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Critical review

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Abstract: Magnetotelluric (MT) surveys are low-cost, ground-based geophysical imaging techniques with the capability to image electrical-resistivity structure at deposit or lithospheric scale. A magnetotelluric survey consisting of 26 sites undertaken during the summer of 2009 in tandem with ongoing bedrock mapping of Cumberland Peninsula has been analyzed to provide preliminary images of the subsurface geometries of its major geological boundaries and crustal-scale architecture. There is a good correlation between three electrically distinct layers and the three significant lithological components of the Peninsula: the Archean basement gneiss complex, and both the Paleoproterozoic cover sequence and the Qikiqtarjuaq plutonic suite. The structural fabrics mapped at the surface are reflected in both the shallow and deep MT sections. An apparent crustal-scale boundary exists beneath the southern part the survey area. Future 3-D modelling should unravel structural fabrics within the shallow portion of the crustal stack that can be used to constrain geological cross-sections.

Résumé : Les levés magnétotelluriques (MT) sont des techniques d'imagerie géophysique au sol, réalisées à faible coût, qui peuvent produire des images de la structure de résistivité électrique à l'échelle d'un gisement ou à l'échelle de la lithosphère. On a analysé les résultats d'un levé magnétotellurique constitué de 26 sites, réalisé à l'été 2009 en conjonction avec un programme en cours de cartographie du substratum rocheux de la péninsule Cumberland, pour créer des images préliminaires de la géométrie des principales limites géologiques de la péninsule en profondeur et de l'architecture à l'échelle crustale. Il existe une bonne corrélation entre trois couches distinctes sur le plan électrique et les trois composantes lithologiques d'importance de la péninsule, à savoir le complexe gneissique de socle de l'Archéen ainsi que la séquence de couverture et la suite plutonique de Qikiqtarjuaq du Paléoprotérozoïque. La fabrique structurale cartographiée à la surface se reflète dans les coupes MT à faible et à grande profondeur. Il existe une limite apparente à l'échelle crustale sous la partie sud de la zone visée par le levé. La modélisation 3D à venir devrait permettre de mieux comprendre la fabrique structurale dans la partie peu profonde de l'empilement crustal, qui pourra être utilisée pour encadrer l'interprétation des coupes géologiques.

INTRODUCTION

Natural Resources Canada's Geo-mapping for Energy and Minerals (GEM) program, initiated in 2008, is acquiring new geoscience knowledge that will enhance private-sector exploration and guide jurisdictional land-use decisions, including the creation of parks and other protected areas. An important component of the program is geological mapping of Nunavut, given that modern bedrock and surficial maps exist for roughly only one-third of the territory. Geophysical, geochemical, and isotopic surveys in support of geological mapping provide value-added knowledge, critical to deciphering crustal architecture, unravelling tectonic history, and allowing correlation of major crustal blocks. Collectively, these data and the involvement of northerners in the data collection, are intended to contribute to the creation and retention of prosperity and well-being in Canada's North.

The Cumberland Peninsula, Nunavut, is a frontier region for resource exploration and development comprising an area roughly 58 000 km^2. Its location, north of recently discovered diamondiferous kimberlite occurrences on Hall Peninsula (Fig. 1), coupled with the potential for a wide range of metals such as Cu-Ni-PGE, gold, SEDEX Pb-Zn, has highlighted the need to update the spatially limited mapping conducted in 1970 (Jackson, 1971). Current tectonic models of North America incorporate Cumberland Peninsula within the Paleoproterozoic Trans-Hudson Orogen (Hoffman 1988, Lewry and Collerson 1990), a Himalayan-scale collisional orogenic belt that ultimately marks the collision between the lower plate Archean Superior Craton and an upper-plate collage of Archean crustal blocks (e.g. Rae, Hearne) and associated Paleoproterozoic supracrustal sequences (St-Onge et al., 2009, Corrigan et al., 2009). Within this overall context, however, are uncertainties regarding the affinity and role of Cumberland Peninsula, including the nature of its basement, the location of paleo-suture zones and the timing of regional tectonometamorphic events. St-Onge et al. (2009) postulated a continental-margin setting for Cumberland Peninsula with basement of Rae affinity that collided at ca. 1.88 to .86 Ga with Meta Incognita microcontinent to the south, such that an intervening suture

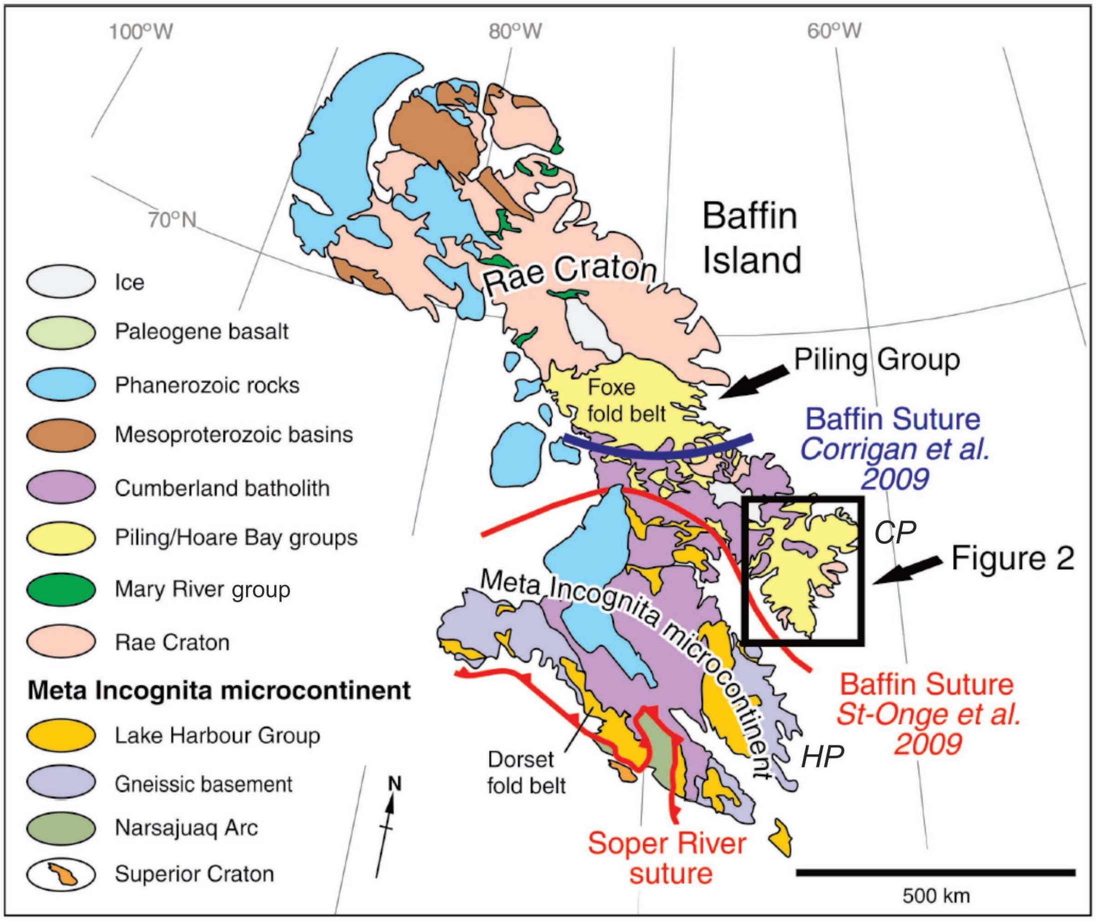

Figure 1. Simplified geological map of Baffin Island showing the extent of Paleoproterozoic supracrustal units: the Piling, Hoare Bay, and Lake Harbour groups, as they were thought to exist prior to GEM Cumberland bedrock mapping in 2009 and 2010. Locations of proposed sutures shown in red (St-Onge et al. 2009) and blue (Corrigan et al., 2009). CP: Cumberland Peninsula; HP: Hall Peninsula. Figure *modified from* St-Onge et al. 2009.

(the Baffin suture) would be located south of the peninsula along Cumberland Sound (Fig. 1). In contrast, Corrigan et al. (2009) postulated that Cumberland Peninsula had affinity to the North Atlantic (NAIN) Craton, brought into contact with the Rae margin through collision at ca. 1.865 Ga, such that a major suture (the Baffin suture) would be located to the north of Cumberland Peninsula (Fig. 1).

Magnetotelluric (MT) surveys are relatively low-cost portable surveys, conducted by a crew as small as two persons, with the powerful ability to image deposit- or lithospheric-scale structures. Accordingly, a magnetotelluric survey was undertaken in conjunction with ongoing bedrock mapping of Cumberland Peninsula in order to attempt to geophysically discern the subsurface geometry of its major geological boundaries and decipher its crustal-scale architecture.

REGIONAL GEOLOGY

Early reconnaissance mapping (Jackson 1971) had indicated the presence of a thick succession of deformed metasedimentary and metavolcanic rocks across Cumberland Peninsula, designated the Hoare Bay group (Fig. 1), which was thought to correlate with either the Mary River group of north Baffin Island (Jackson and Taylor 1972) or central Baffin Island's Piling Group (St-Onge et al. 2009). Recent systematic mapping and supporting data acquisition as part of the GEM Cumberland Peninsula project has established a new understanding of its geology (Fig. 2; Sanborn-Barrie et al., 2010, 2011a,b,c). The peninsula is now recognized to expose a significant Archean plutonic complex (Fig. 3a,b), which is structural basement to much more restricted Paleoproterozoic cover rocks of the Hoare Bay group (Fig. 3c). Both the plutonic basement and cover sequence are cut by charnockitic-granodioritic rocks (Fig. 3d), recently determined as part of a ca. 1.89 Ga (Rayner et al., 2012) plutonic suite which extends over 300 km between Pangnirtung and Qikiqtarjuaq.

The Archean plutonic basement is mainly tonalitic to granodioritic in composition. Although these foliated to gneissic, biotite-bearing rocks may lack inclusions or crosscutting dykes, they more commonly contain 1 to 20 m thick enclaves and/or layers of Archean supracrustal rocks and mafic-ultramafic metaplutonic rocks. The resultant heterogeneous layered plutonic complex is typically highly strained and shallowly dipping (i.e. Fig. 3b). Supracrustal enclaves are invariably rusty-weathering biotite-garnet ±sillimanite semipelite, which locally may contain up to 8% graphite. Also notable are garnet-rich layers interpreted as metamorphosed manganese-rich chemical metasedimentary units. Mafic volcanic rocks and associated oxide-facies iron-formation form part of the basement complex in the south on Ilikok Island and to its southwest (Fig. 2; Sanborn-Barrie et al., 2011a). Also in the south, mafic to ultramafic intrusive rocks are spatially associated with metasedimentary enclaves, and these metasediment-sill complexes are notably gossanous with rusty-orange-weathering sulphide-rich zones along interfaces between metasedimentary and gabbroic rocks. Ultramafic sills, 3 to 200 m thick, cut the basement.

The Hoare Bay group comprises a thick succession of clastic rocks dominated by psammite and semipelite with lesser pelite (Fig. 2). Thin (40 cm to 2 m) units of tectonized marble ±calc-silicate and quartzite occur close to the contact with mylonitic orthogneiss. Less-strained psammite and semipelite are common further to the north. The present-day highly strained nature of the basement-cover contact, where exposed, obscures insight into whether it originated as a depositional contact. Narrow strands of fragmental mafic and ultramafic volcanic rocks constitute part of the cover sequence, particularly in the northeast near Totnes Road (Keim et al. 2011) and Sunneshine Fiord (Sanborn-Barrie et al., in press). Spatially associated ultramafic and gabbroic sills may be genetically related to the metavolcanic rocks. Mylonitic plutonic rocks along the contact include ca. 1.88 Ga tonalite and ca. 1.87 Ga aplite, suggesting Paleoproterozoic intrusions lubricated faults that juxtaposed the basement and cover rocks.

Relatively homogeneous, variably foliated plutons cut the cover sequence and the underlying Archean basement complex. These plutonic rocks are represented by two main phases. Brown weathering, high-grade monzogranite-charnockite containing up to 15% orthopyroxene, variably retrogressed to biotite, yielded an U-Pb age of 1894 ± 5 Ma (Rayner et al., 2012) near Pangnirtung. This phase is typically cut by pale grey-pink weathering, granodiorite to monzogranite (Fig. 3d) containing 10 to 15% biotite and diagnostic isolated clusters of dark red almandine garnet. This phase is nominally younger than the charnockite, with an age of 1889 ± 3 Ma (Rayner et al., 2012). Both phases may be quartz and/or K-feldspar porphyritic and rarely contain magnetite. Designation of this belt as the Qikiqtarjuaq plutonic suite is based on the extensive exposures of compositionally similar rock types that yield similar U-Pb ages between ca. 1880 and 1894 Ma from seven localities. The suite is ~35 million years older than the 1845–1865 Ma Cumberland batholithic complex (Whalen et al., 2010) exposed to the west and formerly predicted to underlie this region (e.g. Fig. 1).

MAGNETOTELLURIC SURVEY AND DATA ANALYSIS

Magnetotelluric surveys involve deployment of sensors and recorders to measure natural variations in the Earth's electric and magnetic fields caused by solar activity and distant (i.e. southern hemisphere) electrical storms. During the 2009 field season, 26 magnetotelluric stations were installed as two arrays sited across Cumberland Peninsula (Fig. 2). One array formed an approximately north-south transect, at a high angle to the penetrative structural grain of these rocks,

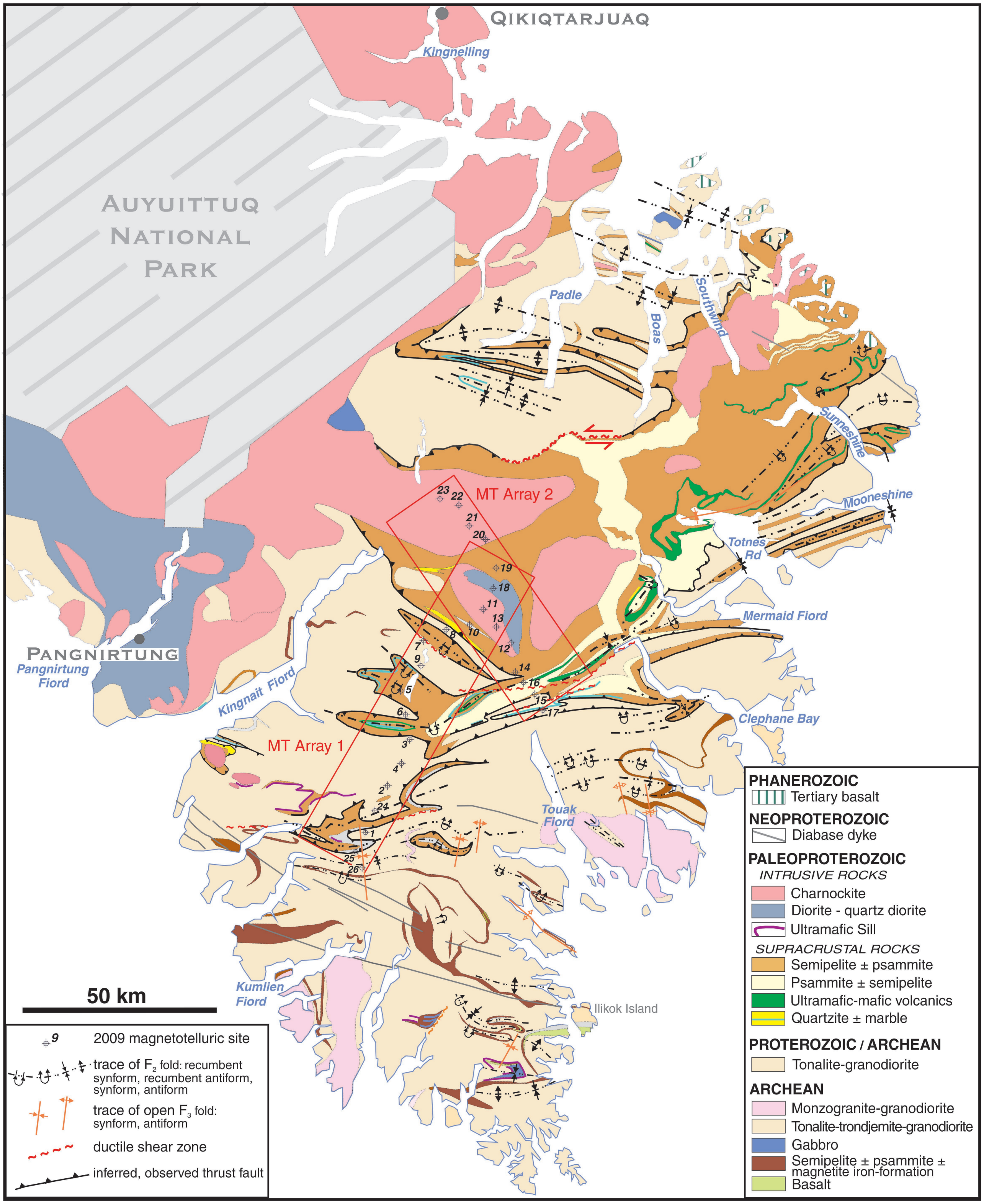

Figure 2. Cumberland Peninsula geology based on GEM bedrock mapping in 2009 and 2010. Red rectangles outline the two magnetotelluric arrays for which data are presented in the text.

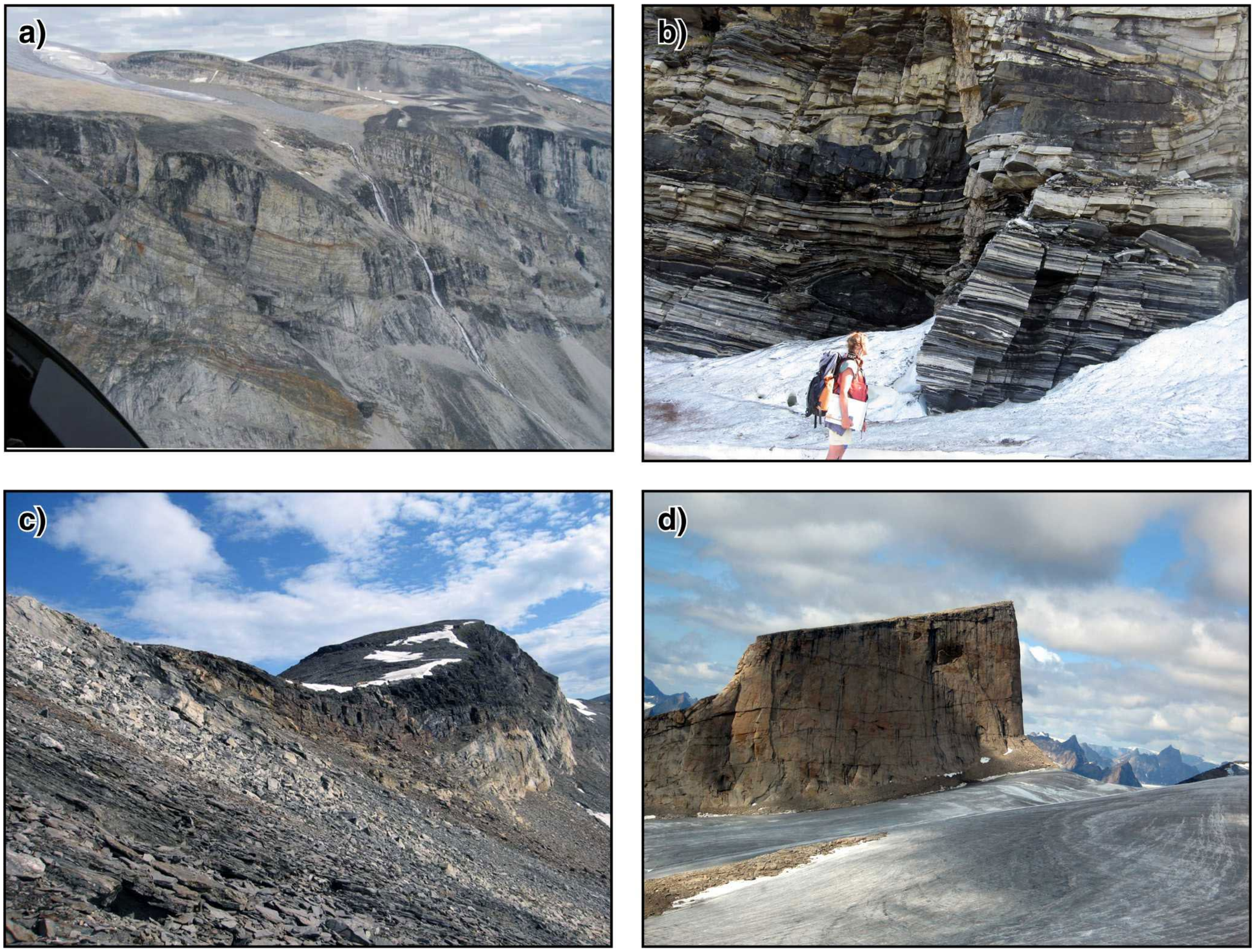

Figure 3. Lithological units of Cumberland Peninsula, eastern Baffin Island. **a)** Grey-weathering cliffs of Archean tonalite-trondhjemite-granodiorite basement complex, containing rusty-weathering metasedimentary and mafic layers and possessing a strong, shallow tectonic fabric. 2012-172. **b)** Detail of high-strain, shallow-dipping, heterogeneous basement gneiss complex. 2012-177. **c)** Oblique view of tectonic contact between buff-weathering plutonic basement and structurally overlying dark brown semipelitic cover sequence. 2012-174. **d)** Monolith of homogeneous monzogranite of the 1.89 Ga Qikiqtarjuaq plutonic suite. 2012-175. All photographs by M. Sanborn-Barrie.

while the other was oblique to array 1 in order to gain further 3-D control on the subsurface geometries. At each site, two sets of electrodes were installed (Fig. 4) to measure the horizontal components of the electric fields. Magnetometers were installed at alternate sites in order to exploit the smoother variation in the magnetic field of the Earth. The vertical component of the magnetic field was recorded at each site where successful installation of the coil was permitted by the local ground conditions. The vertical-field component provides complementary information to the horizontal components and, although not absolutely essential for data analysis, can help identify major fabric directions near the site, as well as help stabilize model calculations. Shorter induction coils were used to measure the vertical field due to their ease of installation; however, these are less sensitive to deeper structure in the crust. Each site was sounded overnight to exploit the stronger ambient signal strengths, which led to some disruption by the local fox population who dug up and chewed cables and electrodes. The use of stainless steel wire was a deterrent in this regard.

Two sites (#12, #13) were positioned on glaciers (Fig. 5) in order to ensure continuity in the field array. At these locations, the contact resistance of the electrodes placed in the snow and ice was greater than the impedances of the standard amplifiers in the recorders. Such conditions favour only the recording of the amplifier's internal noise and preclude any measurement of the Earth's electric field. Accordingly, special amplifiers were used to minimize amplifier internal noise, thereby allowing measurement of the electric field. These special amplifiers have been used in a few cases worldwide (e.g. Wannamaker, et al. 2004; Craven et al., 2009) for MT measurements, but are far from routine. The amplifier frequency response is not measured, but rather is assumed to be frequency independent. Accordingly, the data from these

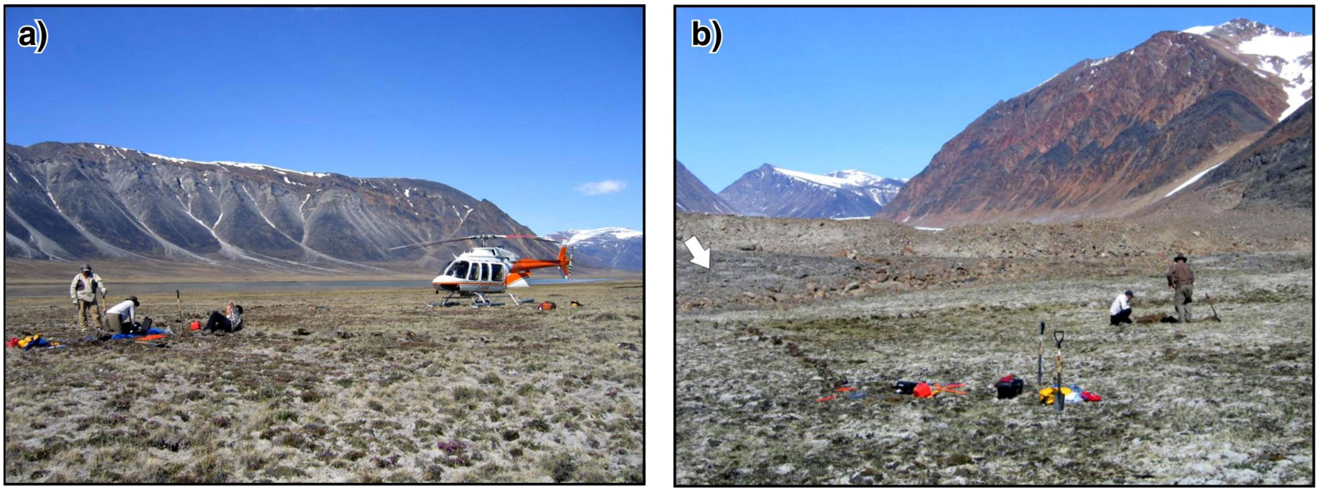

Figure 4. Installation of magnetotelluric recording sites on Cumberland Peninsula. **a)** MT site #4 showing till blanket in U-shaped valley and ridge in background exposing grey-weathering plutonic basement in tectonic contact with uppermost brown-weathering cover sequence. 2012-173. **b)** MT site #14 sited on thin till veneer adjacent to exposed tonalite (white arrow) below ridge of rusty-weathering, graphitic semipelite. 2012-171. Both photographs by B.J. Roberts.

two sites will be compared to the more traditionally acquired data to test for internal consistency, and the results of the comparison between techniques factored into the degree of confidence placed on the MT data sited on glaciers.

The Cumberland Peninsula MT survey was conducted at high geomagnetic latitudes, north of the auroral oval, where auroral current flow is dominantly sheet-like and uniform from local magnetic midnight to local magnetic midday (Evans et al., 2005). This is advantageous from a data-processing point of view because the conversion of the measured time series to earth responses assumes a uniform source field configuration. Time-series data were processed using the techniques successfully employed by Evans et al. (2005) for calculation of apparent resistivity and phase responses. Processing employed the Jones–Jödicke robust code (Jones and Jödicke, 1984; method 6 in Jones et al., 1989) and the remote-reference technique (Gamble et al., 1979) to reduce bias associated with noise in the magnetic field data. In general, the data quality is good to very good (Fig. 6). There is an indication of some static shift (i.e. a frequency independent upward or downward bias of the apparent resistivity curves) and noisy data at selected periods, especially at the extreme ends of the plots, but these effects are relatively minor and are not anticipated to influence the final model.

Figure 5. Magnetotelluric site #12 on alpine glacier, array 2. Photograph by B.J. Roberts. 2012-176

Apparent resistivities and phases are functions of frequency and must be further processed to generate an image of true earth resistivity that is a function of space. This was accomplished through a geophysical inversion procedure after discretizing the conductivity structure in the vicinity of the site in some manner. Using a layered-earth discretization, with layers increasing in thickness logarithmically beneath each site, and by contouring or 'stitching' the individual site models together, profiles of relatively shallow electrical response beneath array 1 (Fig. 7) and array 2 (Fig. 8) were generated. The contouring was performed with a smoothing distance which has been set to 50 m for the shallow profiles to ensure small-scale structure is not smoothed out. This can lead to drop outs in data used in the contouring near the edges of profiles at depths greater than 1 km or so (e.g. north end of Fig. 8).

The underlying layered-earth assumption, while regionally invalid, is deemed appropriate in our study area given the dominant, strong, subhorizontal tectonic structures (Fig. 3a,b,c) and the observation that shallow-dipping subsurface stratigraphy can, in places, be traced up to 60 km along strike without major breaks (Keim et al., 2011). The advantage of this assumption is that the image can be computed reasonably quickly. A disadvantage of the approach is that strongly dipping geometries will not be accurately

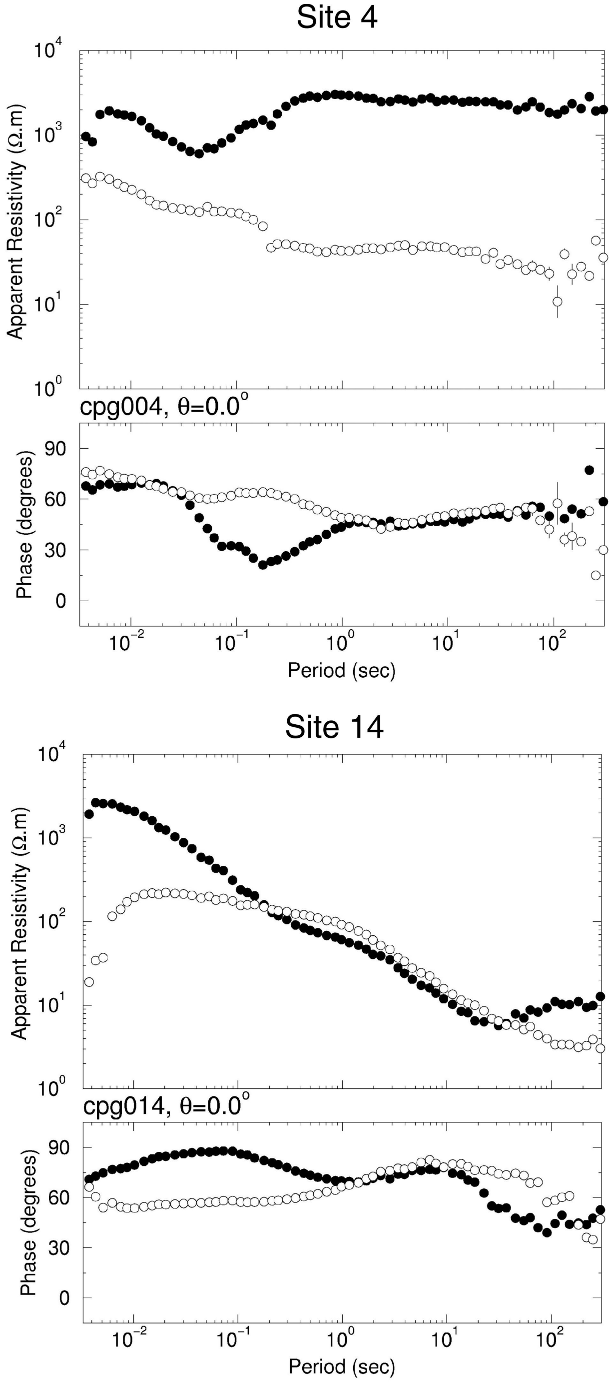

Figure 6. Plots of data at sites 4 and 14. Two response curves are calculated at each site due to the use of orthogonal pairs of electric and magnetic field measurements. The filled circles refer to responses obtained using north-south electric field components and east-west magnetic field components. The open circle estimates are obtained from east-west electric field and north-south magnetic field components. The stronger influence of nearby pelitic material may be reflected at site #14 by the comparatively higher phases and lower apparent resistivities.

portrayed. Vertical geometries, such as those associated with folds with near vertical axial planes, will not be resolved. The images were created using an implementation of the Occam algorithm (Constable et al., 1987) applied to the geometric average of the responses at each site. The Occam algorithm introduces the minimal number of changes to a starting model in order to fit the data, and thus is quite useful in situations where little information exists about the subsurface. These images are based on 1-D analyses and, as such, the geometrical relationships portrayed and highlighted by solid lines, although compelling in terms of what they reveal in the subsurface, must be considered preliminary. More sophisticated 3-D analysis is ongoing.

A deep section to 50 km (Fig. 9) was constructed using the same scheme as for the shallow sections; however, a larger amount of smoothing was required to compensate for the decreasing resolution in MT data with depth. The white regions at the edges of the section in Figure 9 represent areas of the model unconstrained by sufficient sites. A dashed line in the section is used to highlight possible vertical breaks at depth; however, their geometry will be better illustrated via 3-D modelling. Solid lines highlight the apparent shallow dip in electrical layering in contrast to the sub-horizontal Moho at 30 km (Snyder, unpub data) measured at site CMBN (Snyder et al., 2012).

DISCUSSION

Shallow magnetotelluric data from Cumberland Peninsula (Fig. 7, 8) highlight a three-layer electrical response in the upper crust. Below both arrays, this three-layer response comprises a near-surface (0–500 m thick) highly resistive layer (blue), a less resistive middle layer (green), and a lowermost conductive zone (yellow-red). Ground control through bedrock mapping shows good correlation between homogeneous (lacking inclusions or enclaves), foliated plutonic rocks and the near-surface resistive layer. This correlation applies to either Archean tonalite mapped at surface at sites 1 to 4 (Array 1) or to exposed plutonic rocks of the ca. 1.89 Ga Qikiqtarjuaq plutonic suite (foliated diorite-charnockite-granodiorite) at the northern ends of both arrays. Correspondence between the Qikiqtarjuaq plutonic suite and the resistive layer further suggests that these plutons may form ca. 1 km thick sheets. The MT data below sites located on metasedimentary cover rocks of the Hoare Bay group (site 5, Array 1; sites 14 and 16, Array 2) correspond to a less resistive response (green layer in Fig, 7, 8), which forms a north-dipping layer on both arrays. An increase in the presence and thickness of the Hoare Bay group northward was noted during the course of mapping. Conductive rocks at depth and thicker at the southern part of the arrays appear to correspond to the Archean plutonic basement complex, where the complex contains screens and enclaves of supracrustal and mafic plutonic rocks. Both arrays appear to show reasonable correlation with surface bedrock exposures and with tectonic structures recorded across this

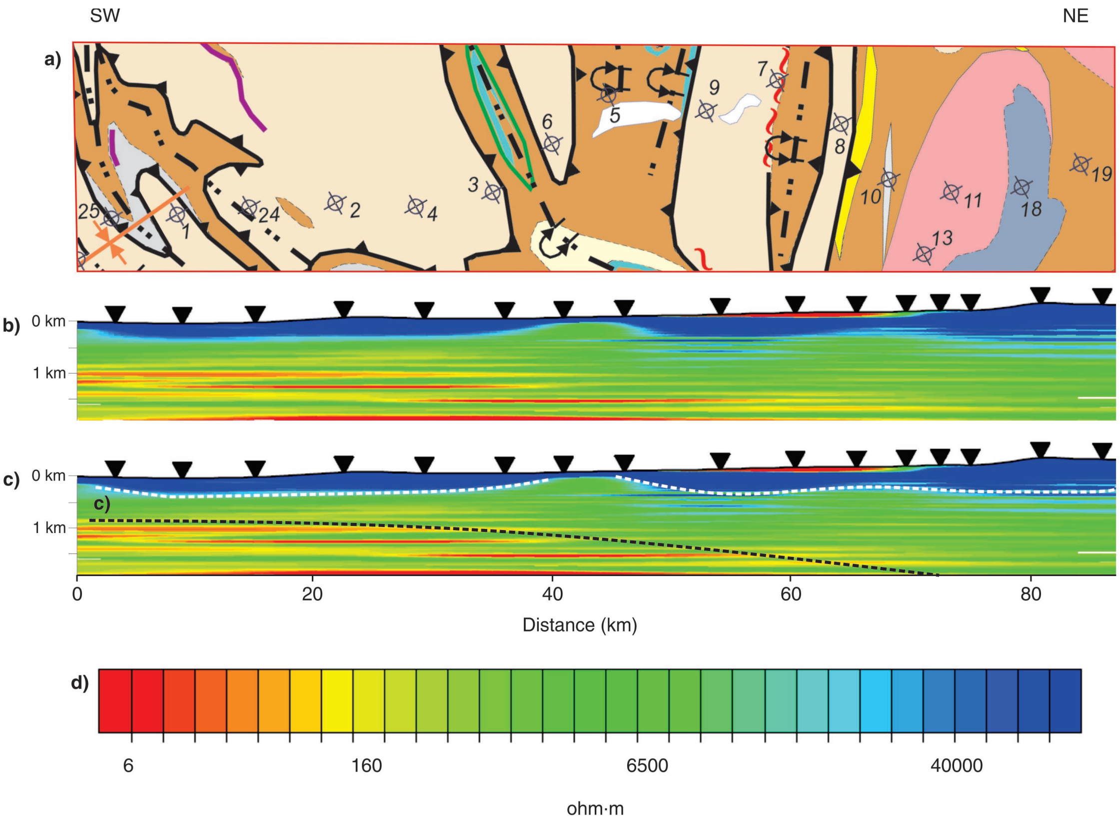

Figure 7. MT section to 1.5 km depth for array 1. **a)** Plan view of geology (legend as in Fig. 2) showing location of MT sites and data processed according to a layered-earth discretization. **b)** The resulting profile consisting of a highly resistive (blue) near-surface response, a north-dipping moderately resistive middle layer and a more conductive zone below 1 km. **c)** Interpretive contact between more conductive and more resistive layers, appearing to dip northward at a depth of 1.5 km. **d)** Resistivity colour scale.

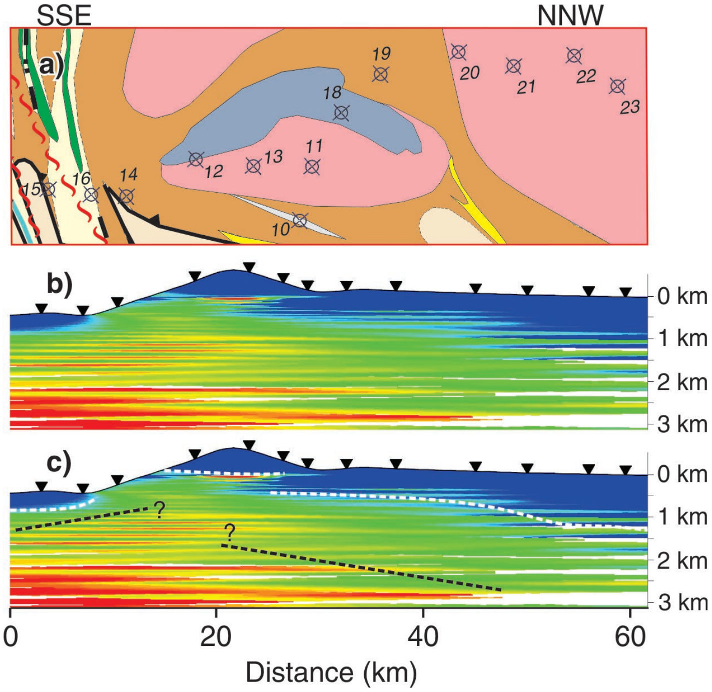

Figure 8. MT section to 2.5 km depth for array 2. **a)** Plan view of geology (legend as in Fig. 2) showing location of MT sites and data processed according to a layered earth discretization. **b)** The resulting profile consists of a near-surface highly resistive (blue) response, a moderately resistive middle layer (green) and a conductive zone 1.0 to 2.5 km deep beneath the southern part of array 2. Note lack of near-surface, blue resistive layer at MT site #14 situated close to bedrock (*see* Fig. 4b). **c)** Interpretive contacts between more conductive (red-yellow) and more resistive (green and blue) layers to a depth of 2.5 km. Colour-scale same as Figure 7d.

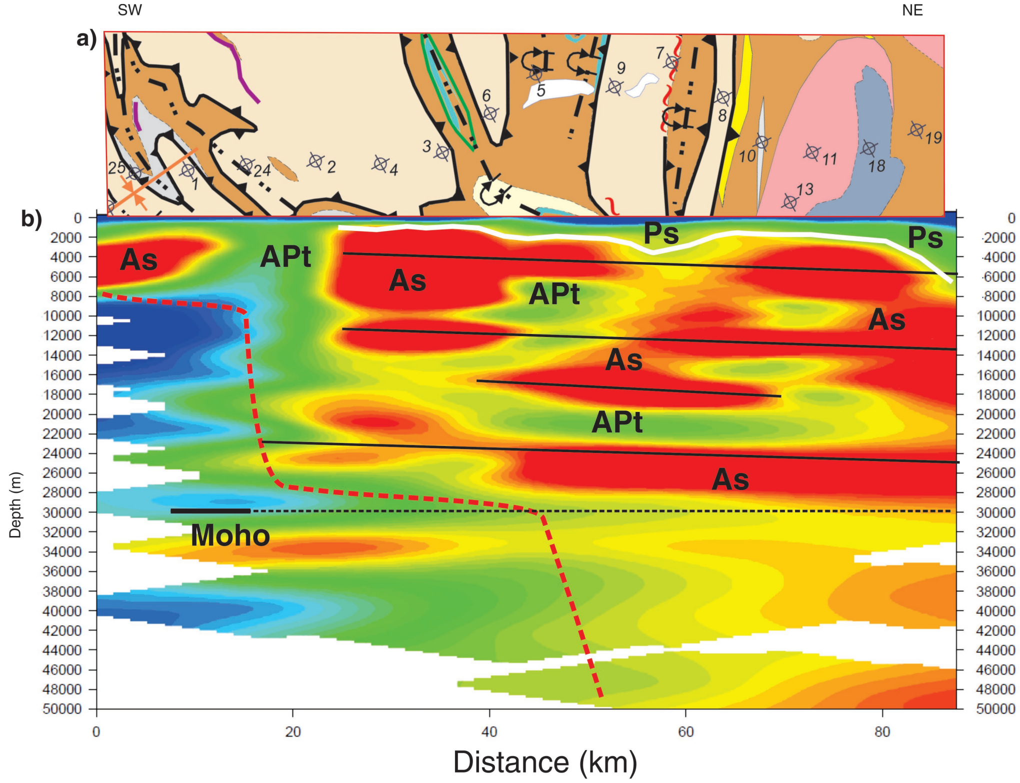

Figure 9. MT section to 50 km depth for array 1. **a)** Plan view of geology (legend as in Fig. 2) showing location of MT sites and data processed according to a layered-earth discretization. **b)** Profile showing crustal and upper mantle structure and interpretations discussed in the text. Colour-scale same as Figure 7d), As: Archean semipelite; Apt: Proterozoic/Archean tonalite; Ps: Proterozoic semipelite.

region. They show a general northerly dip of the interface between conductive and resistive layers, possibly attributed to a structurally repeated basement and cover contact. This relationship is documented on the ground through north-dipping tectonic fabrics and south-vergent, recumbent folds of basement and cover.

Shallow MT data from Cumberland Peninsula contrasts with that from central Baffin Island where Paleoproterozoic cover rocks are mostly conductive, mainly owing to the presence of the Astarte River formation (Jones et al. 2002; Evans et al. 2005). The Astarte River formation comprises rusty-weathering sulphide schist, graphitic black shale, and sulphide-facies iron-formation which forms a continuous marker horizon at the interface between carbonate platform strata and foredeep turbidites (Scott et al., 2003). The conductivity of the primary lithological components on Cumberland Peninsula is also likely a function of presence of graphite and degree of layering. In contrast to central Baffin Island, however, on southern Cumberland Peninsula these attributes appear to correspond to the Archean plutonic basement complex where metasedimentary enclaves, layered mafic plutonic rocks, iron-formation and garnetite layers make up a notable (10–20%) component, and where the degree of straight and continuous magmatotectonic layering can be intense (Fig. 3b). In contrast, cover rocks of the Hoare Bay group transected by the MT arrays tend to be biotite-sillimanite semipelite and biotite psammite. Candidates for conductive units belonging to the cover sequence are mainly exposed to the northeast, in a topographically high region unsuited to extensions of the geophysical profiles.

If the shallow constraints that are effectively ground-truthed by bedrock mapping are applied to the deep resistivity model (Fig. 9), it would imply that cover rocks of the Hoare Bay group (labelled as ‘Ps’ in Fig. 9) form a shallow, north-dipping, least resistive (green) veneer that extends from surface in the south to 8 km depth at the northern end of array 1. Near-surface resistive plutonic rocks corresponding to the Qikiqtarjuaq plutonic suite are included within this veneer as they do not appear to be resolvable at this scale. Underlying basement rocks (labelled As and APt) appear to extend from 8 km in the south to depths of approximately 25 km in the north. More conductive layers may reflect tectonic panels of cover rocks at depth; however, the MT section is overplaying the volume of semipelitic material and underplaying the amount of tonalite. Layered inversions, like the technique used in this analysis, will smooth the base of conductors such as the semipelite at the expense of a more resistive unit such as a tonalite below it due to the lower sensitivity of MT to resistive rocks. The conductive crust below the northern half of the profile is characterized by shallow, north-dipping structure (thin black lines in Fig. 9) which contrasts with a flat response at shallow depths (e.g. Fig. 7b) and at ~30 km depth interpreted as the Moho (Snyder, unpub data). There is a substantial change in the character of the MT image below site 24, where a more resistive response corresponds to the mid- to lower crust (>8 km) at the southern end of the array. If geologically meaningful, this response is clearly distinct from that which characterizes much of array 1, known to be underlain by Archean plutonic basement and Hoare Bay group cover rocks. This resistive domain may suggest the potential presence of a distinct block of mid to lower crust below southern Cumberland Peninsula. Such an electrically distinctive, resistive response may correspond at shallow depths to discrete Neoarchean plutons, a large domain of homogeneous Archean tonalite, or perhaps at greater depths in the crust to a separate microcontinental block, such as Meta Incognita.

SUMMARY

Magnetotelluric data from 26 sites across southern Cumberland Peninsula were collected over a two-week period, including two sites collected using novel approaches to deal with issues posed making recordings on glaciers, provide images to Moho depths.

There is a good correlation between three electrically distinct layers and the three volumetrically significantly lithological components of the Cumberland Peninsula, the Archean basement gneiss complex, the Paleoproterozoic cover sequence, and Paleoproterozoic Qikiqtarjuaq plutonic suite.

The north-dipping structural fabric observed on the surface appears to be reflected by the data in both shallow (Fig. 7, 8) and deep (Fig. 9) sections;

An apparent crustal-scale boundary exists beneath the southern part of Array 1. The resistive feature to the south of this break is possibly an amalgam of features including discrete Neoarchean plutons or a large domain of homogeneous Archean tonalite at shallow depths and possibly the Meta Incognita block at depth.

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