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Abstract: Earthquakes recorded at the Canadian National Seismic Network station FRB at Iqaluit, Nunavut between 1993 and 2009 were analyzed using receiver-function and SKS-splitting techniques in order to determine seismic discontinuities and anisotropy beneath the station. Discontinuities typically represent strong, localized changes in rock properties and therefore can indicate the presence of multiple or dipping layers if these layers are regionally continuous. Both methods produce consistent results. Several stacked layers are interpreted to dip at approximately 15° to the northeast beneath station FRB at depths between 50 km and 150 km. The layers are defined primarily by their anisotropic characteristics that typically represent different rock fabrics. Geochemical evidence from kimberlite xenocrysts located 125 km to the northeast suggests that the layers are partly composed of harzburgite. Surface geological models suggest that the layers represent underthrusted or subducted parts of the Sugluk or Meta Incognita microcontinent blocks. A Moho depth of 43 km is estimated beneath station FRB.

Résumé : Les séismes enregistrés à la station FRB d'Iqaluit (Nunavut) du Réseau séismographique national canadien entre 1993 et 2009 ont été analysés en utilisant les fonctions récepteur et les techniques du dédoublement des ondes SKS afin de déterminer les discontinuités sismiques et l'anisotropie sous la station. Les discontinuités représentent généralement des changements localisés et importants des propriétés des roches qui peuvent indiquer la présence de couches multiples ou de couches inclinées, si ces couches sont continues à l'échelle régionale. Les deux méthodes procurent des résultats concordants. Selon notre interprétation, plusieurs couches superposées et inclinées d'environ 15° vers le nord-est sont présentes sous la station FRB à des profondeurs variant entre 50 et 150 km. Ces couches sont définies surtout par leurs caractéristiques anisotropes, qui témoignent généralement de fabriques de roches différentes. Les preuves géochimiques tirées de xénocristaux dans des kimberlites situées à 125 km au nord-est suggèrent que ces couches sont composées en partie d'harzburgite. Les modèles géologiques de surface suggèrent que ces couches représentent les parties sous-charriées ou subductées des blocs microcontinentaux de Sugluk ou de Meta Incognita. Une profondeur de 43 km est estimée pour le Moho sous la station FRB.

INTRODUCTION

The Canadian National Seismograph Network (CNSN) added a permanent seismological observatory (station FRB) near the airport of what is today Iqaluit, Nunavut (Fig. 1) in 1972. The station was converted to a digital, 3-component, broadband station in 1992. In 2006 the STS-1V seismometer was replaced by a CMG-3T seismometer. Global earthquakes larger than magnitude 5.5 are considered suitable for applying both so-called receiver function and SKS-splitting analyses. Between May 1993 and November 2009, the distance, azimuth, and magnitude of 286 earthquakes were deemed appropriate for multi-azimuthal receiver function studies and 162 for multi-azimuthal SKS-splitting studies. In both analyses, the seismic waveforms were bandpass filtered between 0.01 Hz and 12 Hz and windowed on the relevant phases.

MULTI-AZIMUTHAL RECEIVER FUNCTIONS

The receiver function analysis was done using the method of Bostock (1998) in which the principal component of the data are assumed to represent the source function and is therefore deconvolved from higher order components to estimate the Earth response beneath the receiver. The analysis separates the function into the radial component, which lies within the plane containing the great circle between the station and earthquake, and the tangential component, perpendicular to the plane of propagation. The 286 earthquakes were sorted by epicentral distance (30° <Δ <95°) to determine moveout signatures and thus infer whether an arrival was primary or a reverberation. Earthquakes were next binned by back azimuth to the source earthquake. Bins covering 5° of azimuth typically contained the 2–20 earthquakes necessary for robust analysis, and 12 bins contained no earthquakes (Fig. 2).

The radial (R) and tangential (T) components shown in Figure 2 each represent the surface of a vertical cone with its apex at station FRB that opens out at depth so that its radius is approximately one third of the depth. The radial component has a prominent red (positive) response that occurs consistently at 43 km, and appears irregular or disrupted only at back azimuths of 190–245°. At most azimuths this phase is a couplet with a decrease in velocity or density indicated immediately below the strong positive phase. The cause of this strong response is interpreted to be the Moho. The strength of the contrast across this discontinuity produces positive and negative reverberations (multiples) at 140 km and 170 km depths, respectively (Fig. 2). Signatures of weaker discontinuities appear to dip from 270° toward 90° in the mid-crust and less coherently between 70 km and 110 km in the uppermost mantle.

The tangential component conic section displays one of the richest patterns of dipping discontinuities observed at Canadian National Seismograph Network stations to date. Because these discontinuities are primarily observed on this component and not on the radial one, they probably represent seismic anisotropy caused by changes in large-scale (kilometres) rock fabric and not bulk physical properties, similar to the uppermost mantle beneath the central Slave Craton (Snyder, 2008). If due to anisotropy, seismic phase polarities should flip (black to red) approximately every 90° of back azimuth in simple cases (Savage, 1998). The pattern is somewhat incoherent and inconsistent with several planar, dipping layers indicated. The general trend is that layers at 50–150 km depths dip downward from about 250° toward 070° (west-southwest to east-northeast) at about 15°. A stack of slightly discordant layers or tapered lozenges about 30–40 km thick are indicated.

MULTI-AZIMUTHAL SKS-SPLITTING ANALYSIS

Shear waves travelling through an anisotropic medium are propagated at varying speeds dependent on their orientations. The difference in arrival times between the fastest and slowest first arrivals of a particular seismic wave phase is called the delay and the azimuth with the earliest arrival (least delay) is called the fast polarization direction (ϕ). Seismic waves emerge from the Earth's core as pure P-wave and, upon conversion to S-waves, can acquire a splitting signature only beneath the receiving station. No splitting can be inherited from the source side of the journey before transit of the core. These waves are called the SKS phase. The precise depth beneath the receiving station where splitting occurs cannot be constrained. Variations in fast direction and delay times with varying back azimuth can be diagnostic of mantle structure only if this structure is relatively simple: one or two layers, single-dipping layer (Savage, 1999). A single layer is characterized by a single unique pair of these parameters. Two layers have a beating signature that repeats every 90° of back azimuth. A dipping layer results in a linear dependence in fast polarization direction that repeats every 180° of back azimuth. Here analysis will be confined to analytical models that are strongly guided by the receiver function observations.

Sufficient earthquakes arrived at 22 back azimuths to provide robust estimates of the splitting parameters (Table 1). Neither the delay times nor fast polarization direction indicate a clear, single value for station FRB (Fig. 3). Averages with two standard deviations are 82 ± 27° for fast polarization direction and 0.81 ± 0.41 s for the delay time. The data are continuous and well constrained between back azimuths of 272° and 380° (same as 020°). Although this represents a range barely greater than 90°, no repeating 'beating' pattern every 90° is discernible in either the delay time or fast polarization direction. Several possible linear trends in fast

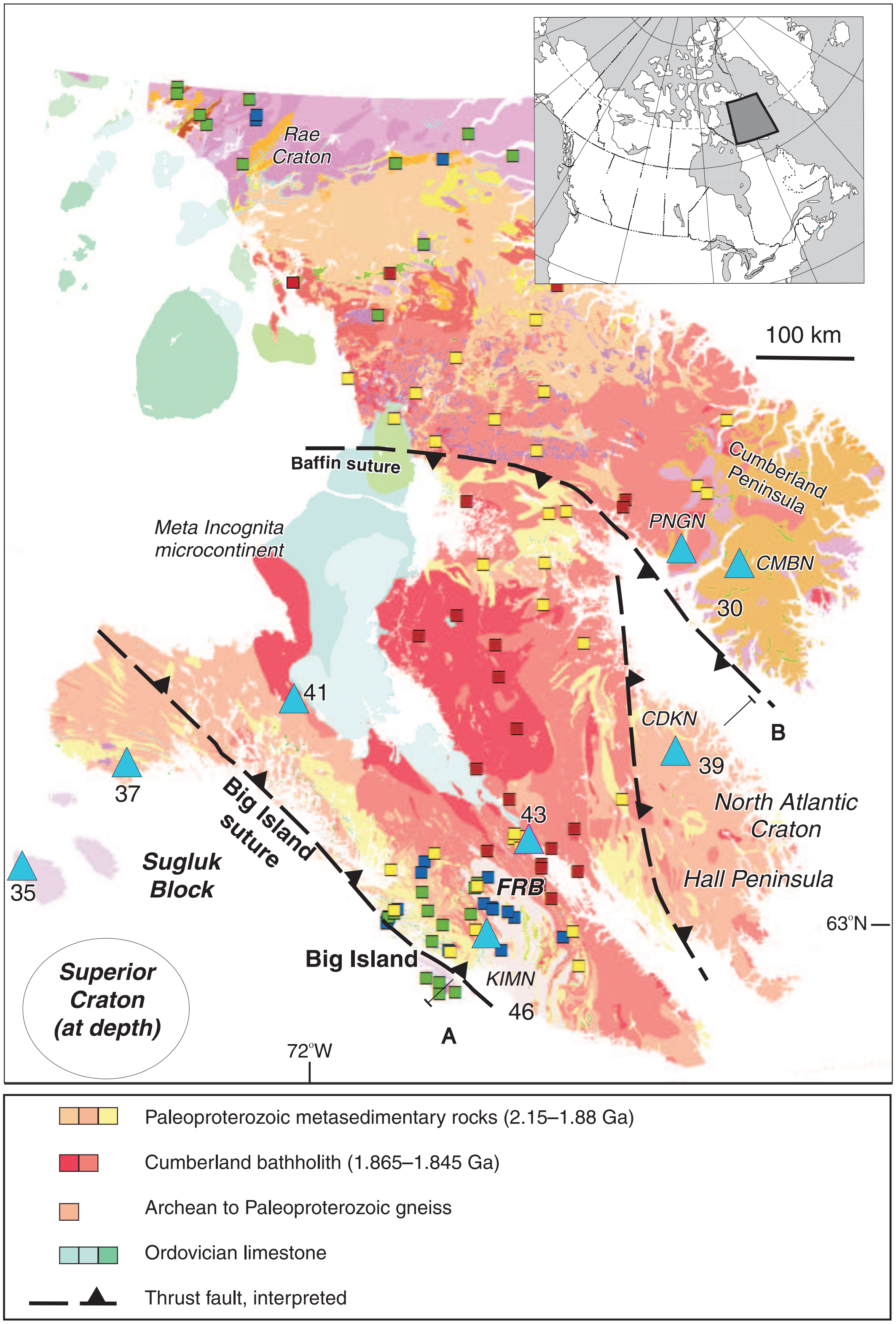

Figure 1. Location map showing geology (*modified from* Whalen et al., 2010) and seismic station locations (triangles). Numbers at stations are Moho depth estimates from receiver functions. A–B marks the location of profile in Figure 4a. The surface expression of the Superior Craton, the Cape Smith fold belt, and Narsajuaq Arc lies to the southwest of this map. KIMN, CDKN, PNGN, and CMBN are station names.

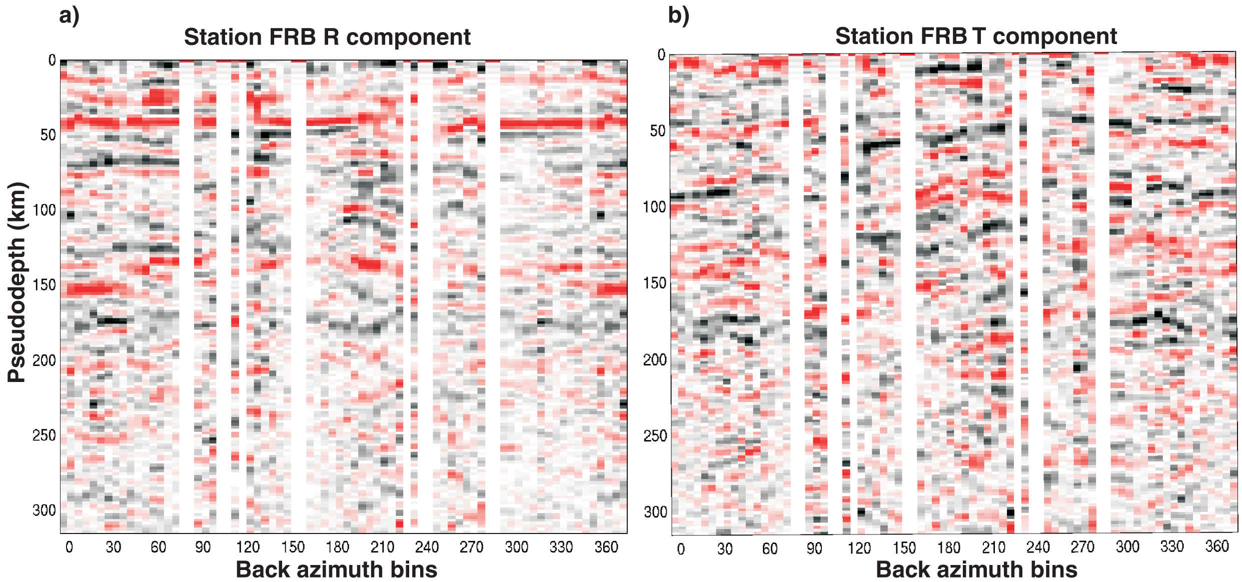

Figure 2. Multi-azimuthal receiver function for station FRB: **a)** radial component (R) and **b)** tangential component (T). Depth conversions assumed a constant speed of the shear waves of 4.5 km/s. Receiver functions for each 5° bin were bandpass filtered between 0.04 Hz and 0.75 Hz.

Table 1. Averaged splitting parameters for SKS seismic waves recorded at station FRB (63.746917°N, 68.545117°W). Values shown are averages with standard deviations for 2–8 parameter measurements within a 5° bin centred on the back azimuth listed. Two methods for estimating splitting parameters (minimizing transverse energy and maximizing eigenvalues, *see* Savage (1999)) were used.

Back azimuth (degrees)	**Fast direction (ϕ) (degrees)**	±	**Delay (s)**	±
008	16	22	2.2	1
013	16 or -74	13	2.2	0.5
020	-54	4	1.3	0.7
155	52	22	0.93	1
175	61	3	0.41	0.1
180	18	5	0.88	0.2
272	81	6	0.64	0.36
280	89	7	1.07	0.05
290	84	5	0.80	0.2
295	83	7	0.71	0.2
297	88	7	0.71	0.2
300	60	16	0.60	0.14
310	-86	8	0.54	0.13
314	-81	12	0.49	0.18
316	-87	4	0.49	0.1
318	79	8	0.67	0.1
325	-46	22	0.53	1
330	83	3	0.83	0.09
336	n.d.	n.d.	0.87	0.47
340	-71	11	0.98	0.33
344	89	7	1.12	0.73
348	85	4	0.95	0.77
353	-82	22	0.62	1
Averages	**82**	**27**	**0.81**	**0.41**
n.d. = no data				

polarization direction with 180° repetition, characteristic of several dipping anisotropic layers, provide permissible fits to the splitting parameters (Fig. 3). Theoretically, a dipping layer produces minima in delay times at back azimuths coinciding with the strike line. Here 315° has a relatively well defined minima in delay times. The implied downdip direction for this layer would be 045° or 225°; the former is most consistent with the 070° estimated from the receiver functions.

Both methods provide broadly consistent results. The 045° dip direction inferred from SKS-splitting techniques integrates fabric from all lithospheric depths and represents an average value. The 070° estimate and dip of 15° are specific to one discontinuity in anisotropic properties. Several discontinuities with somewhat variable dip are indicated within the 50–150 km depth interval.

STRUCTURAL SYNTHESIS AND INTERPRETATION

The southeastern half of Baffin Island has been the subject of several mapping projects over the past two decades so that its surface geology and tectonic history are now relatively well known (St-Onge et al., 2006a, b, 2009; Corrigan et al., 2009; Whalen et al., 2010). The widely accepted, general model is that several microcontinents became caught in a two-phase, three-way collision of the Superior, Rae, and North Atlantic cratons at about 1.865 Ga and 1.82–1.79 Ga (Fig. 1). Details concerning location of key sutures such as the Big Island (versus Soper River) and Baffin sutures, the origin and nature of the Cumberland batholith and associated lithospheric delamination event (Whalen et al., 2010), and the present-day coherency of the Sugluk and Meta Incognita blocks remain contested (Corrigan et al., 2009; St-Onge et al., 2009). The Baffin suture generally outlines the margin of the Rae Craton (Fig. 1), but is largely obscured by widespread crustal melting and metamorphism associated with the emplacement of the Cumberland batholith (Whalen et al., 2010). A related key, unresolved question is whether the Rae Craton underlies the Cumberland Peninsula. The Torngat

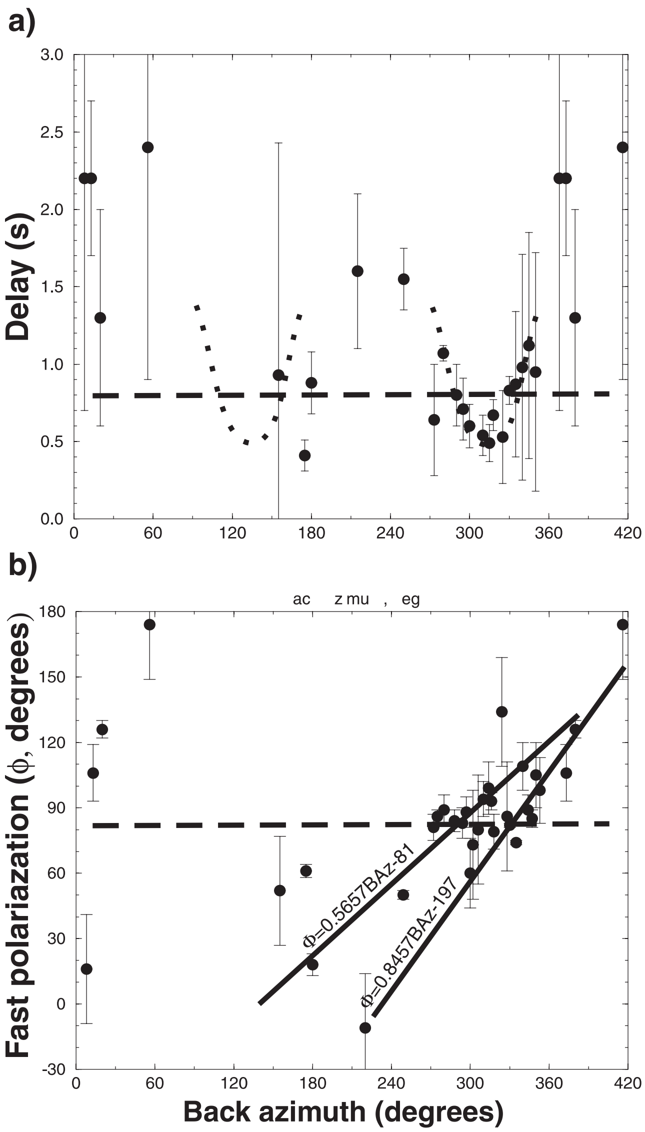

Figure 3. Splitting parameters for SKS seismic waves recorded at station FRB. Table 1 lists only averages of multiple events at a back azimuth; single-event parameters are also shown here. Horizontal dotted lines in both the **a)** splitting delay and **b)** fast polarization direction plots indicate an average of the data points. Hyperbolic dashed lines in Figure 3a indicate a trend that would be expected for dipping anisotropy with a strike at 135°. Solid lines in Figure 3b indicate two alternative least-square regressions of subsets of data points. BAz = back azimuth.

Orogen represents the western margin of the North Atlantic Craton, which was rifted apart by the opening of the Davis Strait and Labrador Sea so that part of it presently resides in western Greenland (Grütter and Tuer, 2009; St-Onge et al., 2009). The North Atlantic Craton is thought by some workers to underlie the Hall Peninsula as well as the Cumberland Peninsula. Other workers link it to the Torngat region of mainland North America. Station FRB and Iqaluit reside on the Meta Incognita microcontinent that is bordered on its northern margin by the 1.88–1.865 Ga Baffin suture and on its southern margin by the ca. 1.865 Ga Big Island suture (Fig. 1). The Meta Incognita Block is further separated from the Superior Craton by the south-verging Sugluk Block, the Narsajuaq Arc, and Cape Smith fold belt (St-Onge et al., 2009).

Northeastward-dipping layers within the uppermost mantle at 50–150 km beneath station FRB would thus be interpreted tectonically as underthrust parts of the Sugluk Block (crust and mantle), the Narsajuaq Arc and Cape Smith fold belt and the Superior Craton at greater depths. This distal part (away from thermal effects of the Cumberland batholith) of the Meta Incognita microcontinent or the Sugluk Block would be expected to have 40–80 km of mantle lithosphere attached to its crust so that several seismic discontinuities must be internal to this block. Subducted oceanic crust and uppermost mantle is known to have strong seismic anisotropy (Bostock, 1998) that could explain dipping discontinuities at 90–150 km depths beneath station FRB if underthrust equivalents of the Narsajuaq Arc and Cape Smith fold belt occupied that position (Fig. 4a).

SUPPORTING GEOCHEMICAL ANALYSIS OF MANTLE XENOCRYSTS

Kimberlite eruptions have sampled the mantle beneath the Hall Peninsula and brought both mantle peridotite xenoliths and indicator mineral xenocrysts such as garnet to the surface for analysis. The most important area lies 190 km northeast of station FRB at Chidliak (CDKN in Fig. 1). Geochemical analysis of the garnet xenocrysts permits them to be typed using standardized analysis (Grütter et al., 2006) and depths of crystallization estimated from the inferred pressure-temperature petrogenesis of the garnet grains (Fig. 4b). The relative Cr-Ca ratios of some garnet grains (G10) indicates that they originated in depleted, harzburgitic peridotite at pressures greater than 39 kbar (about 120 km depth); a few such garnet grains came from depths as great as 190 km.

The mantle layers inferred at 50–120 km depth beneath station FRB would project to 100–160 km depths beneath Chidliak if the modelled 15° were constant over this 125 km distance. A combination of underthrust oceanic and microcontinental mantle layers would provide appropriate protoliths for the indicator mineral garnet grains reported from Chidliak. The G10 pyrope garnet grains shown in

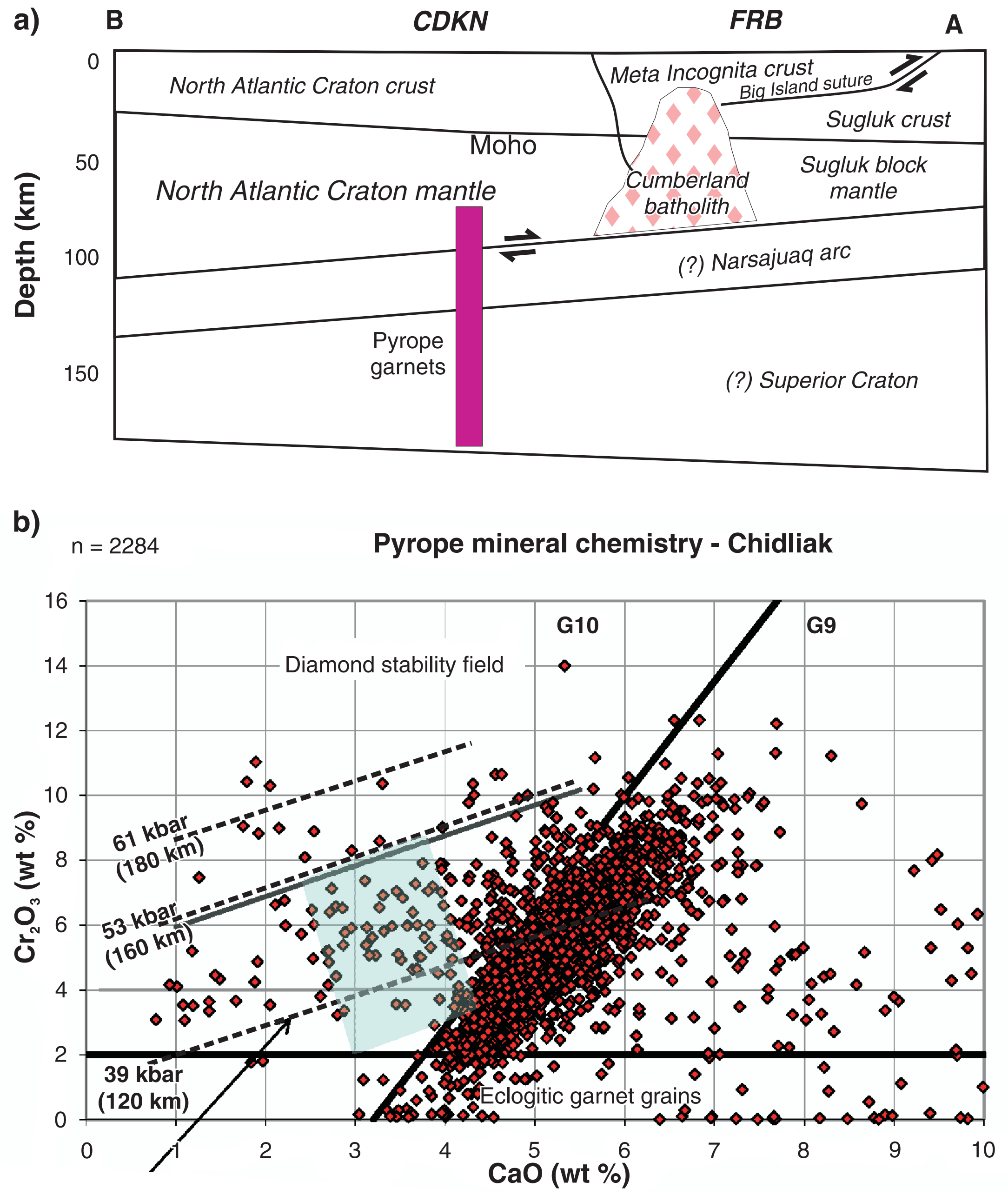

Figure 4. **a)** Interpretative cross-section of the mantle lithosphere, located as profile A–B on Figure 1. FRB and CDKN are seismic stations at Iqaluit and Chidliak, respectively. Moho depths constrained by receiver function analysis as indicated in Figure 1. Purple rectangle refers to depth estimates of garnet petrogenesis, taken from Figure 4b. **b)** Geochemistry of pyrope garnet crystals (diamonds) from Chidliak where dashed contour lines show the modelled pressure (depth) of origin for some G10 garnet crystals (Grütter et al., 2006; *modified from* Peregrine Diamonds Ltd. website, http://www.pdiam.com/i/pdf/chidliak5.pdf [accessed March 19, 2010]). Shaded rectangle indicates the modelled depth range of seismic discontinuities.

Figure 4b are typically associated with depleted harzburgite and peridotitic diamonds, both of Archean age. The Superior Craton and Meta Incognita and Sugluk microcontinental blocks all provide appropriate crust to match such mantle rock types at depths of 120–190 km indicated by G10 garnet grains. Underthrust oceanic lithosphere related to the Narsajuaq Arc would contain basaltic rocks and carbon-rich sediments that would metamorphose at depths greater than 100 km into eclogite and eclogitic diamond.

ADDITIONAL STATIONS AND FURTHER STUDY

A number of temporary seismic stations are currently operating across southern Baffin Island. Four stations and station FRB form a linear array roughly aligned with the interpreted downdip direction of mantle layers. Two of these stations were installed in 2007 by the University of Bristol, United Kingdom, as a contribution to the HuBLE (Hudson Bay Lithosphere Experiment) project, at the Kimmirut (KIMN) and Pangnirtung (PNGN) airports (Fig. 1). Two remote, solar-powered stations were installed by Natural Resources Canada as part of its Geo-mapping for Energy and Minerals (GEM) Diamond Project in 2009. These stations operate at the Peregrine Diamonds Ltd. Chidliak exploration camp (CDKN) and at the site of a GSC summer field camp on Cumberland Peninsula (Fig. 1). Data recorded by these stations are presently insufficient to undertake the analysis described here for station FRB, but preliminary estimation of Moho depth is possible and indicated on Figures 1 and 4. From southwest to northeast, Moho depth decreases from 46–43 km to 39–30 km. The University of Bristol also operates additional stations to the west. Three of these stations are shown on Figure 1 along with Moho depth estimates from preliminary receiver function analysis. Data acquired at all of these stations (excepting FRB) is currently insufficient for robust multi-azimuthal SKS-splitting or receiver function analysis. All of these stations are planned to operate for two to five years so that more robust analysis will become possible and allow comparisons with the results presented here for station FRB.

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