Construction and destruction of some North American cratons

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Introduction

Deep, multi-disciplinary 3-D models based on geophysical and geochemical observations provide important insights into the geological history of cratonic lithosphere and its dimaond prospectivity (e.g. Snyder et al., 2015). Each continent's cratons have different types of observations available and this leads to some diversity and complications in straightforward comparison, but the fundamental tools remain the same. South Africa has the earliest body-wave tomography, extensive magnetotelluric (MT) soundings and the most extensive geochemical database from numerous xenolith suites. Australian cratons have quality seismic tomography and MT data, but limited xenolith locations. Russian cratons have mostly geochemical data from xenoliths. North American cratons have all these observations in reasonable abundance and spatial density and will be the focus here.

Each North American craton was affected by each of four main processes to some degree (Snyder et al., 2017). These include (1) the initial building of basic continental cratonic blocks during the Archean, (2) subsequent assembly of cratons into the North American shield during the Proterozoic, (3) coeval or subsequent weakening by metasomatism, and (4) final partial erosion or delamination of the lithospheric base. Similar processes are assumed to have occurred in most, if not all, cratons however significant differences in diamond fertility argue that not all cratons were created alike. Understanding fundamental deep structure of the lithosphere requires, at minimum, a melding of our geochemical (e.g. Aulbach et al., 2013), geodynamical (e.g. Wang et al., 2014), and geophysical (e.g. Humphreys et al., 2015) observations and understanding. Here that is facilitated using multidisciplinary three-dimensional models that overlay different knowledge layers to enhance our understanding of at least the spatial interrelationships (Snyder et al., 2015). What we have found is that variably sparse xenolith samples calibrate geological timing and provide ground truth to continuous geophysically derived physical properties of the mantle. Seismic structures, typically discontinuities, appear to outline fault and shear structures along which cratons were built. Conductivity apparently best maps metasomatism and alteration associated with weakening of the lithosphere, but also its enrichment in metals and carbon.

Tectonics of Construction

Initial ancient (4.0-2.8 Ga) continental lithosphere blocks formed via fractional differentiation of an early Earth semi-stagnant lid into plagioclase-, pyroxene- and olivine-rich layers (Lee et al., 2011). These continental nuclei, several hundred kilometers wide and 90–120-km thick, grew by lateral tectonic accretion of similar, but more juvenile blocks. Seismic observations document wedge-shaped discontinuity surfaces that accommodated horizontal shortening, but no clear seismic evidence currently exists of deeply subducted lithospheric slabs from this period. Isotopic evidence does indicate coeval recycling of near-surface rocks into sub-lithospheric mantle, possibly via pyroxene-rich drips. These composite blocks cooled sufficiently by about 2.6 Ga to possess the strength and buoyancy to survive subsequent collisions and become stabilized cratons. Once subduction started about 2.8 Ga, Archean cratonic blocks eventually interacted and collided along mostly Proterozoic orogenic belts to form a North American continental shield that has largely survived to the present. Today this shield has layered lithosphere that generally gets younger with depth and is 180–220 km thick. Seismic discontinuities beneath many Proterozoic orogenic belts document subduction of intact (oceanic?) lithospheric slabs as is observed in modern subduction zones (Snyder et al., 2015).

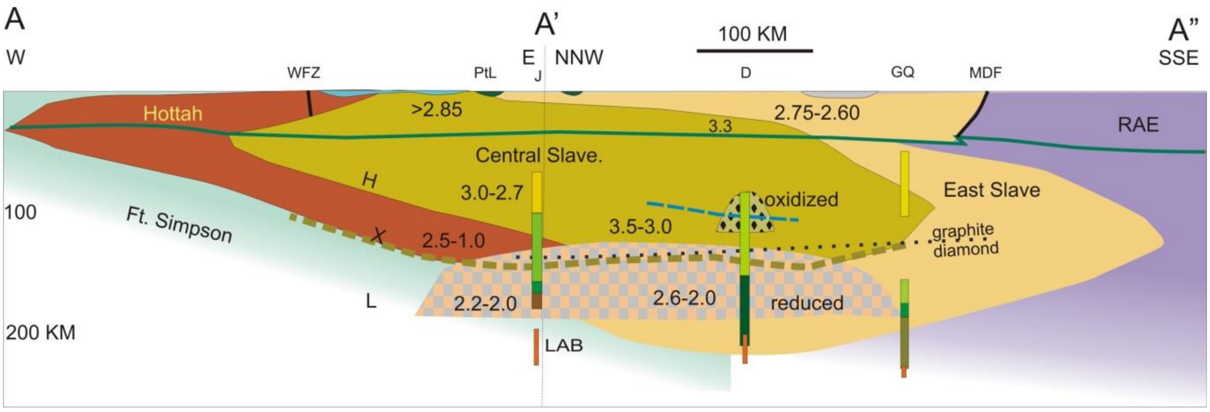

Figure 1. Summary cross section of the Slave craton showing that a Central Slave nucleus grew tectonically outward by wedging apart first the accreting East Slave block at 2.6 Ga, the Rae craton at 2.0-1.9 Ga, and then the Hottah terrane at 1.85 Ga (Snyder et al., 2017). WF and MDF are the Wopmay and MacDonald strike-slip faults. Numbers are rock ages in Ga. The vertical columns labelled J, D, and QG are xenolith suite rock types from Jericho, Diavik/Ekati, and Gahcho Que, respectively. Dashed lines mark seismic discontinuities. LAB is the lithosphere-asthenosphere boundary inferred from geotherms; H, X, and L are discontinuities.

Metasomatism: Prelude to Destruction

Sub-cratonic lithosphere is pervasively metasomatized and locally melted or recrystallized numerous times wherever it has been studied to date via xenoliths (e.g. Aulbach et al., 2013; Heaman and Pearson, 2010) or as inferred from enhanced conductivity. Upwardly migrating small percentage melt intrusions apparently introduce pyroxene-garnet (eclogite) assemblages, often with associated diamonds. Metasomatic fluids are often reducing and significantly weaken the lithosphere. These fluids are apparently rich in carbonates, silica or brine and therefore widely enhance conductivity as shallow as 90–120 km depths. Old, stacked, weakened sub-cratonic lithosphere is variably eroded or underplated by asthenospheric convection. Sparse indicators of lithosphere thickness during the Phanerozoic suggest thicknesses of 150–220 km. Subsidence or uplift indicated by surface basins is modest, only a few kilometers. One prominent exception is the Wyoming craton beneath which the Farallon flat slab was subducted. This process removed the Archean lithospheric base below about 140 km and replaced it with Mesozoic oceanic lithosphere (Humphreys et al., 2015).

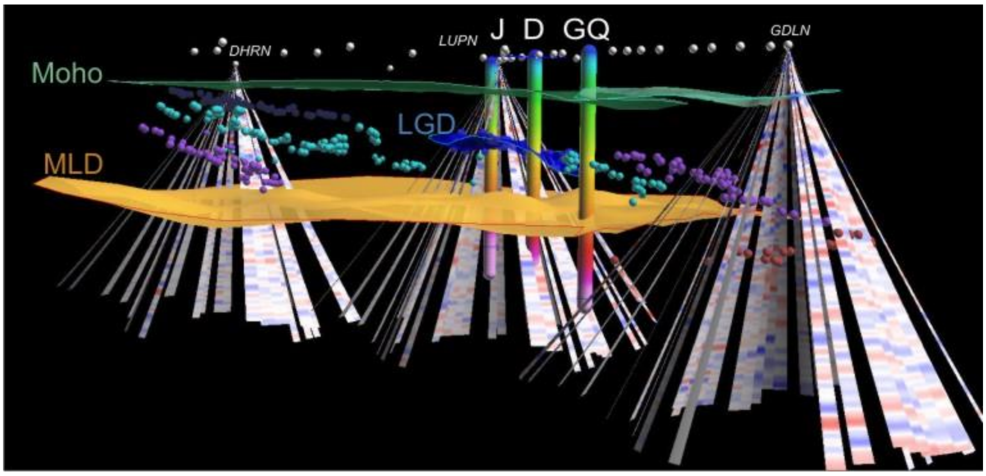

Figure 2. North-looking perspectives of a lithospheric-scale 3-D model of Slave craton structures inferred from seismic discontinuities and xenolith studies (modified from Snyder et al., 2017). Five structural surfaces are observed: a horizontal Moho (green), an undulating (LGD) surface at about 100-km depth (royal blue), a northeast-dipping surface associated with the Hottah terrane (purple), an east-dipping surface associated with the Ft. Simpson slab (blue), and a horizontal mid-lithospheric discontinuity (MLD) at 140-150 km depth (gold). The latter is mapped primarily by its seismic anisotropy, but also coincides with a marked increase in surface

wave velocity. Picks for two other discontinuities are represented by red and violet dots for easier viewing; these wedge-shaped discontinuities partly delimit the central and east Slave blocks at depth. J, D, and GQ are as in previous figure. Cones show 3D Ps receiver functions displayed at three representative seismic stations.

Model Probabilities & Uncertainty

Multi-disciplinary subcontinental lithospheric models present unique challenges if one attempts to move beyond a 'preferred' model and estimate the uncertainty of that model, or alternatively the probability of that or other models being correct. Each variety of seisimic observation or MT data or geochemical analysis of xenoliths or xenocrysts has associated differences in analysis uncertainty.

Resolution thresholds and uncertainty within deep multidisciplinary 3-D models based on geophysical observations exist at a minimum of three levels. Seismic waves and potential or elctromagnetic field measurements have inherent limitations in resolution related to their dominant wavelengths. Formal uncertainties can be assigned to grid-search type forward models of observable parameter sets. Both of these estimates are typically minor when compared to resolution limits related to the density and shape of a specific observation array used in seismology, electromagnetic, and potential field surveys. Seismic wave source distribution additionally applies in seismology. Comparing results obtained using independent seismic wave phases provides another measure of resolution of particular physical properties. Extremely sparse xenolith suites have systematic uncertainties associated with crystallization temperature and pressure estimates, but provide the only direct correlation of rock type with observed or modelled physical properties. Correlating diverse physical properties in a single 3-D model foremost requires accurate registration, but co-location of anomalies depends on the uncertainties and resolution limits specific to each method. Some physical properties may simply prove unrelated or primarily related to different rock properties and structures. Self-adapting grids, co-kriging and probability estimates increasingly appeal as more practical formulations of uncertainty or resolution in assessing 3-D models than traditional uncertainty criteria. The Canadian Moho map provides one instructive example combining refracted and converted seismic wave co-analysis with gravity modelling. Weaker, deeper lithospheric discontinuities and structures are even more uncertain and lack lateral continuity.

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