GEOLOGICAL SURVEY OF CANADA
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2013

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doi:10.4095/292655

This publication is available for free download through GEOSCAN (http://geoscan.ess.nrcan.gc.ca/).

Recommended citation
Snyder, D.B., Hillier, M.J., Kjarsgaard, B.A., de Kemp, E.A., and Craven, J.A., 2013. A 3-D compilation of data sets from the Slave craton, northwest Canada; Geological Survey of Canada, Open File 7395. doi:10.4095/292655

Publications in this series have not been edited; they are released as submitted by the author.

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Introduction

The GEM program was designed to map Canada's North. In order to support diamond exploration, this mapping is best done at 150-300 km depths, the so-called 'diamond window'. Fully three-dimensional mapping using geophysical methods, as calibrated by rare samples from xenoliths and garnet xenocrysts is required (e.g., Davis et al., 2003). A compilation of several co-registered regional 3-D data sets now exists for the Slave craton within the Canadian Shield and can be presented in stereo using gOcad software. The Slave region of northwest Canada has undergone relatively intense exploration by the diamond industry so that geochemistry of the mantle can be estimated where diamondifereous kimberlite deposits have been discovered and studied. Observed or modelled geophysical properties can thus be indirectly calibrated or 'ground truthed', understanding the uncertainties of pressure-temperature depth estimation, in these sparse locations and extrapolated outward across North America. Our new 3-D models place this 'spot', 1-D geochemical information into a fuller context on a continental-wide scale and allow comparisons with cratons on other continents. New insights may suggest new avenues for exploration.

One goal of Natural Resource Canada's GEM (Geo-mapping for Energy and Minerals) program's Diamond project is to study the deep lithosphere beneath the Slave and Churchill provinces of northern Canada, better understand the potential for diamonds, and thus reduce risk during their exploration. From 2007 to 2012, new xenolith, seismic and magnetotelluric (MT) data were acquired and analyzed throughout the Northwest Territories and Nunavut to contribute in obtaining this goal. These data enhance and complement previous data of similar types as well as geologic and potential-field data sets. All available data or derived models have been incorporated into a multi-disciplinary geoknowledge cube encompassing the Slave craton (Figure 1).

Component data sets

One-dimensional (drill holes) data

<u>Xenoliths, garnet xenocrysts</u>

Dated kimberlite deposits source mantle xenoliths, garnet xenocrysts and diamonds that can be used for geochemistry/petrology analysis that provides knowledge of "what is down there". This information includes rock types, elemental abundances, ages of whole rock crystalization or of metamorphism or of inclusions in diamonds (e.g., Griffin et al., 1999; Kopylova and Caro, 2004). This information was incorporated within the model as 'drill holes' colour-coded as to rock type (Figure 6) as compiled by Kopylova and Caro (2004).

Paleogeotherms

Mantle xenoliths brought to the surface in kimberlite eruptions also provide suites of rocks whose mineral assemblages can be used to calculate the pressure-temperature at which those assemblages formed (e.g., Mather et al., 2011). Robust, if imprecise, lithosphere-asthenosphere boundary (LAB) determination is important to define the bottom of the prospective "diamond window". This information was incorporated within the model as 'drill holes' colour-coded for paleotemperature (Figure 2) as it was determined by Mather et al. (2011).

Two-dimensional (near-surfice maps) data

Digital elevation model

Extracted from national database.

Bedrock geology

New digital geological maps of the three Canadian territories were produced within the past few years. Relevant parts were extracted and imported into the 3-D model of the Slave craton (Figure 1) (D. Paul, personal communication). Also see Bleeker (2003) for further description and references on bedrock geology maps.

Gravity

Extracted from national database maintained by Canadian Geodetic Information System, Gravity & Geodetic Networks Section, Geodetic Survey Division, Geomatics Canada, Earth Sciences Sector, Natural Resources Canada.

Contact: http://gdcinfo.agg.nrcan.gc.ca/contact_e.html#DataCentre

Aeromagnetics

Extracted from national database maintained by Canadian Aeromagnetic Data Base, Airborne Geophysics Section, GSC - Central Canada Division, Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada.

Contact: http://gdcinfo.agg.nrcan.gc.ca/contact_e.html#DataCentre

Three-dimensional data

P-wave speed tomography model

Relatively short-wavelength P-waves were modeled in order to map +/- 1% variations in P-wave speed using an early, limited array of seismic stations deployed in the Slave region (Straub et al., 2004). Such models have fair lateral resolution, but very poor vertical resolution and require regularly spaced (grid) arrays to produce optimum results. A regular grid was never available here.

Surface-wave velocity tomographic models

Long-wavelength seismic waves that travel near the Earth's surface are also recorded at the stations and can be used to produce alternative wave speed models of entire continents, here North America. These models have used an updated, denser set of stations (Van der Lee & Frederickson, 2005; Bedle & van der Lee, 2009). These models have fair vertical resolution, but poor lateral resolution. Only the part of the North American model within the Slave craton region was extracted and incorporated in the Slave 3-D model (Figures 4 and 5).

Conductivity

Earth conductivity can be estimated and modelled from magnetotelluric survey records of changes in the Earth's electric and magnetic fields over several hours to days. Recording sites in the central Slave were used to model conductivity to about 200 km depth in 2-D and 3-D (see Jones et al., 2003; Spratt et al., 2009 for description of the observations and data). The 3-D conductivity models shown here (Figures 1, 3 and 4) were developed for this study using methods described by Siripunvaraporn and Egbert (2009) and implemented as described by Roberts and Craven (2012).

Seismic discontinuities from receiver functions

Seismic discontinuities can be detected where changes in rock types cause seismic waves to convert (P- to S-waves). Where sufficient incoming earthquake waves are recorded in 360 compass degrees, a 3-dimensional cone can map such seismic discontinuity structure in 3-D (e.g., Snyder, 2008). The Moho (crust-mantle boundary) is typically the strongest discontinuity within the lithosphere. Here, for the first time in publication, the estimated ray path of the seismic wave was calculated using the mean distance to earthquake sources within each 5-degree azimuthal bin in which at least 5 earthquakes were recorded; these are shown as ribbons where bright blue or red bands indicate that wave conversions occurred (Figure 2). Overlapping coverage by the cones formed from these ribbons permits a common surface to be built based on numerous discontinuity picks (Figure 2). Three distinct surfaces were mapped within the Slave craton: the Moho, a local feature beneath the Lac de Gras kimberlite field, and at mid-lithospheric depths of 140–155 km (Figures 2 and 6).

Seismic anisotropy from SKS-splitting parameters

Seismic fabric (typically called anisotropy) can be detected where foliation, fluid-filled fractures, or dyke-like structures in rock cause much larger seismic S-waves to undergo birefringence, a phenomenon where orthogonal shear waves travel at different speeds (Silver 1996). The split or delay time between arrivals indicates the strength of the anisotropy or fabric, the fast polarization direction indicates the strike of the fabric planes. Only relatively simple fabric can be resolved by this method. Typically models are restricted to hexagonal symmetry with a horizontal axis, so vertical fabric planes are assumed. Three layers of this type of fabric are incorporated in the 3-D models (Figure 6) using parameters from the analysis of Snyder and Bruneton (2007).

The Slave 3-D Compilation

The 3-D data were integrated using Paradigm SKUA (gOcad) version 2009 3 patch 3. It incorporates objects such as: point sets (kimberlite locations, station locations, discontinuity picks, SKS splitting parameters), curves (drill cores), surfaces (seismic discontinuities, receiver function cones, surface geology, digital elevation model, gravity field, aeromagnetic field) and voxets (conductivity, surface wave velocity, P-wave velocity). The surface geology and digital elevation models are especially dense and slow to manipulate, they should be selected for viewing with care. Some surface objects (receiver function cones, surface geology, digital elevation model) were simply imported, others (seismic discontinuities) were modeled within gOcad from point sets picked using features observed on other objects.

Users can assess the quality of the constraints on the discontinuity surfaces themselves by viewing each receiver function cone and its associated discontinuity picks before viewing the picks with the resulting surface (Figure 2). Both the accuracy and significance of a discontinuity surface can then be assessed by viewed the surface in conjunction with a voxet, such as conductivity, and also to investigate possible correlations. Voxets are best viewed via three orthogonal slices: depth, north-south vertical, east-west vertical planes. For example, by moving these planes across the central Slave craton region, one notes that the more highly conductive areas of the mantle fall largely between the Lac de Gras and mid-lithosphere discontinuities at 90–150 km depths (Figure 3). The mid-lithospheric discontinuity coincides with a relatively sharp vertical gradient in surface wave velocity (Figure 5) and also with observed changes in rock types as determined from xenoliths (Kopylova and Caro 2004; Snyder 2008).

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Figure Captions

Figure 1. Location map and surface bedrock geological map of the Slave craton (GEM Tri-territorial compilation, unpublished). A new three-dimensional model of Central Slave mantle conductor (Jones et al., 2003) is shown here as a contour mesh; it appears again in Figure 4 as a solid surface. Red dots are known kimberlite locations.

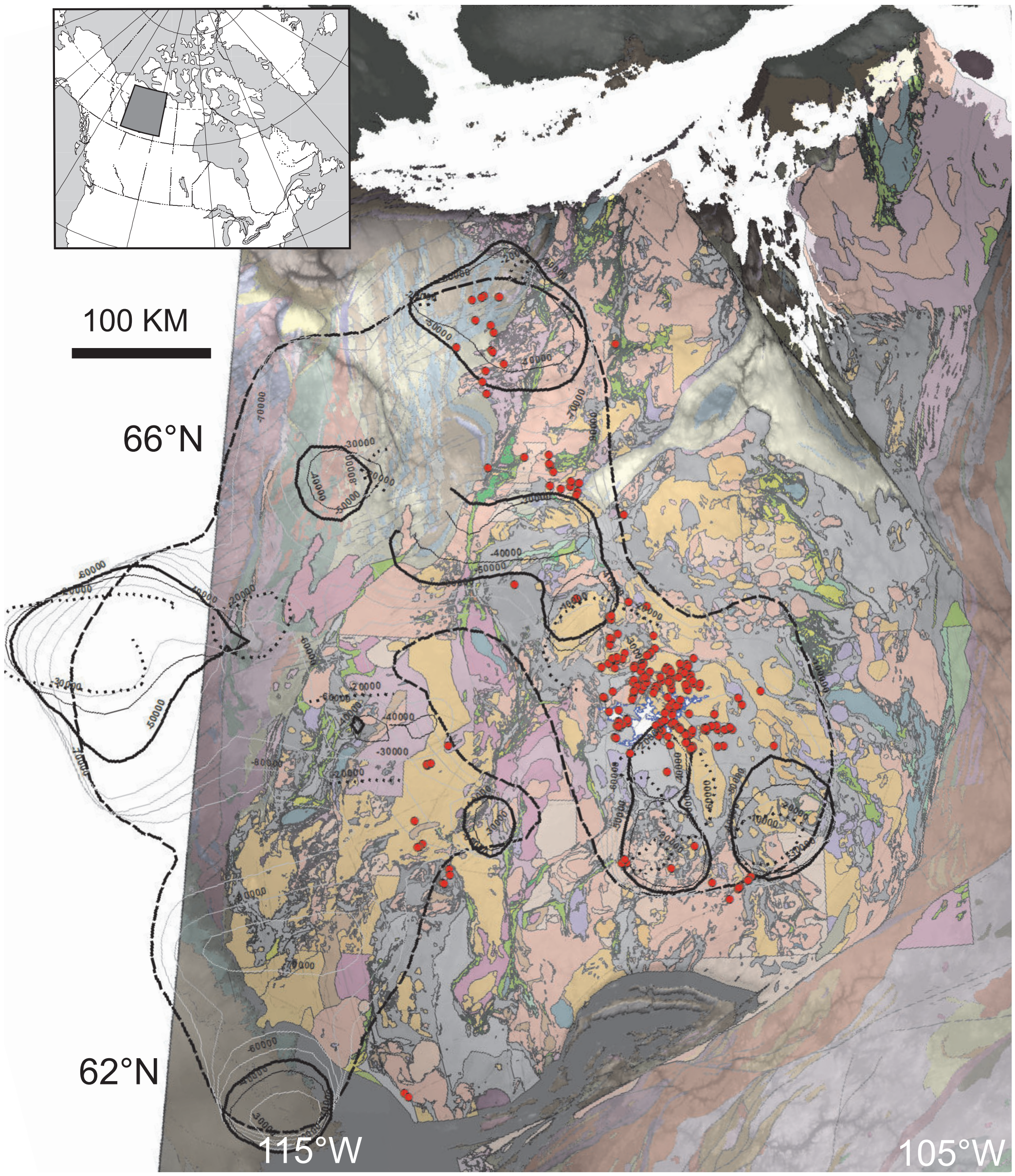
Figure 2. Illustration of Slave seismic discontinuities as viewed from the side (a) and at altitude (b). Multi-azimuthal receiver function studies described in Snyder (2008) appear here as conical sections where each ribbon represents the calculated seismic wave path within a 5º azimuthal bin for seismic waves arriving at that seismic station. Prominent, laterally consistent anomalies on each receiver function (red or blue bands) were annotated using coloured balls; all such balls were then used to fit a surface for each discontinuity. Green balls and surfaces represent the interpreted Moho discontinutity at 37-40 km depths, blue marks a southeast-dipping surface at 80–110 km depths associated with the Lac de Gras kimberlite field, and gold marks a mid-lithophere discontinuity at 140–155 km depths. Note that these 'picks' are more widely distributed (larger diameter conical sections) with increasing depth. "Drill holes" show paleo-geotherms based on pressure-temperature studies of xenolith (Mather et al. 2010); red is about 1200ºC, blue is 0–200ºC and the base of the lithosphere is estimated at 180–220 km.

Figure 3. Three-dimensional model (can be rotated) showing conductivity sections compared with Lac de Gras (blue, 80-100 km depths) and mid-lithospheric (gold, 140–155 km depths) discontinuities (see Figure 2). Red indicates resistivities of <10 Ohm-m, green 100–300 Ohn-m.

Figure 4. Cube comparing 3-D conductivity model with 3-D North American surface wave model (Beadle and van der Lee, 2009). Conductivity surface is contoured at a resistivity of 250 Ohm-m. Seismic velocity depth slice is at 150 km depth; colour (green to magenta) variations represent a 200 m/s change in seismic S-wave velocity.

Figure 5. Rotatable cube comparing 3-D North American surface wave model (as in Figure 4) with mid-lithosphere discontinuity determined from receiver function analysis (Figure 2; Snyder, 2009). A strong vertical gradient in velocity corresponds with the seismic discontinuity at 140–160 km depths.

Figure 6. Seismic anisotropy of the Slave craton as determined from SKS-splitting techniques (Snyder and Bruneton, 2002). Vertical red shingles indicate fast polarization direction (strike) and modelled splitting delay time (size of panel) within three depth layers and compared to seismic discontinuities discussed previously. Vertical columns are rock 'cores' as determined from xenolith suites (Kopylova and Caro, 2004). Cones are representative multi-azimuthal receiver functions at stations GALN and GDLN. Grey balls at top mark all seismic station locations. (a) View here is from the side at about 180 km depth, towards the northeast (approx. 050º), along strike with the deepest layer anisotropy. (b) View from below allows correlation of fast polarizations with Lac de Gras discontinuity (blue surface) and surface geology. Note alignment of much of the shallowest SKS layer anisotropy with major bedrock structures such as greenstone belts (green units). (c) View from below shows deepest layer SKS anisotropy markers against the bottom of the mid-lithospheric discontinuity (gold surface); objects as in (a). Note consistent change in fast polarization across dashed line, dividing the central and southern Slave craton.



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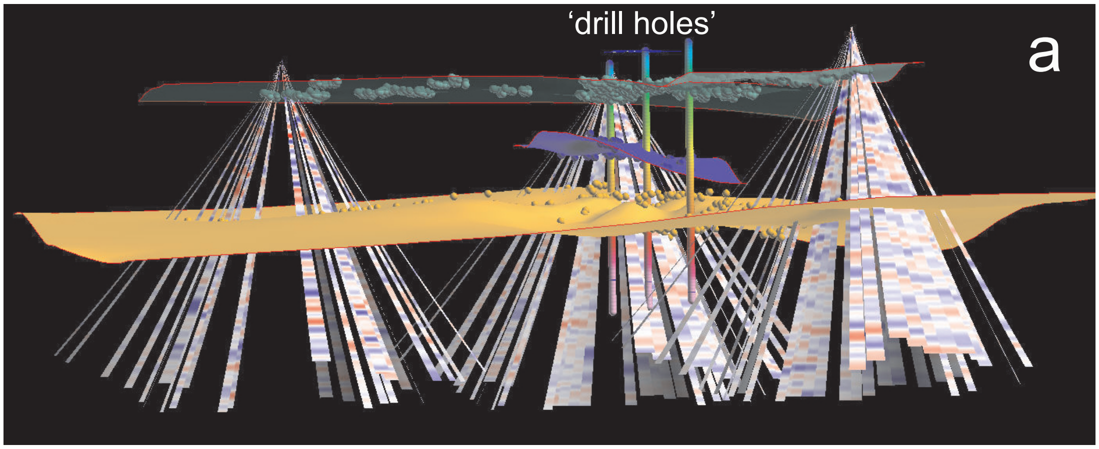
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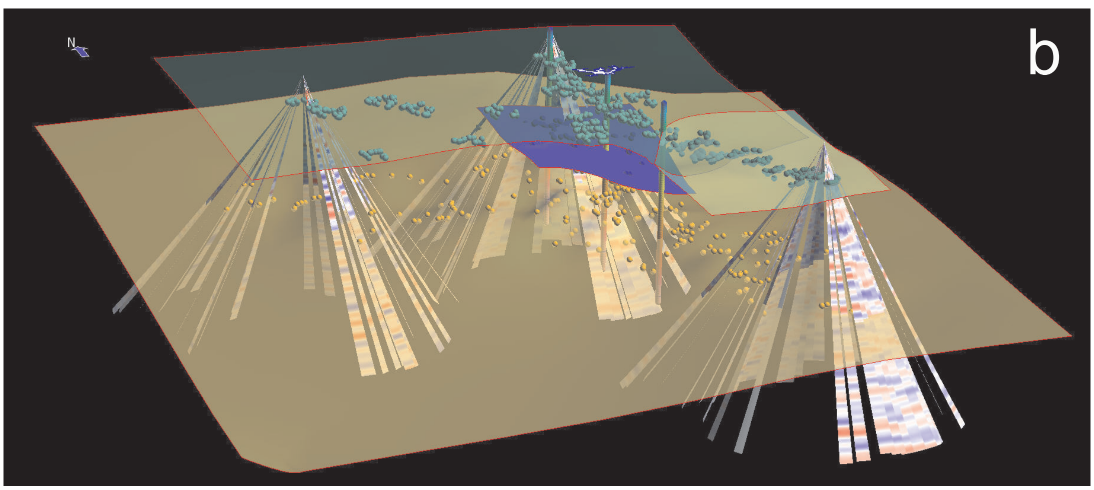
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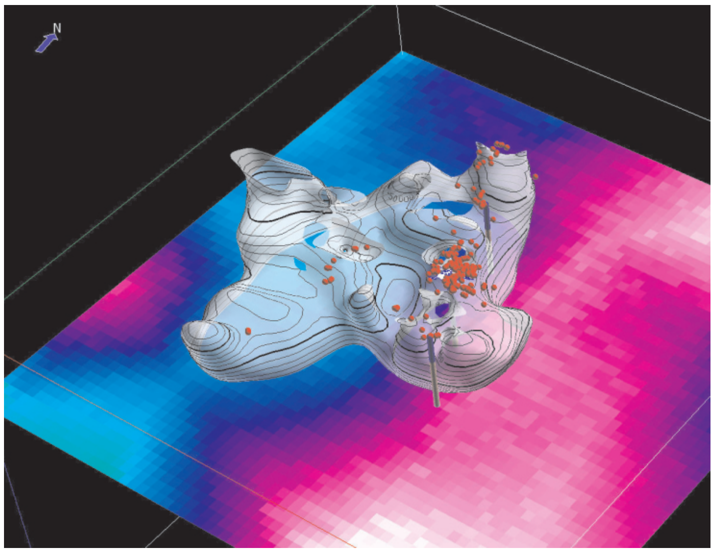
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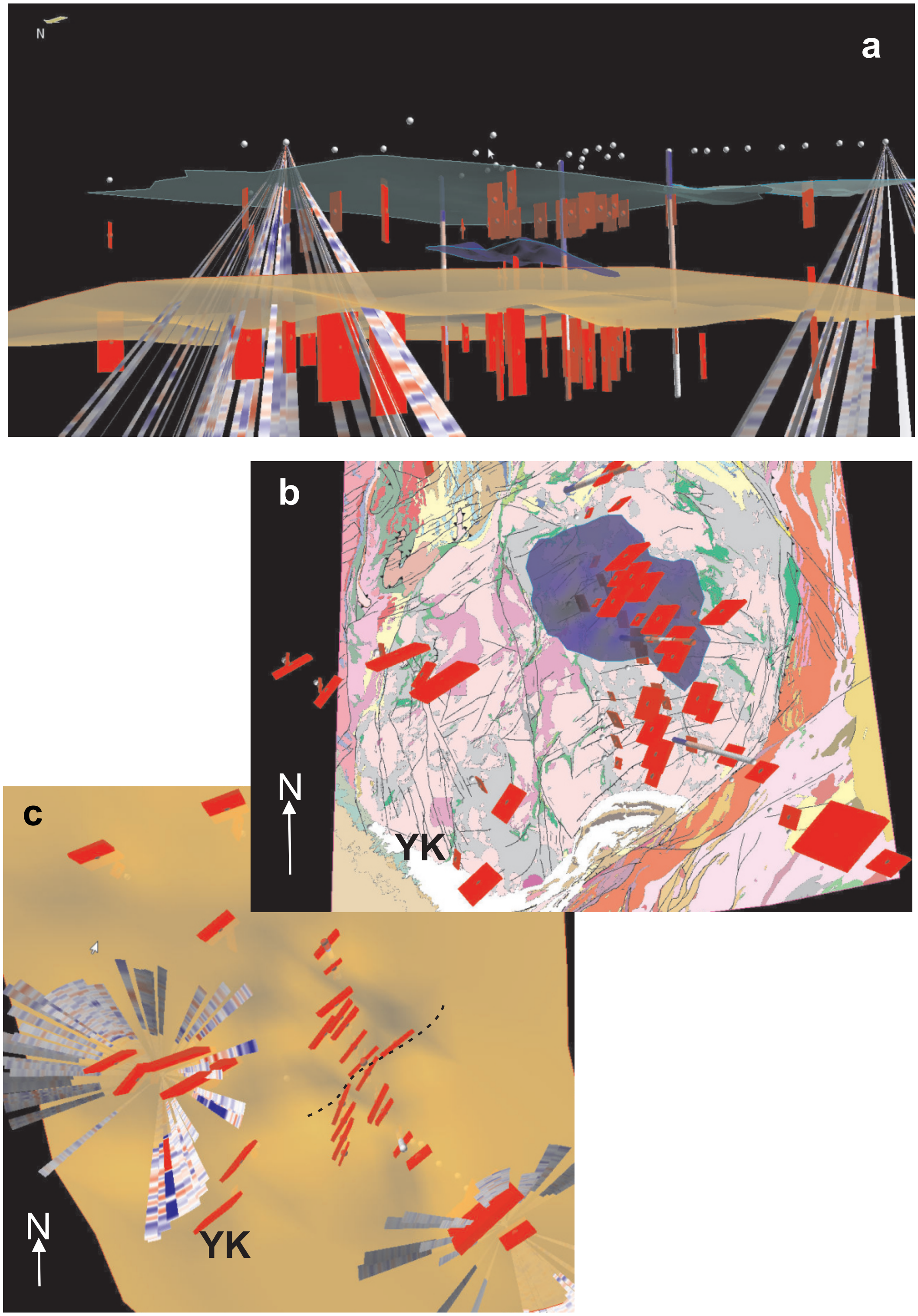
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