Tectonophysics

T11A CC: 516 D Monday 0830h

Deep Structure of the Continental Lithosphere: Combining Seismic, Heat Flow, and Other Geophysical Data I *(joint with G, GP, S, V, NS, MR)*

Presiding: **J Mareschal,** University of Quebec**; D Canil,** Victoria University

T11A-01 0830h INVITED

Seismogeothermics of Crust and Upper Mantle

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Direct methods to estimate temperature employing measured surface heat flow may fail in the regions of the strong convective heat transfer commonly associated with recent tectonic activity. In such regions high-resolution seismic observations may provide alternative way to estimate temperatures. Seismic velocities in crustal and upper mantle rocks are sensitive to temperature. However, a plenty of other factors may affect seismic velocities, thus masking temperature effects. In the crust, due to the large effects of chemical composition and pores/cracks, temperature variations can be reasonably well detected by seismic methods only when high temperatures (700-800C) are achieved in the felsic upper crust leading to alpha-beta quartz transformation and partial melting. Seismic signatures of such transformations, predicted by petrophysical modelling are observed in Tibet and in Central Andes allowing mapping depths to the "critical" isotherms (700-800C) in the crust. In the upper mantle, the effect of rocks composition on seismic velocities is relatively unimportant which favours temperature interpretation of seismic velocities derived from seismic tomography. However such interpretation involves a number of sources of uncertainties from which the major are: (1) poorly known temperature sensitivity of seismic velocities at high temperatures;(2) ambiguity of seismic models and uncertainty of the magnitudes of seismic anomalies;(3) unknown contribution of seismic anisotropy. The uncertainty (1) can be minimized using both laboratory experiments and seismic observations to calibrate parameters controlling effects of anelasticity on seismic velocities. Uncertainties 2-3 can be minimised jointly inverting the P- and S- wave travel times for temperature distribution in the upper mantle. First results of such inversion for the local source P- and S-wave seismic data in the Central Andes are very suggestive. Obtained patterns and magnitudes of the temperature anomalies are remarkably similar to the results of the thermomechanical models replicating delamination of the lithospheric mantle of the South American plate associated with tectonic shortening of the lithosphere. Reliability of the inversion is confirmed by similarity of the predicted and observed seismic attenuation and gravity.

T11A-02 0850h INVITED

The Mantle Beneath Southern Africa: Insights from Seismic Tomography and Mantle Xenoliths

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We impose geologic constraints on computed tomographic structure of the upper mantle beneath southern Africa by calculating seismic velocities and rock densities from approximately 120 geothermobarometrically calibrated mantle xenoliths from the Archean Kaapvaal craton and adjacent Proterozoic mobile belts. Velocity and density estimates are based on the elastic and thermal moduli of constituent minerals under equilibrium P-T conditions at the mantle source. The largest sources of error in the velocity estimates derive from inaccurate thermo-barometry and, to a lesser extent, from uncertainties in the elastic constants of the constituent minerals. We show that seismic velocity variations between cratonic and non-cratonic xenoliths are controlled dominantly by differences in calculated temperatures, with compositional effects secondary. Different temperature profiles between cratonic and non-cratonic regions have a relatively minor influence on density, where composition remains the dominant control. Low-T cratonic xenoliths exhibit a positive velocity-depth curve, rising from about 8.13 km/s at uppermost mantle depths to about 8.25 km/s at 180-km depth. S-wave velocities decrease slightly over the same depth interval, from about 4.7 km/s in the uppermost mantle to 4.65 km/s at 180-km depth. P and S-wave velocities for high-T lherzolites are highly scattered, ranging from highs close to those of the low-T xenoliths to lows of 8.05 km/s and 4.5 km/s at depths in excess of 200 km. These low velocities, while not asthenospheric, are inconsistent with seismic tomographic images that indicate high velocity root material extending to depths of at least 250 km. The high-T mantle xenoliths, most of which were erupted ca 80-90 Ma, appear to have been affected by localized non-equilibrium thermal perturbations occurring around the time of the kimberlite eruption as well as by compositional modifications associated with emplacement of metasomatic fluids into the deep tectospheric root. We consider how these effects may be related to a craton-wide thermal disturbance in Cretaceous time. Seismic velocities and densities for cratonic mantle differ significantly from those predicted for both primitive mantle peridotite and mantle eclogite. A model primitive mantle under cratonic P-T conditions exhibits velocities about 1% lower for P and about 1.5% lower for S, a consequence of a more fertile composition and different modal composition. Primitive mantle is also about 2% more dense at 150-km depth than low-T garnet lherzolite at cratonic P-T conditions. Similar calculations based on an oceanic geotherm are consistent with the isopycnic hypothesis of comparable density columns beneath oceanic and cratonic regions. Calculations for a hypothetical "cratonic" eclogite (50:50 garnet/omphacite) with an assumed cratonic geotherm produce extremely high VP and VS (8.68 km/s and 4.84 km/s, respectively, at 150 km depth) as well as abnormally high density (3.54 gm/cc). The very high velocity of eclogite should render it seismically conspicuous in the cratonic mantle if present as large volume blocks or slabs. We will discuss how the seismic velocity data from both xenoliths and generic petrologic models of the upper mantle differ from those commonly used standard earth models IASPEI and PREM.

T11A-03 0910h INVITED

Thermal structure of old continental lithosphere from the inversion of surface-wave dispersion with thermodynamic a priori constraints.

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We present a reformulation of the seismic surface wave inverse problem by replacing the ad-hoc seismic parameterization with physical parameters that describe the thermal state and evolution of the upper mantle. We apply the method to estimate the thermal structure of old continental lithosphere that can be described with a steady-state temperature model. The inverse problem is recast in terms of three thermal parameters: temperature in the uppermost mantle directly beneath the Moho, the mantle temperature gradient (or mantle heat flux), and the potential temperature of the sublithospheric convecting mantle. In addition to the steady-state constraint, prior physical information on the model parameters is based on surface heat flow and heat production measurements, the condition that melting temperatures were not reached in the crust in Proterozoic times, and other theoretical considerations. The combination of seismic and thermal data is based on the interconversion between temperature and seismic velocity. The inversion is formulated as a Monte-Carlo sampling of model space which results in an ensemble of models that fit the data, providing estimates of uncertainties in model parameters. We apply this Monte Carlo inversion of surface wave data with the "thermal parameterization" subject to the physical constraints in order to determine the upper mantle shear velocity and temperature structure of the Canadian Shield.

T11A-04 0930h

The Lithosphere of Arctic Canada and Southern Greenland From Surface Wave Studies.

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Two recent projects, CHASME (Canadian High Arctic Seismic Monitoring Experiment) and GLATIS (Greenland Lithosphere Analysed Teleseismically on the Ice Sheet), are providing valuable new information about the structure of the lithosphere in Arctic Canada and Greenland respectively. We use Rayleigh waves from regional and teleseismic earthquakes to model the isotropic S_V velocity structure of the region to a depth of approximately 300km. A two-station method is used to estimate phase velocity dispersion curves from teleseismic signals. 45 paths across Greenland and 60 paths across Arctic Canada are combined to produce sets of phase velocity maps for a range of Rayleigh wave periods. The results of the phase velocity inversion are used to construct localised dispersion curves in parts of Arctic Canada and along two parallel north-south profiles in southern Greenland. These curves, along with several of the original two-station dispersion curves from Canada, are inverted for shear wave velocity structure. Initially, a linearised inversion scheme (Herrmann & Ammon, 2002) is used to estimate mantle S_V structure. The best-fitting models are then simplified and used as starting models in a Monte-Carlo modelling scheme (Shapiro et al., 1997). Group velocity curves from regional earthquakes are also estimated, using frequency-time analysis and multiple-filter analysis, and the results are combined to construct maps of regional group velocity variation. Beneath southern Greenland and the areas of Arctic Canada underlain by continental shield, the models typically show a high-velocity lid structure, which we interpret as the seismological lithosphere. The lid overlies a zone of relatively low velocity, beneath which the S_V velocity gradually increases with depth. The thickness of the seismological lithosphere varies considerably across the region, but typically lies within the depth range 100-200km. Across the Canadian Arctic archipelago, the mantle models are more variable in nature; in places, a prominent high-velocity lid is required to match the data, but in other areas the velocities are relatively close to those of global reference models.

T11A-05 0945h

Lithosphere Composition and Thermal Regime Across the Dead Sea Transform in Israel and Jordan

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Integration of (1) geophysical data from seismology, gravity, receiver-function analysis, (2) petrological data from upper-crustal surface rocks and lower-crustal and mantle xenoliths entrained in Cenozoic basalts, (3) petrophysical data (density, thermal conductivity, radiogenic heat production), (4) mineral-thermobarometrical data showing the P-T conditions in the upper mantle, and (5) surface heat flow was fundamental in improving the knowledge on structure, composition, and thermal state of the lithosphere across

the Dead Sea Transform (DST). Knowledge of the thermal state of the lithosphere is essential for understanding the complicated geodynamic setting that gave rise to the DST. Steady-state geotherms for the area east of the DST, calculated using surface heat flows of 50 and 60 mW/m^2 and the P-T-dependent thermal conductivity values for a three-layered lithosphere, result in Moho temperatures of resp. 600 $^{\circ}$C and 840 $^{\circ}$C, and mantle heat flows of 22 and 32 mW/m^2. In contrast, a published geotherm for the area west of the DST, based on surface heat flow of 40 mW/m^2, implies a considerably colder lithosphere, with a Moho temperature as low as 390 $^{\circ}$C. This geotherm cannot explain the absence of earthquakes generated in the uppermost mantle and underestimates the xenolith-derived mantle temperatures for Israel by about 500 $^{\circ}$C. Underestimation of mantle temperatures (850-1050 $^{\circ}$C; 1.2-1.8 GPa) is evident also for the Jordan geotherms of higher heat flow. This discrepancy argues for transient thermal conditions in close proximity to the DST and east of it owing to lithosphere thinning and asthenosphere upwelling.

T12A CC: 516 D Monday 1030h

Deep Structure of the Continental Lithosphere: Combining Seismic, Heat Flow, and Other Geophysical Data II *(joint with G, GP, S, V, NS, MR)*

Presiding: **M Ritzwoller,** University of Colorado at Boulder**; S Sobolev,** GeoForschungsZentrum Potsdam

T12A-01 1030h INVITED

Three Dimensional Deep Electrical Structure of the Slave Craton, Canada

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The lithospheric-scale structure of the Archean Slave craton, northern Canada, has been studied using magnetotelluric surveys over the past decade. Novel MT acquisition techniques were required given the lack of all-weather road access, and included measurements on frozen lakes in winter and deployment of ocean-bottom instrumentation in lakes from float airplanes. Measurements were made at a total of 138 sites over different frequency ranges. Areal MT coverage of the craton is excellent in the south and center, but limited to the north and west. A subset of these data are being modeled using a new 3-D code which inverts the geomagnetic vertical field transfer functions jointly with all four elements of the MT impedance tensor. The inversion is challenging given the regional nature of the problem, the differing site density and the differing acquisition frequencies. Preliminary models exhibit conductivity features broadly consistent with prior 2-D results and 3-D trial-and-error forward modelling, but with superior resolution of detail. A crustal structure on the eastern boundary of the craton can be associated with Paleoproterozoic orogenesis as the Slave craton indented into the Churchill Province. The known Central Slave Mantle Conductor (CSMC) is shown to commence at depths of 70-80 km initially as two separate bodies coalescing at approximately 100 km. Contrary to the forward modelling, these preliminary inversions suggest that the CSMC does not extend appreciably to the west, but this result requires further verification particularly as site density is poor in this region.

T12A-02 1050h INVITED

Petrological Constraints on Seismic Properties of the Slave Mantle and its Deep Structure.

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Mantle xenoliths is one of few major sources of petrological information on the cratonic mantle. This study uses mantle-derived xenoliths of the Slave craton (NWT, Canada) to constrain the thermal state, composition, chemical zoning and seismic properties of the mantle. The Slave peridotites are equilibrated on a cold geotherm characteristic of Archean craton; the SE Slave peridotite is cooler than the mantle beneath other cratons and other Slave terranes. All terranes of the Slave mantle show broadly similar compositions and are markedly distinct from low-T peridotites from the Kaapvaal and Siberian cratons. Olivine-poor, orthopyroxene-rich, low-T peridotite is absent on the Slave craton, and compositions of its olivine extend to less magnesian values. A pronounced contrast in chemical compositions between the shallow and deeper lithosphere characterizes all Slave mantle terranes. Everywhere the shallow mantle shows greater chemical depletion than its deeper portion. The minimum lithospheric thickness of the Slave craton varies greatly between terranes, from 250 km in the SE Slave to 190 km in the N Slave. Variously depleted peridotites of the Slave craton provide an excellent natural laboratory that allows us to investigate effects of depletion on the chemical and physical characteristics of rocks. We computed seismic velocities for the variously depleted peridotites of the N and SE Slave based on single-crystal elastic moduli and volume fractions of constituent minerals. The depleted peridotites enriched in MgO have lower Vp and higher Vs, where lower Poisson's ratios are due to orthopyroxene enrichment. The correlation observed on the Slave craton contradicts the established view that peridotite depleted in basaltic magmaphile elements has higher seismic wave velocities. However, evidence amassed in the past 15 years suggests that cratonic mantle peridotite is chemically distinct from off-cratonic peridotite and depletion in the cratonic mantle may have a distinct seismic signature compared to the off-cratonic mantle. Our data suggest that chemical depletion of peridotite could also be mapped by a magnetotelluric survey. Ultra-depleted shallow harzburgitic layer of the Central Slave craton has low electromagnetic conductivity. The latter can be explained by a higher abundance of graphite, which should be the prevalent carbon-bearing mineral in the reduced shallow mantle. Our Mossbauer spectroscopy data confirm the low fO2 of the Slave spinel peridotite.

T12A-03 1110h

Peridotites, Garnets, Trace Elements, and the Structure of Mantle Lithosphere Beneath the Archean Superior Province

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A recent large data compilation of trace element analyses on over 1700 mantle peridotite whole rocks and 80 peridotitic garnets from the literature leads to simple correlations between garnets and whole rock data that can be applied to empirically estimate the degree of depletion, mineralogy and potentially seimic velocity and density in the peridotite sections represented by kimberlite-borne garnet xenocrysts. More than 70 percent of the Yb in whole rock analyses of garnet peridotites is contained in garnet. Studies of garnets and coexisting whole rocks indicate that Yb in garnet Gt(Yb) can serve as a simple proxy of Yb in a whole rock garnet peridotite WR(Yb). The correlations of Gt(Yb) with WR(Yb) can then be used to estimate the whole rock Al content of a peridotite WR(Al) from which a garnet xenocryst was derived. Al is a useful depletion index in peridotites, and furthermore correlates very well with modal garnet in well-characterized peridotite samples, and with bulk Mg/(Mg+Fe) (Mg#) in world peridotite datasets from ophiolites, ocean basins, off- and on-craton volcanic-hosted xenoliths. The above correlations are applied to internally consistent trace element datasets (n=800+) we have determined by LAICPMS on garnet suites from 17 kimberlites in North America. Using Ni thermometry in the garnets projected to xenolith-derived geotherms, we construct lithospheric sections of WR (Al), WR (Mg#), and modal garnet with depth in the subcontinental lithosphere beneath cratonic regions. In almost all regions sampled in the Superior Province, depleted peridotite the shallowest sections (<120 km depth) of the lithospheric mantle, supporting the compositional buoyancy inferred to support the cratonic root against convective removal. A different trend with depth is observed for garnet suites from 1.1 Ga kimberlites and alkaline rocks, perhaps due to a different mantle structure at this time. Differences in the chemical signatures between garnet suites in kimberlites within only kilometers of one another across major fault grabens in the Lake Timiskaming region imply chemically modified mantle lithosphere along extremely narrow zones that are still observed there today by seismic tomography. From correlations of WR(Al) with WR(Mg#)we can potentially invert the garnet geochemical profiles to obtain information on density and seismic velocities with depth in the craton, using correlations of these parameters in garnet-facies mantle peridotite as elucidated by C.T. Lee (2003, J.Geophys. Res., 108).

T12A-04 1125h

Mechanical anisotropy of the lithosphere in the Canadian Shield

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We investigated the anisotropy in the flexural response of the elastic lithosphere. We have used three different methods to determine the azimuthal variations of the coherence between Bouguer gravity and topography. The Fourier spectra were calculated with the standard windowed Fourier transform, and averaging was performed with a moving window in wavevector space. We have also estimated the coherence over overlapping azimuthal sectors and averaged on annuli in wavevector space. With the multitaper method, direct estimates of the coherence for each wavevector are obtained by stacking the spectra of orthogonal representation of the data. Synthetic data were generated following the method of *Swain and Kirby* [2004][1]. Using these synthetics, we verified that the three methods recover the anisotropy of the data, but the multitaper method offers a greater variance reduction and is the only unbiased 2-D coherence estimator. We hence applied these methods to the Canadian Shield data set. The isotropic effective elastic thickness in the Canadian Shield has been estimated by different methods. These studies show that T_e varies from 30 to > 120 km. Regions of high and low T_e are found throughout the Shield. The mean T_e is the same for all provinces (90 ± 40 km) except for the Grenville, where T_e is lower (70 ± 27 km). The study of anisotropy shows a marked contrast between the eastern Shield, where the weak axis is trending N-S, approximately perpendicular to the Grenville Front, and the western Shield, where the weak axis is trending WNW, roughly perpendicular to the structure of the Trans-Hudson Orogen. [1]*Geophys. Res. Lett., 30*, 2014, 2003

T12A-05 1140h

Subduction Zone Backarcs, Continental Mobile Belts, and Orogenic Heat

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Two important problems of continental tectonics are resolved by recognizing that all subduction zone backarcs are hot and have thin weak lithospheres over considerable widths: (1) the origin of long-lived active "mobile belts" contrasted to the stability of cratons and platforms, (2) the origin of the heat of continental collision orogeny. At many continental margin plate boundaries there are broad mobile belts with a long history of distributed deformation. They are mobile because they are sufficiently weak to be deformed by the forces developed at plate boundaries. We conclude that mobile belts are weak because they are hot, and they are hot because they are in present or recent backarcs. Most continental backarcs are very hot, not just those with extensional and rift zones. Moho temperatures are 800-900C and lithosphere thicknesses are 50-60 km, compared to 400-500C and 200-300 km for cratons. Due to the temperature differences, backarc lithospheres are more than a factor of 10 weaker than cratons. Backarcs may be hot because shallow asthenosphere convection results from viscosity reduction by water released from the underlying subducting plate. Hot weak former backarcs are the locus of most deformation during continent or terrane collision orogeny, i.e., the vice or inherited weakness model. We conclude that the orogenic heat indicated by plutonism, high grade metamorphism, and ductile deformation, comes from the pre-existing hot backarc lithosphere, not from the orogenic deformation process itself.

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