the boundary layer model in linking the kinematics of seafloor spreading to the depth and heatflow of <70 Ma old lithosphere represents the strongest evidence so far that plate tectonics and convection are linked. However, the boundary layer model breaks down at 70 Ma after which the heat flow and seafloor depth saturate at constant values. At the same time, it appears from seismic studies that the TBL thickness also saturates at a maximum value of 90-100 km. Many models have been proposed to explain the discrepancy between the predictions of the boundary layer model and the geologic features of post-70 Ma lithosphere. Most of these models, however, are difficult to test. Here, we present a testable model that explains the evolution of oceanic TBLs by invoking a pre-existing chemical boundary layer (CBL). We base this hypothesis on a growing understanding of the deep thermal and compositional structure of continents. Continents are underlain by a thick melt-depleted and dehydrated mantle layer, the former resulting in buoyancy and the latter resulting in increased viscosity. Radiogenic isotopic studies indicate that these CBLs do not significantly deform over billion year timescales, implying that on the timescales of mantle convection, such CBLs act as rigid lids resting on top of and separated from the convecting mantle. For this reason, the upper TBL of the convecting mantle therefore consists of a purely conductive layer (represented by the rigid CBL) and a convective sublayer (CS-L), which lies just beneath the CBL and represents the actively convecting part of the TBL. We show using petrologic and geodynamic arguments that the thickness of the CBL beneath continents may limit the thickness of the convective sublayer and accordingly, the thickness of continental TBLs. Petrologic observations require that the seafloor also be underlain by a melt-depleted and dehydrated mantle layer, albeit thinner than that beneath continents. The base of this layer roughly coincides with the thermal thickness at which the boundary layer model breaks down. By analogy with our continental studies, we suggest that the presence of a CBL beneath oceanic crust may also be responsible for maintaining a constant thickness of oceanic TBLs beyond 70 Ma. A future test of this hypothesis would be to seismically map whether there exists a crossover between the CBL and TBL beneath oceans and, if so, whether the crossover occurs at 70 Ma.

T21B-05 0830h POSTER

Geodynamic Setting of Kimberlites

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As an alternative to the plume/hotspot hypothesis for kimberlite distributions, the role of inherited lithosphere anisotropy and episodic deviations to the lithosphere stress state is reviewed using Southern Africa as a test case. The analysis includes (a) a framework of lineaments defined by geology, aeromagnetics, gravity and geomorphological data, (b) the distribution of some 2000 kimberlites, 10 % of which have been dated, (c) the record of global tectonic events. The distribution of kimberlites in Southern Africa is strongly clustered. Occurrences within clusters resolve variable trends, depending on the age and position of the cluster. Rocks are commonly hosted by en-echelon fault arrays, (anti-)Riedel, P- or T-structures. However, on a regional to continental scale, the distribution of clusters appears controlled by trans-continental and probably trans-lithospheric structural elements, e.g., an association of kimberlites with tips or shoulders of rifts, with major pre-existing dyke swarms, with bends or step-overs of continental fracture zones. This deviation from the conventional plume/hotspot model is supported by a strong dependence to the inherited lithosphere architecture, but also the common lack of time-progressive volcanic tracks, and parallellism of same-age volcanic tracks across the subcontinent. Similar lithosphere trends are observed as anisotropies associated with the cratonic keel, craton edges and marginal orogenic belts, the Karoo event, the East Africa Rift, as well as the extension of oceanic fracture zones into the African continent. We suggest that peaks in kimberlite magmatism in southern Africa at 140, 120, 85 and perhaps 67 Ma are caused by major plate reorganizations following the break-up of the supercontinent Gondwanaland. These events are also closely associated with internal deformation of interior basin and passive margin sediments of the African plate and abrupt changes in the relative plate vector of Africa with respect to Eurasia. It appears that the lithosphere structure (rheological anisotropies) not only localised sites of eruption but also provided the required conditions for melting. Bulk horizontal shear strain and resultant transtension caused localized decompression melting of metasomatised mantle lithosphere, generating kimberlites and related magmas.

T21B-06 0830h POSTER

The surface geodynamic expression of ongoing density stratification in heated continental crust

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In addition to vertical density variations, continental crust has significant lateral density variations caused by lithological differences. In stable crust, these loads are supported by elastic stresses. Thermal reactivation of the crust thins the elastic upper crust, reducing its ability to support such loads. Mid-crustal loads may detach entirely from their elastic support if this thermally induced thinning is pronounced enough, and sink through the ductile lower crust to a depth where they are neutrally buoyant. Over time, this process should help generate stable density stratification of the crust despite magmatic processes that should lead to density inversions, as noted by Glazner (1994). We have numerically modelled this process with a fully coupled large deformation thermal-viscoelastic code (THERMAX2D, based on the commercially available FEMLAB PDE solver). The (Newtonian) viscosity is temperature-dependent; upper crustal brittle failure is modelled in a distributed way using a plastic yield stress. We confirm Glazner's approximate analytic estimates of foundering velocities of several km/Ma. A new and striking result is that vertical displacements of intracrustal material of 20 km or more can occur with a relatively minor geodynamic expression at the surface . Once the elastic upper crust sheds a load into the ductile lower crust, it is almost completely mechanically decoupled from the load's further behaviour. A basin with a depth of a few km develops initially as the elastic crust initially thins; after the load is shed, this basin inverts in response to residual flexural stresses in the upper crust.

URL: http://physics.utoronto.ca/~bailey/

T23A CC: 516 D Tuesday 1330h

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

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

T23A-01 1330h

Formation and Exhumation of UHP Metamorphic Crustal Rocks Within an Evolving Mantle Lithosphere Downwelling

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Ultrahigh-pressure (UHP) metamorphism of certain crustal rocks suggests that such material has traversed to significant sub-crustal depths and back to the surface while being maintained at relatively cool temperatures. The process has commonly been explained in terms of plate subduction, with the continental crust subducted to great depths and then returned within a subduction channel or as an extruding slice. Using numerical models of the thermomechanical evolution of the crust-mantle system, we investigate an alternative mechanism to account for the genesis of UHP crustal rock. The numerical experiments show that in the early stages of collision, packages of lower crustal material are entrained to depth into a thickened mantle lithosphere root beneath the young model orogen. Subsequently, the mantle lithosphere root "drips" into the mantle as a Rayleigh-Taylor-type gravitational instability, resulting in deep burial of the entrained crust. The buoyant crustal material eventually separates from warming mantle drip and rises to the base of the crust. Late stage exhumation of the crust to the surface occurs more slowly, related to exhumational processes operating within the still active collisional orogen. The P-T evolution of the buried crust is tracked in the experiments and we find its history is consistent with those observed for UHP metamorphism. We propose this model of burial and uplift of crustal material encased in an mantle lithosphere drip/downwelling during young, cold continental plate collision as an alternative to traditional subduction models of UHP crustal burial. The mantle drip model is consistent with a number of geological observables of UHP rocks in continental collision zones and may have several favourable features over a subduction channel/extruding slice models.

T23A-02 1345h

Admittance Functions for Axisymmetric Loading of a Viscous Layered Lithosphere

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Direct detection of small-scale convection beneath the continental lithosphere is difficult because the amplitude of measurable anomalies produced by the convection is likely to be small relative to those caused by internal lithospheric structure. Even for a simple lithospheric structure, the convection signature is filtered and possibly attenuated by the overlying lithosphere. The response of an elastic lithosphere to external loading is relatively simple, and is well understood in principle. The layered lithosphere can deform only by flexure, and the resulting surface elevation and gravity anomalies are simply expressed in terms of horizontal wavenumber. The amplitude of deflection in the wavenumber domain may be expressed either as the convolution of the impulse response and the load function, or as a filter that acts on the load function in the wavenumber domain. For an elastic layer the important parameter is the flexural rigidity, proportional to elastic modulus and to layer thickness to the third power. In some circumstances, however, the lithosphere demonstrates a viscous response as well as an elastic response. Vertical loading then produces a response that drives the relaxation of internal density interfaces such as the Moho and the upper surface. For each interface the relaxation may be described as exponential decay for a pure harmonic initial deflection, assuming that the stratification is stable and viscosity is Newtonian. Typically, the deflection function includes a broad harmonic content, and the responses from multiple internal interfaces interfere, so that surface response and gravity signal may show complex time dependence. Using a 2D finite element method, numerical solutions can be obtained for the response of a viscous layered medium to axisymmetric loading. Admittance functions (ratio of gravity to topography in the wavenumber domain) are widely used to infer elastic properties of the lithosphere, but may also be defined for a viscous lithosphere. In this paper we examine the variation of viscous admittance functions for the case of axisymmetric loading by normal stress at the base of a viscous lithosphere, and contrast these with the widely used admittance functions for top and bottom loading of an elastic lithosphere.

T23A-03 1400h INVITED

Flow Down Below: Mantle Deformation in Supra-Slab Wedges Sensed with Birefringent Shear Waves

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Studies of seismic anisotropy indicators have become a standard part of efforts to understand the dynamics of the upper mantle. Among various techniques that can sense seismic anisotropy at depth the shear wave birefringence method stands out due to its apparent simplicity, both in terms of performing measurements, and interpreting the results. A common logical pathway for an observed shear wave to associates an estimate of its fast polarization direction with the lattice-preferred orientation of olivine crystals along the wave's path, leading to conclusions about mantle flow direction. However, as the data base of shear wave birefringence measurements has grown, pitfalls in common interpretations have emerged. In this presentation we re-examine the relationship between birefringence and the flow pattern in the supra-slab mantle wedge. Computer simulations of S waves in a corner-flow deformation pattern confirm the expected similarity between the flow direction and the fast shear polarization. Important caveats emerge, however, regarding the robustness of measurements in a region close

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 − 17mW m^{-2}) for India as for Canada, but higher (15 − 22mW 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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