, Cocos, Juan de Fuca, Pacific and Philippine) were fit with a residual norm of $<$ 1 degree positional error. Thus, collectively, the observational Euler poles exhibit the signature of plate motions driven by basal shear forces; the deviations show that these forces are perturbed (by shear-coupling, buoyancy and edge forces).

T24A-02 1545h

Constraints on Mantle Flow Stratification and Three-Dimensional Structure From Joint Inversions of Global Seismic and Geodynamic Data

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Global scale surface observables associated with mantle convection, such as tectonic plate motions, free-air gravity anomalies and dynamic surface topography, provide fundamental constraints on the structure, composition and dynamic state of the convective flow. A number of recent studies based on the simultaneous inversion of global seismic and geodynamic data have highlighted the importance of the latter data in helping to constrain the deep structure of convection [Grand & Forte, 2002; Forte & Grand, 2003; Grand et al., 2003. The necessity for a joint inversion strategy is underlined by the ongoing difficulty in obtaining unique constraints on 3-D mantle structure using seismic data alone. While it is now true that seismic models agree on several large scale structures, seismic models from different groups still differ in many regions indicating that issues of resolution remain. We have developed a hypothesis-testing strategy to overcome this difficulty by jointly inverting the global seismic and convection-related data, and to directly evaluate the extent to which we may fit the geodynamic data. We can thus fully explore how the seismic constraints on mantle structure can be used to discriminate the extent of layering of the mantle convective flow at different depths in the mantle. An important ingredient in the formulation of the geodynamic constraints is an adequate model of the mantle rheology. The joint inversions we present here will be based on the most recent models of mantle viscosity which have been derived through simultaneous inversions of post-glacial rebound and mantle convection data [Mitrovica & Forte, 2004]. We will show that the joint inversions carried out to date suggest whole mantle flow is favoured over a model with a barrier to flow near 660 km depth. We will extend these tests to evaluate the plausibility of chemical barriers located deeper in the mantle.

T24A-03 1600h

Are boundaries in the Earth's lower mantle vertical or horizontal?

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Current tomographic models of the Earth display perturbations to a radially stratified reference model. However, if there is a chemically dense structure at the base of the mantle with low thermal expansivity, high conductivity, and viscosity, and low Rayleigh number (Anderson , 2002), it will develop enormous relief, perhaps with boundaries closer to vertical than radial (Davaille , 1999). Typically, we plot record sections of seismograms (data shifted in distance for alignment) when exploring for horizontal structure and in azimuth (fan-shots) when searching for vertical structure. Such plots for various S-phases gathered from the South African Array show more orderliness in azimuth than in distance indicating a preponderance of vertical structure and can be explained with a large-scale ridge-like velocity anomaly beneath Africa. Conventional record sections show sharp jumps in slowness when ray paths cross the structured boundaries at right angles. Paths crossing at other angles usually display multi-pathing (complex waveforms) which can be modeled by 3D methods involving sharp boundaries. The geometry for such paths control the multi-pathing and dictates a preferred orientation of data assembling. Vectors produced in this manner point towards the center of the ridge-structure. The structure starts from the southern Indian Ocean and extends a few thousand km northwestward into the Atlantic Ocean, with its base on the core mantle boundary rising about 1200km into the mid-mantle. The structure has a 3% in shear velocity, while the compressional velocity is PREM-like. Sharp and vertical boundaries, anomalous P/S ratio, possible increased density and huge volume all support a chemical origin of the structure

T24A-04 1615h

The Evolution of Small, Cool Plumes in the Mantle

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There has been significant debate recently over the attributes and even existence of mantle plumes. Among the arguments being raised against plume-like upwellings are that models of both heads and tails suggest plumes may be overly hot and volumetrically too large to match surface observables. Results are presented from numerical experiments on the growth, rise and dispersion of mantle plumes. We use a finite element method to solve for the conservation of mass, momentum and energy, as well as chemical transport. Models include distributions of eclogite and harzburgite material within the plume source region (e.g. D//). This material is heavy and light with respect to ambient mantle at similar temperatures. The 670 km boundary is represented as a phase and/or a chemical interface. Results show the evolution of plumes with distinct morphologies from the D// thermal boundary layer. One mode involves the growth and rise of relatively cool, small-headed plumes driven by the buoyant harzburgite component. Results also show the 670 km boundary may act as an efficient warm-pass filter for rising plumes that also modulates the chemical mixture within the plume as it passes through the upper mantle. Both a chemically heterogeneous source region and filtering influence of the 670 km interface may result in near-surface plumes that are relatively small and cool. These features generate short, low-amplitude crustal production events.

T24A-05 1630h

Derivation of Large Igneous Provinces of the past 200 million years from long-term heterogeneities in the deep Mantle

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Large Igneous Provinces (LIPs) result from local catastrophically rapid dissipation of great quantities of internal heat. LIPs are overwhelmingly of basaltic affinity representing partial melting of the mantle at shallow depths but whether any of the heat or material involved in the generation of LIP rocks comes from great depth has remained controversial. To address this fundamental issue we restored 25 LIPs of the past 200 My to their eruption sites using a new global palaeomagnetic reference model. 90% of the LIPs, when erupted, lay above low-velocity seismic-shear-wave regions of the D" zone just above the Core-Mantle Boundary (CMB) and 50% overlay CMB low-velocity regions with delta Vs $<= -1\%$. Considering the modifying effects of plume advection, palaeolongitudinal uncertainty and plate circuit errors, the majority of the restored LIPs may in fact overlie regions with delta Vs $<= -1\%$. Because those low velocity regions occupy only 27% of the D" zone, the concentration of LIPs above them indicates that the low velocity (hotter ?) regions are the sources of the mantle plumes that generated the LIPs. We demonstrate that most LIPs of the past 200 My owe their origin to plumes that rose from low-velocity regions of the lower mantle, and that this long-term association indicates that the low-velocity regions have been relatively stationary with respect to the Earth's spin-axis and the core since the Early Jurassic.

T24A-06 1645h

Numerical investigation for the interaction between the Afar plume, the Kenya plume and the Tanzania craton

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Geochemical evidence suggests that the Tertiary basalts along the East African Rift were created by two series of volcanic eruptions from separated mantle sources. The basalts in Tanzania, Kenya, and southern Ethiopia were attributed to the Kenya mantle plume initiated 45 Myr ago, while the Ethiopia-Yemen basalts were products of the younger (31 Ma) Afar plume. We carry out numerical modeling to investigate how this double plume system, the Tanzania craton, and the African plate motion interplay to result in the spatial-time pattern of magmatism observed. The African plate motion and the Tanzania craton were implemented as known physical parameters. The models were then tuned on the locations and strengths of the plumes and the range of rheology of the upper mantle against two critical observations: the coexistence of basalts derived directly or indirectly from the two plumes in southern Ethiopia, and buoyancy flux estimation of the Afar plume. The confrontation between plumes will generate an approximately stationary stagnant streamline between the plumes. Therefore, the plume head material will not mix or underplate each other, making the isolation of the mantle sources for melting. With the plausible physical parameters, our preferred model can generate a good match for the spatial and temporal magma distribution in Ethiopia and Yemen. The south-coming Tanzania craton and the expanding flow front of the Afar plume together deflect the Kenya plume material to the sense of asymmetry. However, it is insufficient to explain the observation in which the abundant magmatism along the eastern branch vs. little on the western branch of the rift. The plume has been eroding the cratonic root since 20 Ma.

T31A CC: 220 C-E Wednesday 0830h

Visualizing the Evolving Fault Zone III Posters *(joint with G, S, MR)*

***Presiding:* P Young,** University of Toronto**; A Schubnel,** Lassonde Institute, University of Toronto

T31A-01 0830h POSTER

Experimental and Modeling Study of Fluid-Pressure Driven Fractures in Darley dale Sandstone

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Fundamental understanding of how fluid-pressure driven fractures progressively nucleate and propagate is crucial to understanding a range of crustal weakening processes. We report measurements of acoustic emissions generated during formation and growth of fluid-pressure driven fractures in cylindrical samples of Darley Dale sandstone (100mm long x 40mm diameter) that were co-axially pre-drilled with an 8mm hole in order to allow an internal pressure to be applied. The experiments were performed in a triaxial cell at a confining pressure of 6.5MPa. A set of 3 to 6 fractures initiate at the wall of the internal bore at a fluid pressure around three times that of the confining pressure, but only 3 propagate to the outer wall of the sample at approximately 120° to each other. Time and spatial distributions of acoustic emissions show two distinct bursts of activity, associated with initiation and propagation, respectively.A Particle Flow Code (PFC) has been used to model the micro-mechanical behaviour of hydrofracturing in sandstone. Micro parameters (particle stiffness, bond strengths, particle packing, etc.) dictate the macro behavior of the material. The models are fully dynamic, and an explicit calculation scheme is used such that stored strain energy can be released from contacts when bonds break and simulated AE can propagate through the system. The numerical model quantitatively reproduces the most important features of the time and spatial distribution of AE observed in the laboratory experiments. This suggests that, for a relatively homogeneous rock in an axisymmetric stress field, the propagation of three evenly distributed radial fractures may represent the most efficient geometry for energy dissipation.

T31A-02 0830h POSTER

Influences of grain comminution on the frictional properties of simulated fault gouge

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Previous DEM (Distinct Element Method) simulations of granular shear have qualitatively reproduced experimental observations of shear zone deformation and also provided insight into the frictional behavior of fault gouge. Gouge deformation, however, was accommodated by grain rolling and sliding alone, with no grain comminution. We examine the influences of grain comminution on frictional behavior of simulated fault gouge using DEM including breakable bonds between adjacent particles. In this way, arbitrarily shaped grains can be generated to reproduce more realistic fault gouge, and grain size and shape can evolve by grain fracture during shear. Two types of grains, rounded grains composed of 7 close-packed spherical particles and triangular grains composed of 6 close-packed spherical particles were designed to generate quartz gouge; Four different grain sizes were generated using four different particle sizes. Both the rounded and triangular grain have four breakable bonds and can break down into two irregular-shaped subgrains due to tensile and shear forces during shear, allowing for a wide range of grain sizes and shapes. DEM experiments were conducted by shearing identical granular assemblages composed of either the rounded or triangular grains under identical boundary conditions (i.e., wall surface roughness), over a range of normal stresses from 5 MPa to 100 MPa. The results show that the intensity of grain comminution is not only a function of normal stress, but also strongly dependent on grain shape. The triangular grains are much easier to break down at certain normal stresses than the rounded grains, a result of the smaller number of intergrain contacts and higher contact forces. The probability of breakage of the smallest grains is much higher than for the larger grains. The results support the constrained comminution mechanism in which the probability of particle fracture is strongly dependent on the relative size of nearest neighbors. As a less expensive deformation mechanism than rolling and sliding at high stress, our results demonstrate that comminution itself weakens the deformed granular assemblage. On the other hand, because comminution also changes grain shape and size, it increases the frictional strength of granular assemblage by increasing grain angularity. Grain shape becomes the most important factor that affects the frictional strength of fault gouge.

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