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Critical review

J. Haggart

Authors

R. Stephenson (r.stephenson@abdn.ac.uk)
School of Geosciences
Geology and Petroleum Geology
Meston Building, King's College University of Aberdeen
Aberdeen AB24 3UE, Scotland
United Kingdom

G.N. Oakey (Gordon.Oakey@NRCan-RNCan.gc.ca)
Geological Survey of Canada
1 Challenger Drive
Dartmouth, Nova Scotia
B2Y 4A2

C. Schiffer (christian.schiffer@geo.au.dk)
B.H. Jacobsen (bo@geo.au.dk)
Institute for Geoscience
Aarhus Universitet
Høegh-Guldbergs Gade 2, 8000 Aarhus C
Denmark

Correction date:

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Abstract: In August 2012, the Ellesmere Island Lithosphere Experiment (ELLITE) completed a two-year field program with the retrieval of passive seismic recorders deployed at six locations along a 480 km south-to-north transect from Alexandra Fiord to Ward Hunt Island. The research was carried out in collaboration with the University of Aberdeen (Scotland), with instrumentation provided by SEIS-UK and Natural Resources Canada's Geo-mapping for Energy and Minerals (GEM) Program. The solar-powered seismic stations operated during summer months and were dormant during the dark winter months. The recorded seismic activity caused by global earthquakes are being analyzed to model the crustal and lithospheric structure beneath the profile and will provide constraints on the magnitude of crustal shortening caused by the collision of Greenland with Ellesmere Island (between 50 Ma and 35 Ma) and its effects on the Sverdrup Basin and the offshore basins of northernmost Baffin Bay.

Résumé : En août 2012, dans le cadre de l'Étude de la lithosphère de l'île d'Ellesmere (ELLITE pour Ellesmere Island Lithosphere Experiment), un programme de deux ans sur le terrain se terminait par la récupération de sismomètres enregistreurs passifs disposés à six endroits le long d'un transect sud-nord de 480 km, allant du fjord Alexandria à l'île Ward Hunt. La recherche a été réalisée en collaboration avec l'Université d'Aberdeen (Écosse), tandis que les instruments ont été fournis par SEIS-UK et par le Programme de géocartographie de l'énergie et des minéraux (GEM) de Ressources naturelles Canada. Les stations sismiques à énergie solaire fonctionnaient pendant les mois d'été et étaient inactives pendant les sombres mois d'hiver. L'activité sismique enregistrée, causée par des tremblements de terre à l'échelle planétaire, sera analysée afin de modéliser la structure de la croûte et de la lithosphère sous le profil, et fournira des contraintes sur l'ampleur du raccourcissement crustal résultant de la collision entre le Groenland et l'île d'Ellesmere (entre 50 et 35 Ma) ainsi que sur ses effets sur le bassin de Sverdrup et sur les bassins au large de la partie la plus septentrionale de la baie de Baffin.

INTRODUCTION

Ellesmere Island comprises a series of approximately southwest-trending tectonic provinces (Fig. 1), the crustal structure and geological expression of which represent a combination of interplate, accretionary orogenesis in the Palaeozoic (Caledonian equivalent and Ellesmerian orogenies) and intraplate orogenesis in the Cenozoic (Eurekan Orogeny). The present-day topography of Ellesmere Island is closely related to the crustal architecture of these tectonic provinces, which includes the adjacent polar continental margin. Oakey and Stephenson (2008) deduced the first-order crustal structure from an analysis of the regional gravity field of the area and that the high topography of northwest Ellesmere Island is isostatically compensated by a thick crust. They further suggested that the Hazen Trough (Hazen fold belt), running most of the length of central Ellesmere Island, is underlain by a shallow Moho and that the central Ellesmere fold- and thrust-belts load (Greenland-Laurentian) cratonic basement that flexes to the northwest beneath it. Oakey and Stephenson (2008) also determined that the isostatic response of topography on Ellesmere Island (and immediate surroundings) is mildly, but statistically significantly anisotropic such that the lithosphere is inferred to be mechanically stronger in a direction roughly parallel to the direction of Eurekan intraplate shortening and large-scale regional basin inversion.

Key issues relevant to the tectonic evolution of Eurekan intraplate deformation (and intraplate deformation in general) plus any linked subsidence and deformation of contiguous sedimentary basins are 1) the location and architecture of the Palaeozoic continental margin and whether the crust of the Hazen Plateau represents the preserved Paleozoic continent-ocean transition zone or oceanic crust of Precambrian–Early Palaeozoic age; 2) the presence, orientation, and seismological characteristics of anisotropy in the crust and mantle lithosphere of Ellesmere Island; and 3) the extent to which the topography of northwest Ellesmere Island is produced by Eurekan shortening or is remnant topography on crust initially thickened in the Early Palaeozoic.

These kinds of tectonic issues and how they are related to the resources of Ellesmere Island and surrounding sedimentary basins require knowledge of the deeper structure of the crust and lithosphere and this means geophysical data. Although regional gravity data exist for the area (cf. Oakey and Stephenson, 2008), there is an almost complete absence of seismological data, these being only two receiver function estimates of Moho depth from permanent seismic observatories at Alert and Eureaka (Darbyshire, 2003). The ELLITE activity was accordingly designed to address the scarcity of crustal information for Ellesmere Island, with its objective to collect sufficient high-quality seismological data, bearing in mind its frontier setting, for helping to constrain crustal thicknesses and to shed light on the postulated presence, geometry, and character of possible anisotropy within the Ellesmere Island lithosphere The results, fully integrated with geology and other available geophysical information also comprises a key element of a Canada-Greenland polar margin lithospheric transect within the CALE (Circum-Arctic lithosphere Evolution) task force of International Lithosphere Programme (e.g. Pease et al., 2011).

FIELD PROGRAMME AND DATA ACQUISITION

The ELLITE seismological array comprises seven 3-component seismic sensors deployed at six locations along a transect extending from Alexandria Fiord (western Kane Basin) in the south to Ward Hunt Island (Arctic Ocean) in the north (Fig. 1). Station information is listed in Table 1. Two different kinds of instruments were deployed — Guralp 3Ts at stations WHI, IBF-B, and AXF; and Guralp EPSDs at stations MCF, TQF, IBF-E, and CNF; note that two observatories (one of each kind of instrument) were established at IBF. The instruments and equipment were provided by SEIS-UK, which is part of the United Kingdom's Natural Environment Research Council (NERC). Each station was equipped with solar panels to provide continuous electrical power for the data-logging system during the summer 'daylight' period and was programmed to shut down for winter hibernation and re-boot in the spring when solar power was renewed. The respective solar panels are slightly different in size and power rating. The stations were established in June 2010 and revisited in June 2011 (with the exception of AXF; *see* below) to service and repair equipment and instruments and to extract data recorded until that time. In August 2012 the seismic stations were removed. Figure 2 shows the WHI and CNF stations, the former having a Guralp 3T seismometer and the latter an ESPD; the photographs were taken at the time of installation in June 2010.

This report, which describes research in progress, deals only with data recovered during the June 2011 service visit. These included excellent data from all ELLITE stations that were serviced; this excluded station AXF. Good first-arrival seismic phases and numerous secondary phases, including important surface waves, are abundantly clear for numerous events that have been inspected. An example of traces from one single earthquake recorded at one site (TQF) is shown in Figure 3.

There was, nevertheless, a significant amount of data lost as a result of (mainly) animal damage to cables in particular. Specifically, no data were collected at stations WHI or MCF after the winter 2010–2011 shut-down, an unfortunate circumstance given that they are the two most northerly sites on the array. It is known for certain that no data were collected at station AXF from June 2011 onward; this station is at the other end of the array and was severely damaged by an animal (probably a bear) sometime after deployment and prior to June 2011. Ground conditions prevented the service aircraft from landing at this location in 2011, but aerial inspection revealed that the seismometer itself had

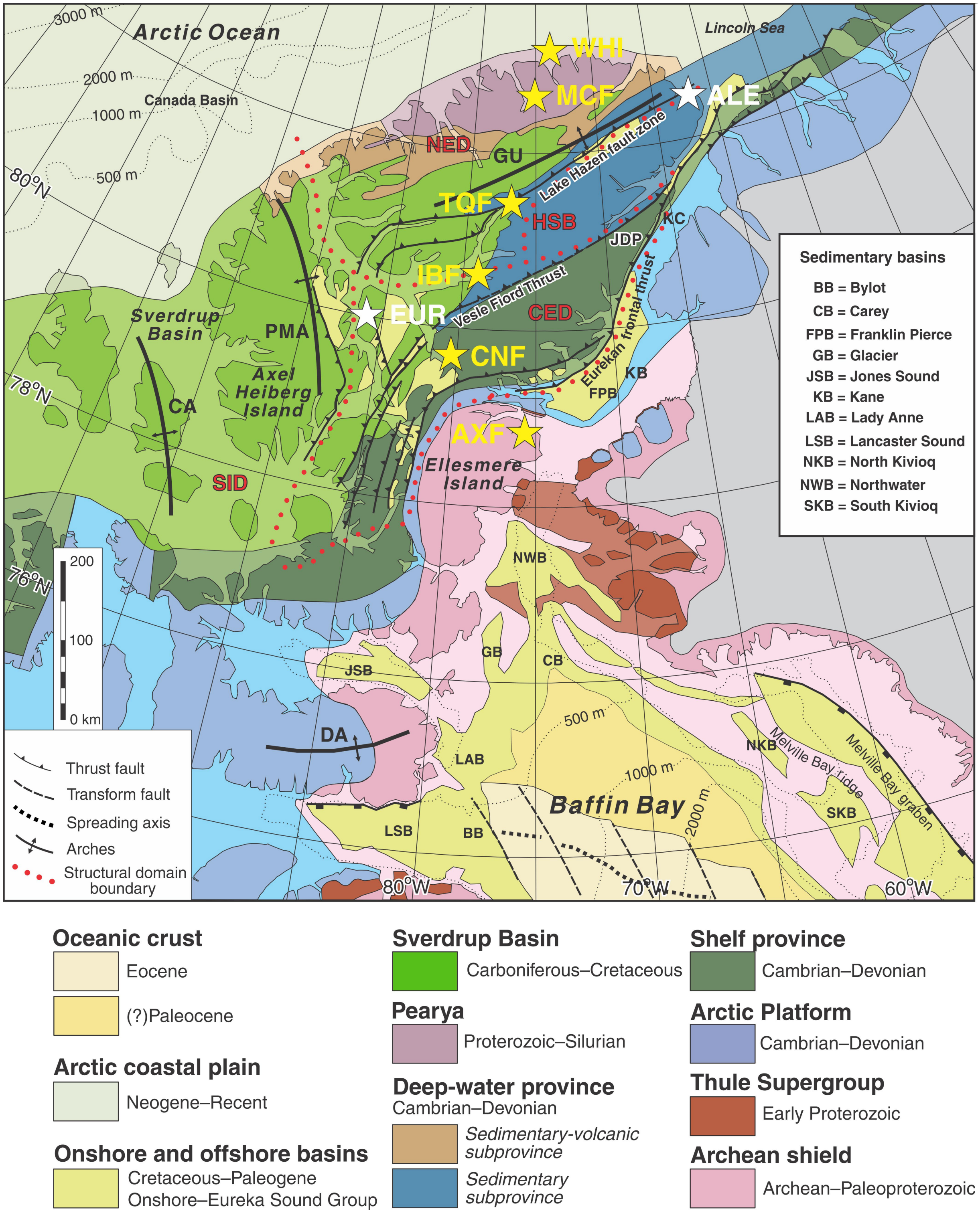

Figure 1. Location of the ELLITE seismological array (yellow stars) on the geological map of the Innuitian region (the latter from Oakey and Stephenson (2008)), showing the main 'structural domains' of the Eurkean Orogen (red letters, separated by dotted red lines; *see* Okulitch and Trettin, 1991): SID = Sverdrup Island Domain; NED = Northern Ellesmere Domain; HSB = Hazen Stable Block; CED = Central Ellesmere Domain. Regional structural features: GU = Grantland Uplift; PMA = Princess Margaret Arch; CA = Cornwall Arch; DA = Devon Arch. Other abbreviations: JDP = Judge Daly Promontory; KC = Kennedy Channel. Grey colour denotes ice-cover in Greenland. Permanent seismological stations are also shown (white stars: ALE = Alert, part of the IRIS/IDA Global Seismograph Network; EUR = Eureka; part of the NRCan Canadian National Seismograph Network).

Table 1. ELLITE seismological array.

Location	Station	Lat. (dd mm.m N)	Long. (dd mm.m W)	Elevation (m)	Map sheet
Ward Hunt Island	WHI	83 05.3	74 08.8	44	340H
M'Clintock Inlet	MCF	82 38.9	75 02.5	99	340E
Tanquary Fiord	TQF	81 24.8	76 50.7	20	340D
d'Iberville Fiord	IBF-E	80 36.3	79 34.6	34	340A
d'Iberville Fiord	IBF-B	80 36.3	79 34.6	34	340A
Canyon Fiord	CNF	79 39.4	80 46.7	43	49H
Alexandra Fiord	AXF	78 52.8	75 47.0	30	39F/E

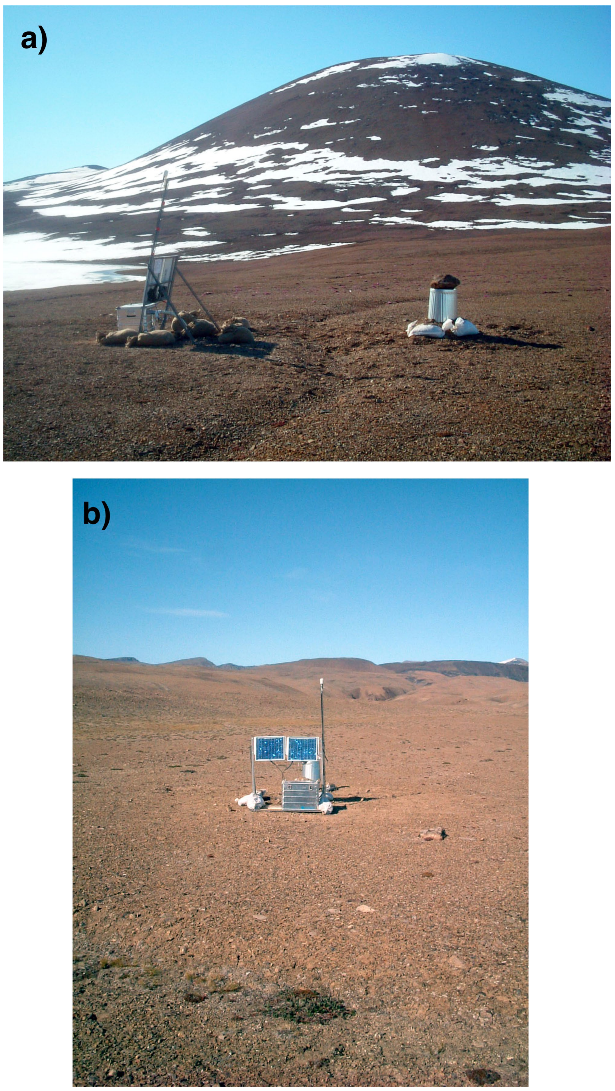

Figure 2. Photographs of the ELLITE seismological stations at **a)** Ward Hunt Island (WHI) and **b)** Canyon Fiord (CNF). The three-component seismometers, which sit on a granite plinth resting in fine sand, are covered by garbage cans. Batteries, voltage regulator, and other equipment such as data recorders (in the case of the Guralp 3T seismometers as at station WHI) and cable connectors are in the aluminum boxes; cables running between these and the seismometers are encased in spa hose (visibly entering the aluminum box in the top image), buried several centimetres beneath the surface. Solar panels face south and a GPS antenna is mounted on the solar-panel frame. The GPS antenna at WHI (Fig. 2a) was adjusted after this photograph was taken to tilt southwards. The height of the GPS antenna is about 2.1 m. 2013-237A, B

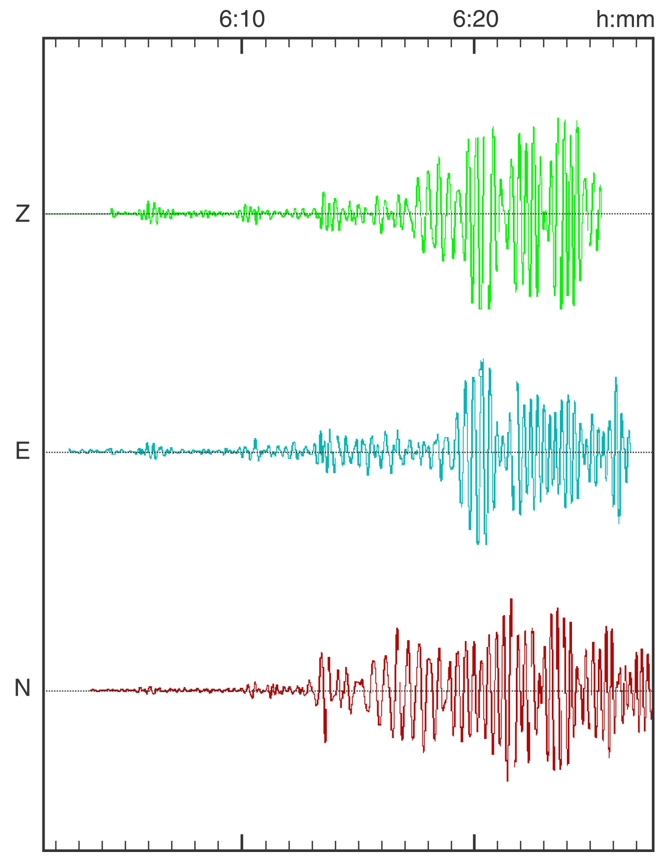

Figure 3. Onset of seismic coda (vertical (Z), east-west (E), and north-south (N) components top to bottom; green, blue, and red, respectively) recorded at Tanquary Fiord (TQF) from a magnitude 6.6 earthquake with focal depth 14 km occurring in the western Aleutian islands, Alaska on 18 July 2010 at 05:56:45 GMT. The horizontal axis is absolute time (hour and minute, h:mm, GMT) and the vertical axis is ground motion with all three traces plotted at the same scale. (Note that the display of each trace fragment starts and ends at slightly different times and that the blockiness of the traces has to do with how they were vectorized for production of this figure.)

been overturned. This was later confirmed by satellite telephone by a University of British Columbia graduate student who was based at Alexandra Fiord for his summer botany-ecology fieldwork in 2011. There was also some data degradation at station CNF, probably as a result of (animal) damage to the GPS (timing) cable and cold weather effects on the power-supply system (mainly the batteries).

TELESEISMIC METHODS AND PRELIMINARY RESULTS

The ELLITE data are to be, in the first instance, analyzed using techniques involving computation of ‘receiver functions’ and in consideration of ‘shear-wave splitting’. The latter uses a seismic wave that travels from an earthquake source to the seismometer destination through the mantle as an S-wave (shear wave), through the Earth’s outer core (which, being ‘liquid’, cannot sustain the propagation of shear waves) as a converted P-wave (compressional wave) and then emerges back into the mantle as a reconverted S-wave. This is called the SKS seismic phase and is useful for studying anisotropy in the mantle (including the lithosphere mantle) beneath the destination region because any anisotropy affecting the waveform as a result of its mantle descent is removed during its passage through the outer core as a P-wave. The recorded wave form is thus affected only by anisotropy in the ascending part of its propagation path. When an S-wave encounters an anisotropic region, its waveform is split into two orthogonal polarized shear waves. If the medium is anisotropic then these will travel at different speeds that can be measured. This is of interest on Ellesmere Island because of the mechanical anisotropy of the lithosphere inferred by Oakey and Stephenson (2008) from their isostatic admittance study. Anisotropy in the mantle can be caused by things like mineral alignments in the lithosphere due to preserved deformation, as well as alignments caused by mantle flow beneath the lithosphere itself. In any case, the goal is to elucidate the presence and direction of large-scale deformational fabrics in the Eurekan Orogen region. The ELLITE data will be augmented by data recorded for much longer periods of time at the two permanent stations in the region, at Alert and Eureka, in a project that will start in early 2013.

‘Receiver functions’ (RFs) are processed versions of the complex waveforms of the first arriving P-wave converted to S-waves at major velocity discontinuities in the Earth near the seismometer, typically, for example, from the Moho (crust-mantle boundary) in the vicinity beneath the recording site but possibly from other important horizons such as the sedimentary layer–crystalline layer intracrustal boundary. Receiver functions from the ELLITE data set are being computed and analyzed by C. Schiffer as part of his Ph.D. studies at the University of Aarhus in Denmark. Preliminary computations have been made based on the data collected from the ELLITE sites during servicing in June 2011.

Figure 4 shows the locations (left-hand panel), azimuthal directions from the station (right-hand panel) and magnitudes of all earthquakes from June 2010 until July 2011 recorded at five ELLITE sites (WHI, MCF, TQF, IBF-B, and CNF) used to compute preliminary receiver functions. The number of earthquakes for each site varies considerably because of variable quality (high noise levels) or lack of recording (due to cable damage and the like as mentioned above) at some sites. Only earthquakes with magnitude greater than 5.5 and with epicentral distances in the range 30°–102° were considered. The P-waves (and converted S-waves) from earthquakes closer than 32° are too oblique when they arrive at the station for useful computation of receiver functions and beyond 102° the direct P phase (travelling through the mantle only) is no longer incident (because of interactions at the core-mantle boundary at distances greater than this). There is a good azimuthal range for the ELLITE stations and this will be relevant for future work on anisotropy and other analyses.

A preliminary set of receiver functions is plotted in Figure 5, using the methods outlined by Clayton and Wiggins (1976). These are by no means the final results, not only because the additional data acquired after June 2011 will be added to the analysis, but because there are many elements of the processing and analysis producing these preliminary results that require fine-tuning and optimization The vertical axis in Figure 4 is Ps conversion time and the events seen on the receiver functions (e.g. positive, red excursions) represent P-wave to S-wave conversions derived at velocity boundaries below the receiver site. Rewriting conversion times in terms of depths to velocity boundaries is not a straightforward matter because it depends not only on the velocities of overlying geological units, but also on composition (inasmuch as this affects the relationship between P- and S-wave velocities in rocks) as well as the epicentral distance to events being considered (because the emergent waves are not vertical, but have an emergent angle depending on the distance to the source earthquake). Nevertheless, as a rough guide, a Ps conversion time of about 4 s could indicate a depth of some 35–40 km.

Some preliminary, speculative remarks on the computed receiver functions seen in Figure 5 are as follows. Station CNF data looks poor and little can be said; relatively few events have been used here because of the problems mentioned above. These data will, nevertheless, be augmented by those recorded after June 2011. The other four stations display events that could be indicative of Moho, with station IBF being the most ambiguous among these. As such, the Moho at station MCF is fairly deep and is deeper than at station WHI. The Moho at station TQF could be similarly relatively deep if the event at 4–5 s is the Moho conversion. There are also shallower events evident at station TQF and other stations and these might well have significance for understanding the tectonic evolution of the area (cf. Oakey and Stephenson, 2008). The final receiver function results, using all of the data recorded through August 2012, are

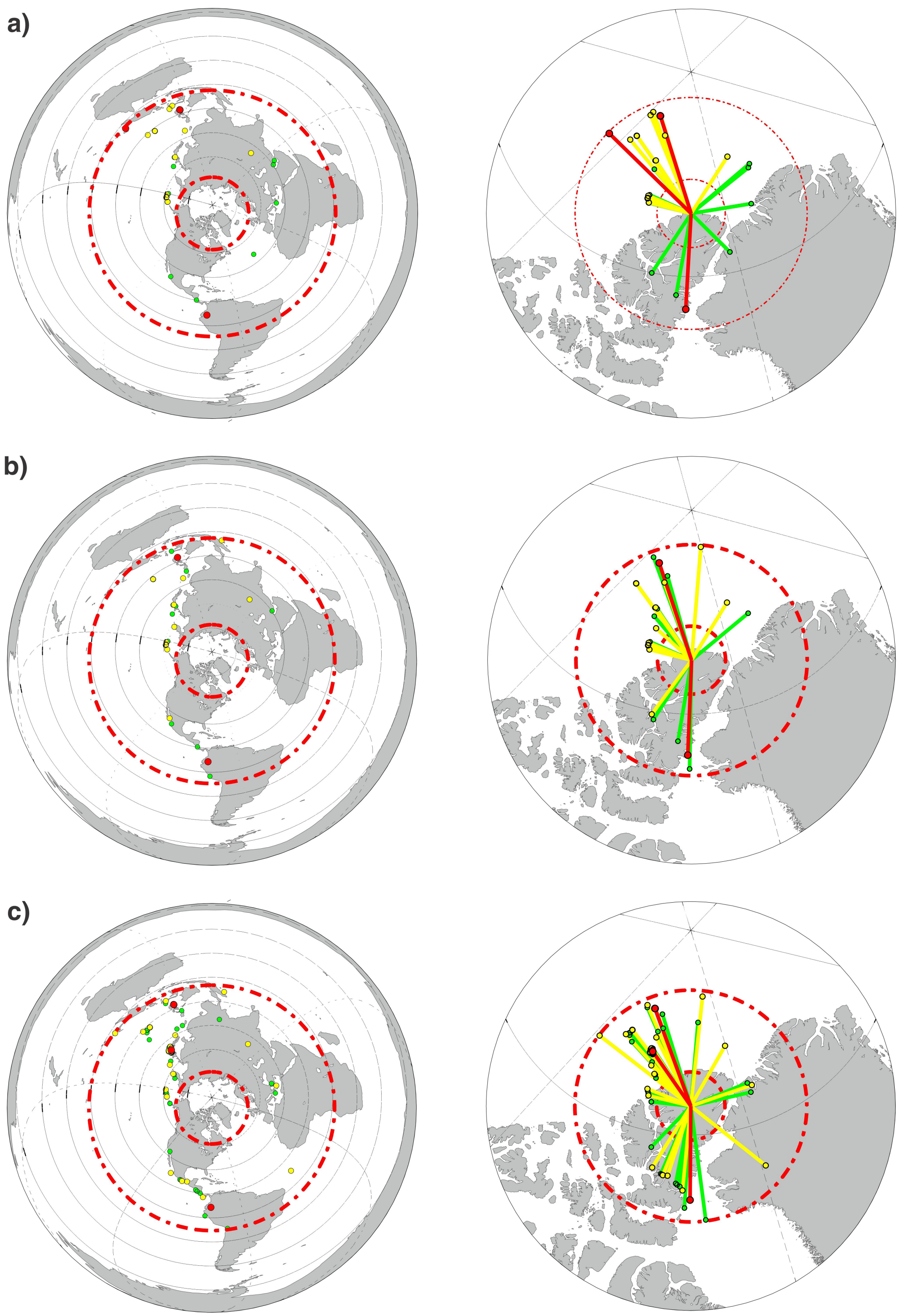

Figure 4. Locations (left-hand panel), azimuthal directions (right-hand panel), and magnitudes of earthquakes recorded between June 2010 and July 2011 used in computing the receiver functions (RFs) seen in Figure 5: **a)** station WHI (34 earthquakes), **b)** station MCF (28 earthquakes), **c)** station TQF (90 earthquakes) **d)** station IBF-E (63 earthquakes), and **e)** station CNF (16 earthquakes). Not only did CNF have fewer events than the other stations, but also displayed a generally poorer signal-to-noise ratio for the events that were recorded. Green events have magnitudes 5.5–6, yellow 6–7, and red greater than 7; the dashed red lines are the epicentral distance limits for computing receiver functions in the range 30–102°.

d)

e)

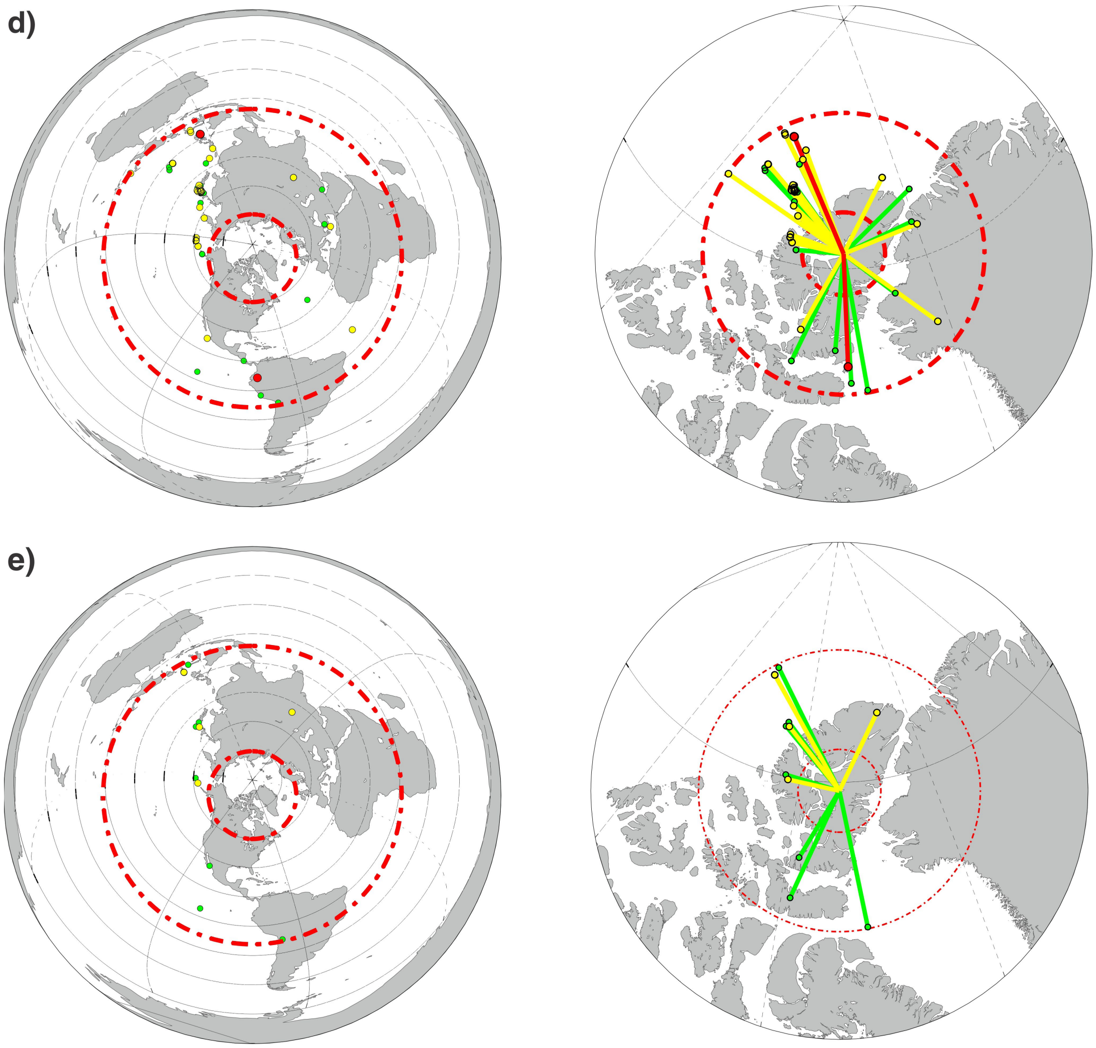

Figure 4. (cont.)

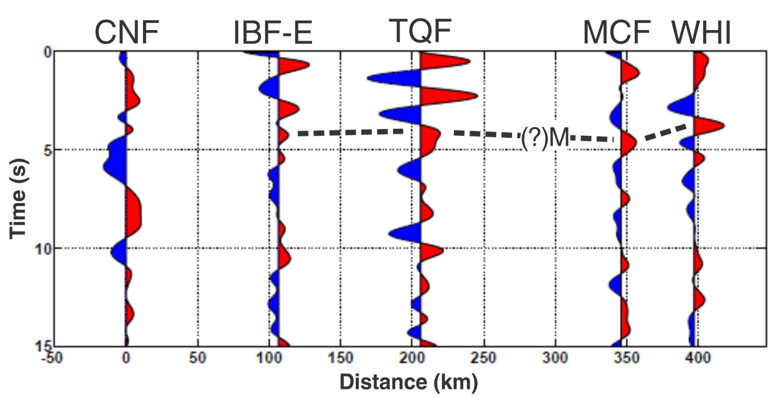

Figure 5. Preliminary receiver functions for sites CNF, IBF-E, TQF, MCF, and WHI plotted according to distance, south to north, left to right. The correlated events labelled '(?)M' may represent a Moho (crust-mantle boundary) conversion. Strong conversions at station TQF at earlier times (t<4 s) indicate large intracrustal velocity discontinuities.

being analyzed at this time and will be integrated with gravity data to develop a crustal transect model of the Eurekan Orogeny for public dissemination in 2014.

SUMMARY AND CONCLUSIONS

The data acquisition phase of a passive seismological experiment on Ellesmere Island, recording global earthquakes (teleseisms) for crustal and lithosphere structure studies, has ended successfully, with all equipment recovered and sites returned to the original states. Data collected from the temporary seismological observatories during servicing in June 2011 included abundant excellent recordings of three-component teleseismic waveforms. Despite the limited scale of the experiment, given the environmental and logistical challenges of the field area and some data degradation as a result of these, it is expected that the project will lead to the first seismologically based constraints on the crustal structure of the Eurekan Orogeny along a transect crossing northeastern Ellesmere Island from Alexandra Fiord (western Kane Basin) in the south to Ward Hunt Island, on the polar continental margin, in the north. The seismological results will be integrated with geology and other geophysical data, notably gravity data, to prepare a regional, lithosphere-scale two-dimensional model of the deeper structure of the Eurkean Orogeny of northeastern Ellesmere Island. The goal is to illuminate the geodynamic processes that led to the formation of this intraplate orogen and its associated topography.

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