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Field-based feasibility study of teleseismic surveys at high northern latitudes, Northwest Territories and Nunavut

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Abstract: During the summer of 2000, seven self-contained seismic stations were established and operated in remote areas of the Canadian north in order to assess their performance throughout the year. Two stations operated most of the year and provided high signal-to-noise ratios in teleseismic observations used to study the lithospheric structure beneath each site. For example, crustal thickness estimates of 40 to 42 (± 5) km were determined for both central Baffin Island and the central Slave Province. Most sites had sufficient thermal insulation and wind- and solar-derived power to operate through much of the cold, dark, winter months. Four stations were damaged during flooding of the vault during the spring melt. These results proved that the technology used is capable of providing useful data, but further refinements and cost-effectiveness analysis are ongoing.

Résumé : À l'été 2000, sept stations télésismiques autonomes ont été déployées dans des endroits éloignés du Nord canadien afin de déterminer leur performance sur une période d'un an. Deux stations ont fonctionné presque toute l'année et ont enregistré de hauts rapports signal sur bruit quant aux signaux télésismiques utilisés pour étudier les structures de la lithosphère sous chaque station. Par exemple, l'épaisseur de la croûte au centre de l'île de Baffin et au centre de la Province des Esclaves est estimée à 40–42 (± 5) km. L'isolation thermique était suffisante pour la plupart des stations. Des éoliennes et des panneaux solaires ont produit l'énergie requise au fonctionnement des appareils. Quatre stations ont été endommagées par des inondations produites par les fontes printanières. Les résultats démontrent que cette technologie peut produire des données utiles. Des améliorations et une étude sur la rentabilité sont en cours.

INTRODUCTION

In order to fulfill obligations to provide three-dimensional (depth) information for projects undertaken by the Continental Geoscience Division of the GSC, feasibility studies were undertaken for the year-round deployment of teleseismic stations in remote northern areas of the country. These stations are passive recorders of seismic waves generated by distant (teleseismic) earthquakes globally. It was optimistically hoped that deployments of tens of these stations in carefully designed arrays would provide scientific information at crustal scales and resolution that is comparable to that provided by transects of the LITHOPROBE program over the past few decades, and at much reduced costs. Such teleseismic deployments have become increasingly popular throughout the world in the past decade (e.g. Silver, 1996; Fouch et al., 2000; Silver et al. 2001), but few, if any, have been undertaken in far northern latitudes during the winter months. The challenge was to continuously record distant earthquakes using only self-contained sources of electricity throughout the bitterly cold winter and the spring melting of the snow and active layer of the permafrost.

Here we report on deployments of eight such stations between September 1999 and September 2001. Three sites were located in central Baffin Island, Nunavut (Fig. 1), the remainder among the diamond exploration camps of the Slave Province, north of Yellowknife, Northwest Territories (Fig. 2). The former was part of a joint GSC–CNGO (Canada–Nunavut Geoscience Office) 4-D regional geoscientific study of central Baffin Island, Nunavut (St-Onge et al., 2001). The latter formed part of the GSC's Targeted Geoscience Initiative to study the Walmsley Lake region of the Slave Province. The GSC's Seismology and Electromagnetism Section provided the equipment and some supporting funds for the development of new electronic equipment.

This report will include a description of the equipment used, some logistics of the deployments, statistics about the recording of earthquake data, and examples of the data recorded and its preliminary analysis.

SEISMIC EQUIPMENT

The basic seismic-equipment design of these studies has been used by government and university geophysicists for at least five years. The sensor is the CMG-40T model made by Guralp Systems in the UK. Its functional bandwidth is rated as 50 Hz to 30 s and it is a passive-feedback three-component seismometer. The recorder is the Orion built by Nanometrics, Inc. in Kanata, Ontario. The recorder stores the data in digital format in memory and automatically downloads these data to a removable hard disk every 0.5 to 6 hours. The 2 gigabyte disks used typically can store 180 to 270 days of three-component data and state-of-health information. Standard sampling rate used here is 20 samples per second.

In order to spin up the hard disk reliably, it must be at a temperature of 10°C. The combined recorder-sensor system requires about 5 watts of power to function in cold climates

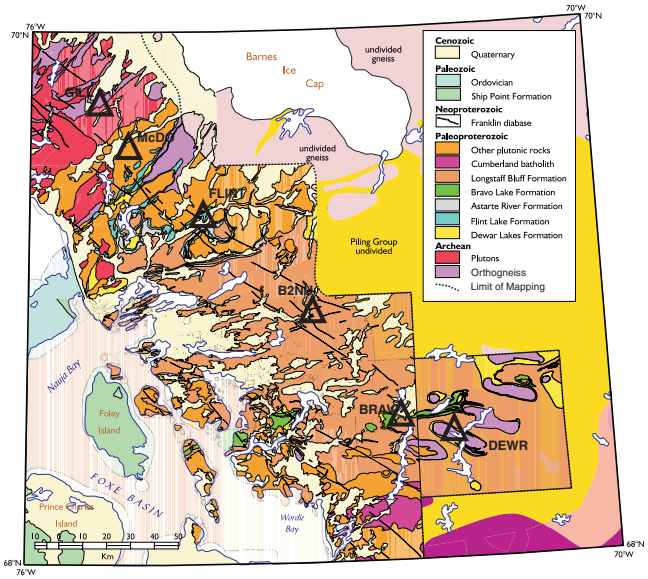

Figure 1. Location map for the central Baffin Island teleseismic stations; base is the project's geological compilation map (Corrigan et al., 2001).

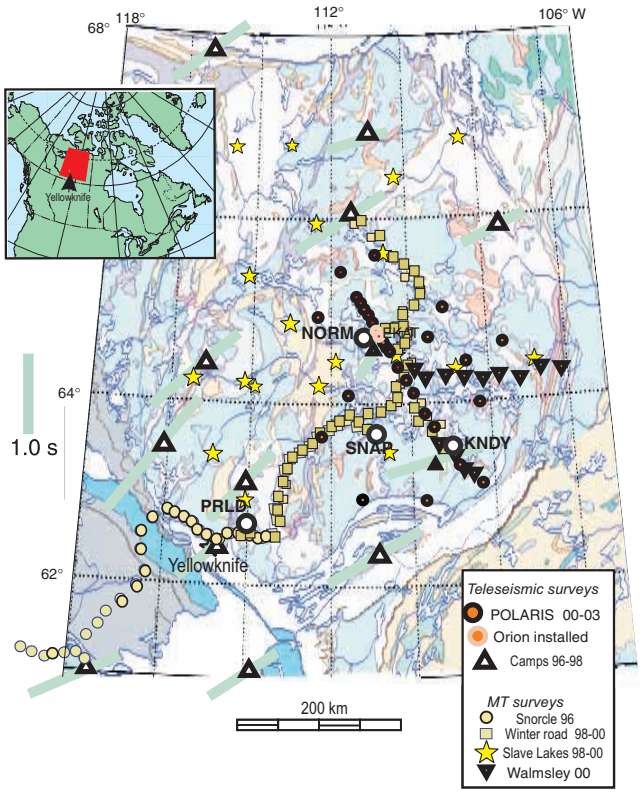

Figure 2. Location map for the central Slave province teleseismic stations; also shown are previous teleseismic and magneto-telluric (MT) sites from closely related studies.

when the disk must be pre-heated. It was assumed that this power requirement could only be met in the harsh climate of high northern latitudes by using a combination of solar panels, wind generators, and storage batteries. These tests used four 30 amp solar panels, a wind generator rated at 50 watts, and four deep-cycle, 100 amp-hour, 12 volt batteries. The Orion and seismometer were buried below the ground surface in a plywood vault lined with styrofoam and fibreglass insulation (Fig. 3). The seismometer occupied one end and sat on a concrete patio tile embedded in the ground; the recorder, batteries, and charge controller had two layers of styrofoam above and below and fibreglass insulation on the sides. The vault was not made water-tight so that any water present could drain out into the ground.

DEPLOYMENT SCHEDULE

Central Baffin Island

Three sites were installed from the GSC's Central Baffin base camp in July, 2000. The equipment was shipped to Iqaluit by ship or air, to the field camp via Twin Otter, and into the field locations by helicopter. Table 1 lists the locations of these three sites (GILL, GSCC, DEWR) as well as three others installed in July, 2001. It typically took 4 to 6 hours for three people to dig the holes required, assemble the solar panels, the wind generator tower, the vault, connect all the components, and activate the site. The equipment was slung as one load by the helicopter.

Slave Province

The stations located in the central Slave Province are based primarily at active diamond exploration camps. Equipment was shipped by land or air to the Yellowknife Seismic Observatory and from there was flown via charter flights (typically Twin Otters) to the exploration camps. Helicopters helped carry the heavy items the few hundreds of metres from the camps to the sites.

Two sites are run off A/C power provided by the operating Ekati Diamond Mine and the recorders are located in heated buildings provided by BHP Diamonds Inc.; these stations provided control conditions as power was assumed to be completely reliable. A third site at Prelude Lake used an insulated vault and 12 volt batteries, but these were charged daily using a portable generator by Hendrik Falck, a geologist with the Government of the Northwest Territories (GNWT). This site was the first installed to test the thermal properties of the vault design and the Orion recorded output from a temperature probe placed within the vault. Table 2 lists the locations of these sites.

Figure 3. *Photographs of the DEWR (B1NU) station taken during installation (above) in July and again in March (below). The solar panel array, wind generator tower and seismic vault lid are visible. The inset shows details of the vault design.*

Table 1. Locations of central Baffin Island teleseismic stations.

	Latitude (N)	Longitude (W)	Elevation	Rock type
GILL	69.6651	-75.2899	43 m on Lake Gillian	gneiss
McDO	69.5199	-74.9084	276 m (near McDonald River)	granite
FLINT	69.293	-74.197	30 m on Flint Lake	quartzite
B2NU=GSCC	68.9216	-73.1973	92 m @base camp	turbidite
BRAV	68.5492	-72.1385	213 m	Mafic lava flows
B1NU=DEWR	68.4619	-71.588	181 m on Dewar Lakes	Gneiss dome

Latitude and longitude are in decimal degrees and are N and W.

Table 2. Locations of Slave Province teleseismic stations.

	Latitude	Longitude	Elevation	Operator
NORMS	64.7797	-110.7865	405 m on Exeter Lake	BHP
KNDY	63.4380	-109.1916	413 m on Kennady Lake	DeBeers
SNAP	63.5951	-110.8684	411 m on Snap Lake	DeBeers
PRLD	62.5772	-114.048	155 m on Prelude Lake	GNWT
BHPN	64.7328	-110.6703	451 m Ekati mine site	BHP
EKAT	64.6985	-110.6097	458 m Ekati airstrip	BHP

Latitude and longitude are in decimal degrees and are N and W.

Data and SOH records

The Orion recorders provide two basic types of continuous record. The seismic channels show the health of the seismometer (e.g. is it level?) and seismic noise levels present at the site. State-of-health (SOH) channels provide information about the hard-disk activity, various internal temperatures, and the voltage provided by the power subsystem (Fig. 4). The latter thus provide indirect information about the number of sunny and windy hours that occurred at each site.

Lessons from the Prelude Lake site

The site on Prelude Lake near Yellowknife was the first installed using the plywood vault design. It was dug, built, and the Orion installed in September, 1999. The site was visited on 26 November and a temperature probe was installed; the probe recorded temperature within the vault (outside the Orion case) onto one of the extra SOH channels on the Orion. The vault temperatures recorded (Fig. 5) can then be compared with those within the Orion (Fig. 6). From 14–20 January 2000, the air temperature within the vault varied between -12 and -14°C while the disk cycled between an ambient temperature of -2 to 0°C and its operating temperature of 9 to10°C (note coinciding spikes in CPU activity). The heating of the disk required in this process is an acceptable power drain during the coldest time of the year, but would be more optimal if the ambient vault temperature was closer to -5°C. It is also interesting to note the temperatures recorded immediately after the vault was closed at 16:00 on 26 November. Outside air temperature was about -15°C and the open vault showed -9°C, rising immediately to -2°C and then going through three diurnal cycles between -2 and -4°C before rising a few degrees (Fig. 5). These temperature observations demonstrated the insulating power of the buried, large vault design.

Lessons from the Kennady Lake site

The Orion vault was established near the DeBeers Kennady Lake exploration camp on 15 August 2000, and was first visited on 23 January 2001. The data log showed that data were recorded during 126 days and lost during 42 days of that period (Table 3). The state-of-health records (Fig. 4) show that battery voltage dropped below 11 volts on 18 December,

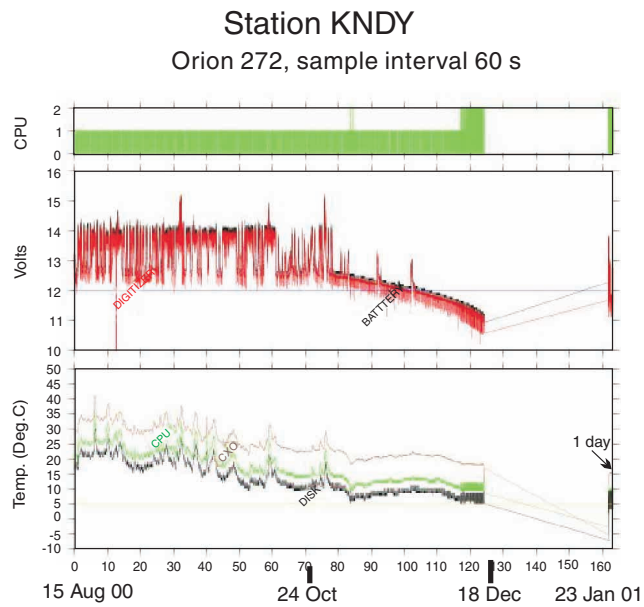

Figure 4. *State-of-health plots for station KNDY in the NWT. The temperature of the disk and voltage of the battery/digitizer are the most significant plots. CPU activity (when writing to the disk) is indicated by the top plot. Straight line segments indicate periods when the recorder was shut down, here 18 December to 23 January.*

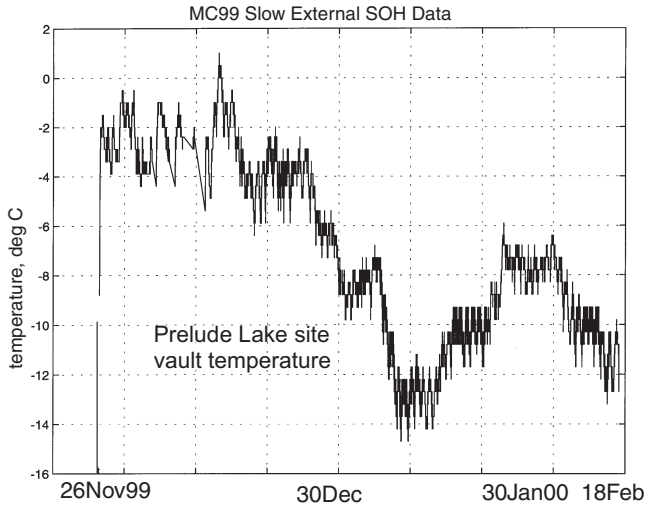

Figure 5. *Temperatures recorded from within the vault at the Prelude Lake site.*

at which time the Orion shut down. Voltage exceeded 12 volts again on 23 January and recording restarted for one day before the site was visited.

Both the solar panels and wind generator are thought to have supplied power during this period. The battery voltage (Fig. 4) shows a sharp decrease about 1 November. After that date the batteries were no longer being charged except on the few days indicated by voltage spikes, probably by wind because one spike occurs about 1 December when little sunlight is available. During this period, the disk temperature gradually drops from about 20°C to 10°C when battery charging ceases and then is constant until shutdown. By comparison with the PRLD site, one infers that vault air temperatures were greater than 0°C during this period. Temperatures recorded 10 m above the ground surface by the Kennady Lake camp's weather station during the previous two years (Fig. 7) suggest that air temperatures ranged from 10°C at installation, to -10°C when the batteries were no longer being charged, to -30°C when the Orion shut down.

Again the buried vault appeared to provide adequate insulation throughout the coldest part of the winter. Wind-derived energy was not sufficient to power this station through the darkest part of the year (1 November to 20 January) when the solar panels did not charge the batteries.

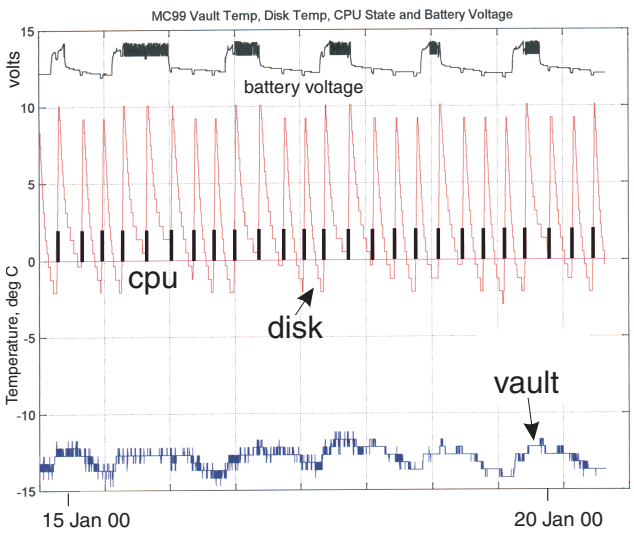

Figure 6. State-of-health plots for PRLD for a week during the coldest part of the year. Voltage of about 14 indicates when the generator was charging the batteries. The CPU (black spikes) was active writing data to disk every 6 hours, immediately after the disk was heated to 10°C.

Lessons from the Norm's camp site

The Orion vault near the BHP Billiton Norm's (exploration) Camp was established 20 August 2000, and first visited on 24 March 2001. The state-of-health records (Fig. 8) show that battery voltage dropped below 11 volts on 3 December at which time the Orion shut down. Voltage exceeded 12 volts again on 9 March and recording restarted, although intermittently through 24 March when the disk was changed.

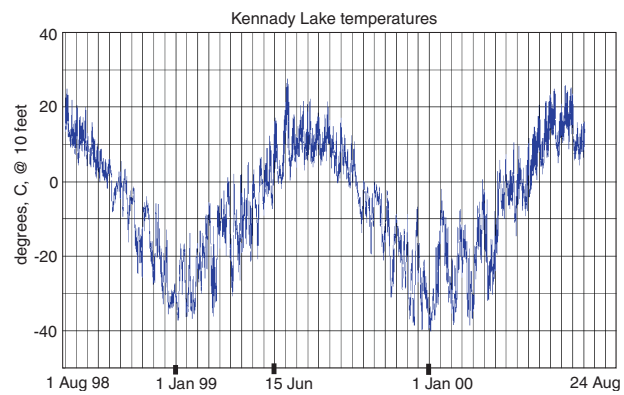

Figure 7. Air temperatures 3 m above the surface as recorded over two years by the weather station at the Kennady Lake exploration camp. Data courtesy of Brian Poniatowski, DeBeers, Canada.

Table 3. Data recorded.

Station	Period				
	I	II	III	IV	V
PRLD	20Sep99–26Nov99 (67/0 days)	–18Feb00 (79/5 days)	–2Aug00	–27Mar01	X
SNAP	X	X	X	23Aug00–28Mar01	X
NORM	X	X	X	20Aug00–24Mar01	--18Aug01
KNDY	X	X	X	15Aug00–23Jan01 (126/42 days)	–12Apr01 (76/1 days)
BHPN (A/C site)	X	X	X	20Aug00–23Mar01	–18Aug01
DEWR	X	X	X	23Jul00–18Mar01 (230/7 days)	–7Jul01 (111/0 days)
GSCCA	X	X	X	21Jul00–18Mar01 (152/38)	?
GILL	X	X	X	X	X

During the March visit it was noted that the solar panels had fallen, face down, onto the tundra before snow fell. That meant that only the wind generator powered this station during this period. The greater variability in battery voltage after early October, when compared to KNDY, for example, is probably indicative of wind-generated power charging the batteries. Weather records from the nearby (10 km) Ekati mine airstrip for August 1993 to January 1995 (Grant Lockhart, unpub. data) indicate that wind speeds exceed 2.5 m/s (9.0 km/hr) 79% of the time. Wind-generator specifications indicate that these speeds are sufficient to generate charging current in our power subsystem. The wind speeds exceeded 5.0 m/s for 43% of the record period. It is unclear why the batteries were not charged from early December through early March (this represents 25% of the year); it may be that the wind generator froze fast, a commonly reported occurrence for anemometers at weather stations in this region.

Disk temperatures were generally much greater here than at KNDY, at times exceeding 40°C in early September when excess power from the solar panels and wind generator were probably 'dumped' to heat sinks in the charge controller. Again these temperatures did not fall below 5°C except after the system was shut down for 3 months and air temperatures were below -30°C in early March.

The performance records from the third Northwest Territories site near Snap Lake are similar to the other two. Both solar panels and wind generator were functional when it was visited in March, 2000. The station had shut down on 5 December due to lack of power and reactivated 2.5 months later on 25 February (Fig. 9). Disk temperatures decreased from 20°C to 5°C at shutdown, and varied between 0 and 10°C upon restarting.

A success story from the Dewar Lakes site

The Orion vault located on Dewar Lakes in central Baffin Island (Table 1, Fig. 1, 3) was established 23 July 2000, and first visited on 18 March 2001. The state-of-health records (Fig. 10) show that battery voltage dropped below 11 volts for about a week on 17 January at which time the Orion shut down. Disk temperatures generally varied between 5°C and 15°C in 2000, then dropping to between -5°C and 5°C in 2001, similar to those in the Northwest Territories.

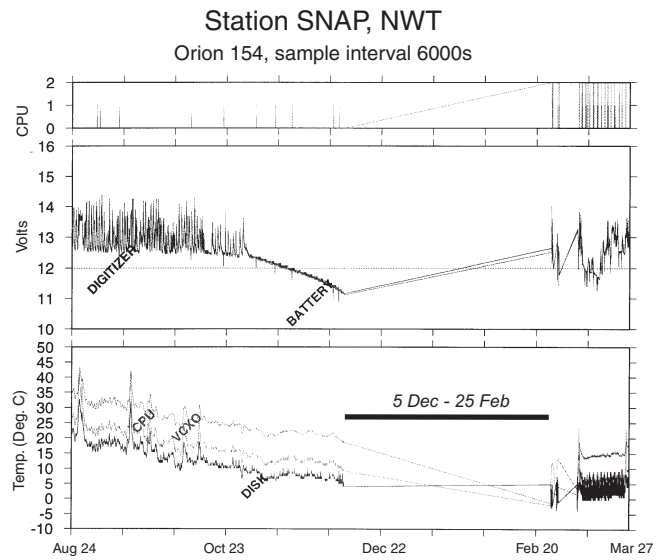

Figure 9. State-of-health plots for station SNAP in the NWT. Display as in Figure 4.

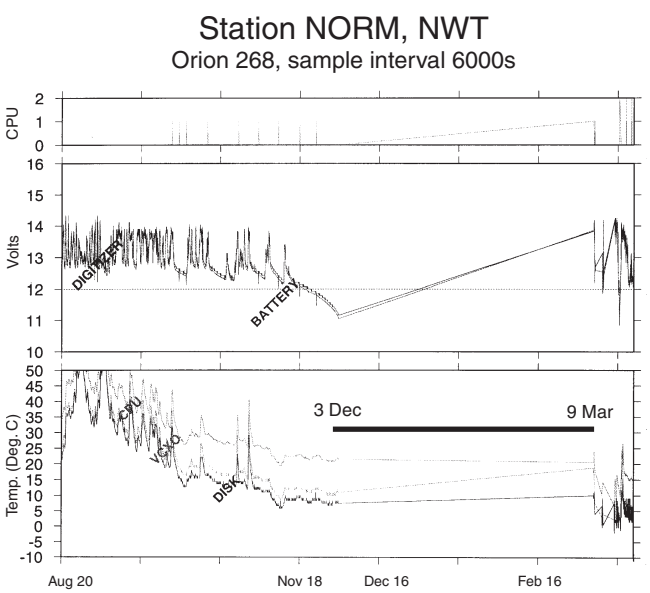

Figure 8. State-of-health plots for station NORM in the NWT. Display as in Figure 4.

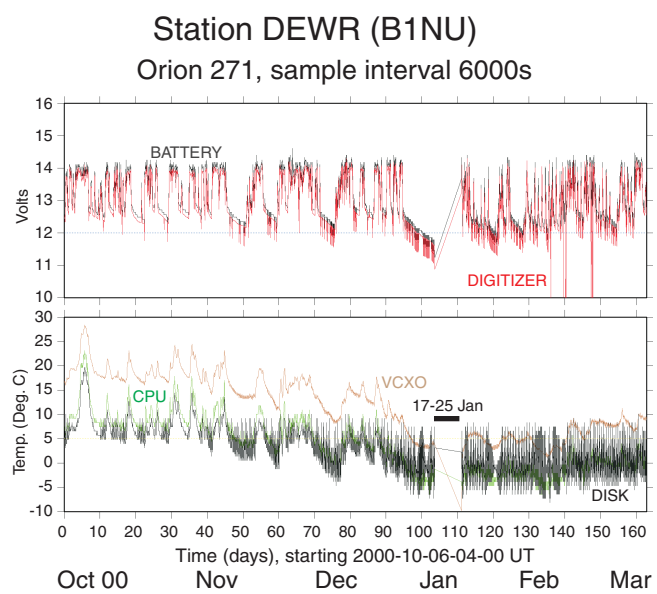

Figure 10. State-of-health plots for station DEWR in Central Baffin. Display as in Figure 4.

The data log (Table 3) showed that during this period the station successfully recorded for 230 days and missed data for only 7.38 days (~3% data loss)! During the following recording period it recorded continuously for 110 days. This station demonstrated that successfully recording teleseismic data at far northern latitudes all year long is possible.

Flooding problems at the Kennady Lake, Snap Lake, Lake Gillian, and GSC camp sites

The station located at the GSC base camp in central Baffin Island also recorded data from the time of its installation on 21 July 2000 until the Orion shut down on 23 December due to lack of power (Fig. 11). Disk temperatures remained high during this period and the batteries were almost continuously charged until about 7 December. From the time of its installation the station recorded 152 days of data through 18 March, missing a cumulative 38 days of data.

All six self-powered sites appeared in good condition when visited in March, 2001, although the station at Lake Gillian was buried under 2 m of drifted snow and the disk could not be changed, nor the Orion examined. Sometime during the spring melt, four of the vaults filled with significant amounts of water, probably due to ponding behind dams of frozen sand and gravel outside the vaults. Orions, charge controllers, and batteries were all submerged in water and many electrical connections became corroded. Only stations DEWR and NORM were functioning when visited in July and August, 2001. In retrospect, the electrical components could have been housed in plastic storage tubs within the vault to prevent this damage, however, heat generated during the warmer months when excess power is dumped to resistors may melt the plastic tubs and ruin some electronics. The current vaults produced summer disk temperatures above 50°C.

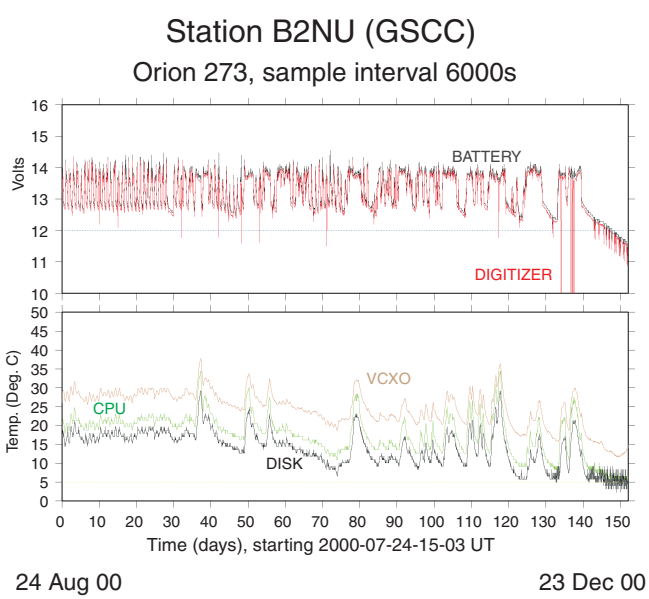

Figure 11. *State-of-health plots for station B2NU in Central Baffin. Display as in Figure 4. Note the shorter record period than the other figures.*

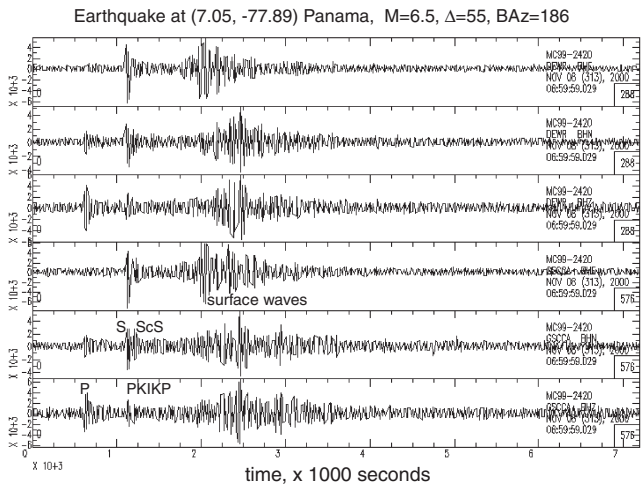

Figure 12. *Example of an earthquake recorded by stations DEWR and GSCC in Central Baffin Island. Three components are shown for each stations: east (BHE), north (BHN), and vertical (BHZ) in descending order. Time and date of the earthquake is also indicated at the right of each trace. This magnitude 6.5 earthquake occurred near Panama. The arrival times of several important seismic-wave phases are indicated on the lowermost traces.*

The two stations undamaged by flooding were situated very similarly to the others on small hills of sand /gravel, and apparently drained as efficiently as was anticipated. The others did not.

EXAMPLES OF EARTHQUAKE RECORDS

Because these sites were chosen as remote and isolated from man-made sources of noise, seismic signal-to-noise ratios are very favourable at these sites. Examples of teleseismic events at Δ=55°, a magnitude 6.5 earthquake near Panama, and at Δ=127°, a magnitude 6.8 earthquake in the Scotia Arc show clear seismic-phase arrivals on all three components of stations DEWR and GSCCA (Fig. 12, 13). These events provided good estimates of crustal thickness and lithospheric fabric/foliation directions, respectively (*see* below).

In addition to providing information about crustal and lithospheric structure for the central Baffin project, the teleseismic stations established on Baffin Island were also incorporated into the ongoing Canadian High Arctic seismic monitoring experiment (CHASME) project of the National Earthquake Hazards Program. The data has therefore been reanalyzed, concentrating on small, regional (Δ<40°) events. The north coast of Baffin Island is one of the more seismically active parts of Canada, and stations DEWR and GSCC did detect numerous events at distances of 150 to 450 km (Fig. 14).

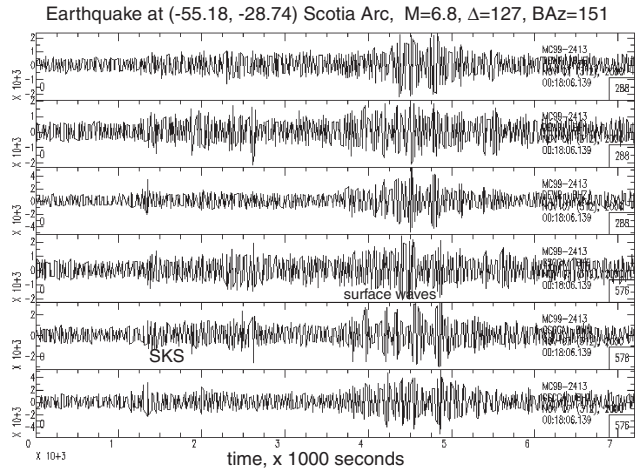

Figure 13. Display similar to Figure 12, here for a magnitude 6.8 earthquake in the Scotia Arc region of the south Atlantic.

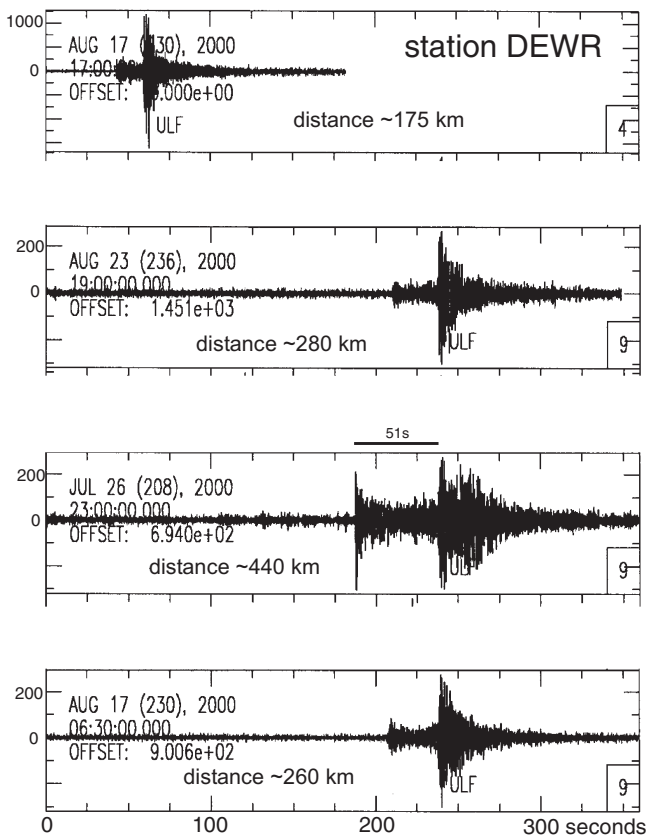

Figure 14. Examples of four regional earthquakes recorded at station DEWR. The arrivals of the direct P- and S-waves provided rough estimates of the distance to the epicentre, no direction is provided by these vertical traces.

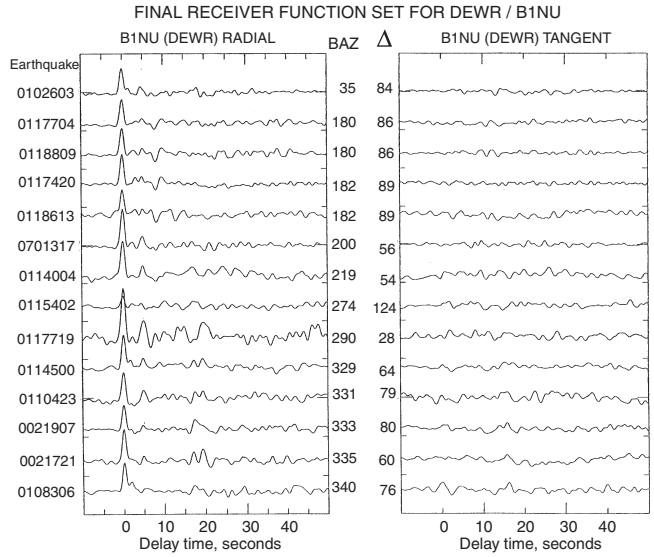

Figure 15. A compilation of receiver functions for station DEWR. The prominent spike at 0 s delay time on the radial component (left) is the self-correlation reference spike, smaller peaks at about 5 s indicate the Moho discontinuity; its variation with back-azimuth suggests either a dipping Moho or very different crustal velocities northwest and south of this station. BAZ is back azimuth (direction to earthquake from station), Δ is the distance in degrees. The earthquake reference format is YYDDDHH where D is the Julian date.

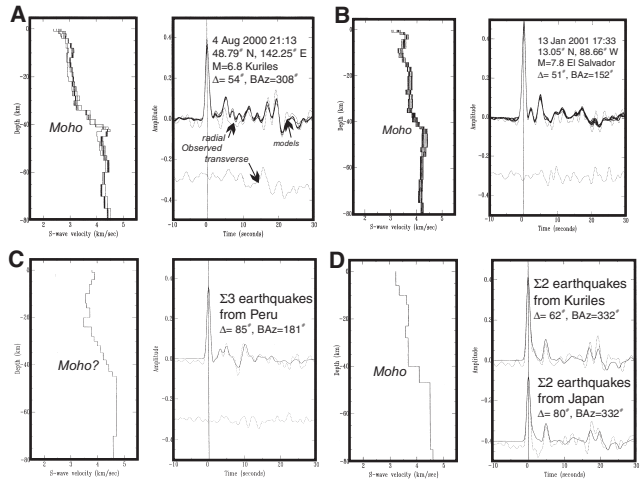

Figure 16. Velocity versus depth models (left) for the receiver function indicated at the right (dash = observed, solid = model). Moho is at 40-42 km depth in all models. A layer of lower velocities appears in models for seismic waves arriving from the south (B&C).

PRELIMINARY ANALYSIS AND RESULTS

Central Baffin Island

Given that only two stations have provided seismic data to date, only two analytical techniques have been applied to these data in order to assess their quality and usefulness. Receiver functions (e.g. Ammon et al., 1990) provide identification of major discontinuities in seismic velocity or density within the lithosphere. The Moho is typically the most prominent discontinuity observed and the clarity of its resolution provides a good calibration on the quality of the data recorded. Fourteen earthquakes have provided useful receiver functions at station DEWR to date (Fig. 15). These functions show systematic variations depending on the azimuth from which the seismic energy arrives (typically called the back azimuth, BAz).

Earthquakes occurring at similar back azimuths can be analyzed separately or grouped together and summed to improve the signal (Fig. 16). Trial-and-error forward models of velocity variations with increasing depth provide indications where major structures occur within the crust and uppermost mantle. In order to estimate the depth to discontinuities, a standard velocity model (iasp91: Kennett and Engdahl, 1991) for continental areas was assumed. Beneath DEWR, the Moho consistently is modelled at 40 to 42 km depth, an unusually thick crust. Velocity models for events arriving from the south typically show layers of relatively low velocity with the crust, varying from 10 to 20 km depths (Fig. 16B, C). This station is thought to lie on a gneiss dome of Archean basement rock, so these layers are not sedimentary and probably lie within crystalline upper crust, possibly related to Proterozoic tectonics associated with the Trans-Hudson orogen. These layers are not clearly resolved using seismic waves arriving from the northwest quadrant.

Estimates of lithospheric-scale foliation using anisotropy of SKS seismic phases (e.g. Silver, 1994) are not as numerous or consistent given the limited period of recording. To date, only four earthquakes have provided reliable estimates at stations DEWR and GSCC. At DEWR, a northwest-southeast azimuth is indicated whereas at GSCC a more east-west trend

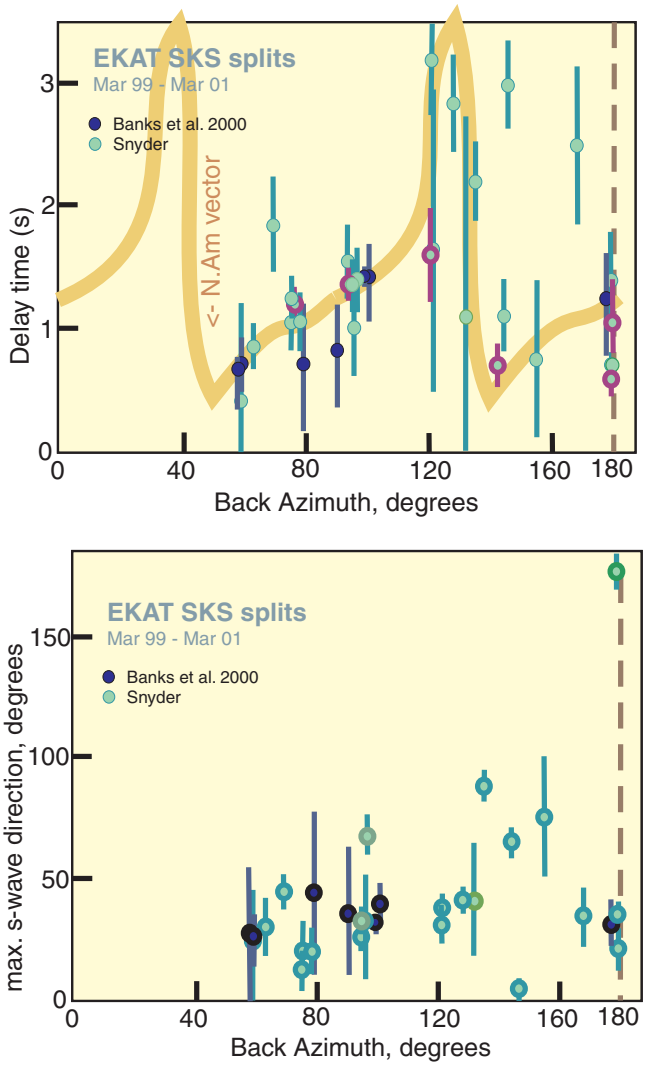

Figure 17. Compilation of delay times and azimuth of maximum shear-wave velocity for about 40 earthquakes recorded at the EKAT station in the central Slave province. These values are indicted by dots with error bars, the solid grey line is the pattern expected for a two-layer model assuming a top layer with dt=0.4 and phi=5, a bottom layer with dt=1.0s, phi=50 (Silver and Savage, 1994).

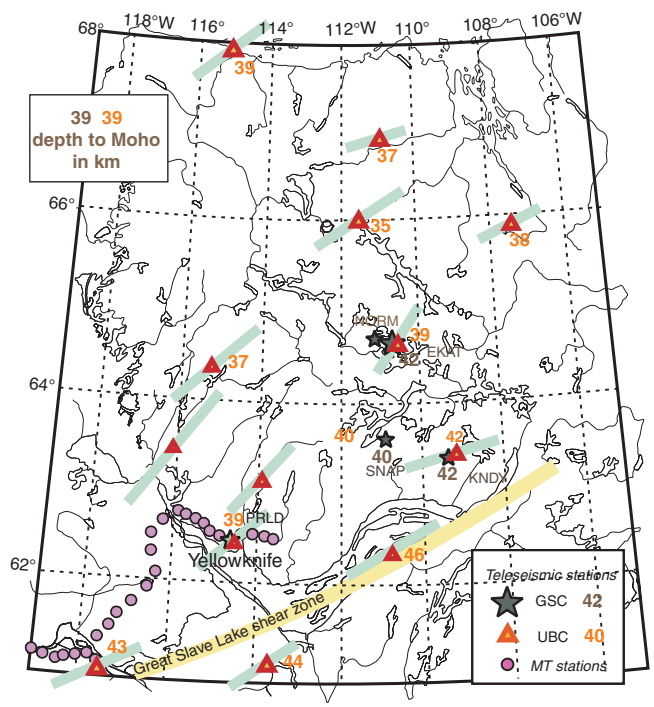

Figure 18. Depth to Moho determinations for the Slave Province. Values near triangles are from Bank et al. (2000). Values near stars are from this project.

appears. Delay times vary between 0.85 and 2.1 seconds with an average of 1.5 ± 0.5 indicating relatively strong anisotropy.

Slave Province

Some stations within the Slave Province have been running longer than those described here and can thus provide a baseline with which to compare results from the newer stations (also *see* Bank et al., 2000). The station at the Ekati mine airstrip (EKAT) now has recorded more than two years of earthquakes and provides a reasonable distribution of back azimuths with which to analyze both depths to discontinuities and anisotropy (Fig. 17). The results from the nearby station NORM are completely consistent with those from EKAT. A crustal thickness of 42 km is modelled beneath EKAT and KNDY, 40 km beneath SNAP (Fig. 18). These are again greater than global averages for continental areas, but consistent with previous results from the Slave Province (Bank et al., 2000). Anisotropy directions are generally northeast-southwest, but two distinct layers are indicated by the variations with back azimuth; delay times are generally between 1.0 and 1.2 s (Fig. 17).

CONCLUSIONS

The successful recording of teleseismic arrivals at remote, self-powered stations in central Baffin Island and the central Slave Province demonstrates that the deployment of instruments for this purpose is possible and provides quality data that can be used for analysis. The failure of several stations to record for several months suggests that more robust electrical charging or storage systems would help; such systems are already being used on the more power-hungry satellite telemetry systems used by the POLARIS project. The catastrophic loss of several stations during the spring melt demands that the electronics be both insulated and waterproof. This is a formidable requirement in that heat must be dumped in the summer, yet retained in the winter and the seismometer must be in solid contact with the ground. Use of plastic storage bins cemented into pads or mostly buried in the ground appears the most promising solution and is in trial this winter.

The hard disks currently used require service visits at least twice each year. In these remote areas, the transportation required is expensive. It costs $10 to 20K per year to install and operate these stations; larger arrays may prove more cost effective. The POLARIS project is currently testing satellite telemetry as an alternative to the hard disk technology.

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