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The 11 October 2010 Novaya Zemlya Earthquake: Implications for Velocity Models and Regional Event Location

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Characterizing the seismicity of Novaya Zemlya and the surrounding Arctic seas requires accurate event location estimates. Low magnitude events in this region are currently observed only by a small number of stations in the European Arctic, with a large azimuthal gap, making the accuracy of regional velocity models all the more important. Regional traveltime calibration is difficult given the scarcity of sufficiently well constrained events. On 11 October 2010, a magnitude 4.5 event occurred close to the northern tip of Novaya Zemlya. This event is significant being the first event in this region to have been recorded both on the relatively recent regional networks and arrays, and also teleseismically with good azimuthal coverage. We examine how well we can constrain the location and origin time using only teleseismic phases. Using only first teleseismic P arrivals, we constrain the epicenter to approximately 76.25N and 64.75E but with no depth resolution. Clear depth phases, notably on stations in the southern United States, indicate a depth between 9 and 15 km. This independent hypocenter and origin time estimate allows evaluation of regional phase traveltime prediction using different models. The predicted Sn traveltime appears to cause the greatest variability in regional location estimates. The 3-dimensional RSTT (Regional Seismic Travel Times) models provide excellent Pn traveltime estimates for Barents Sea paths but may slightly overestimate Sn traveltimes from this source region. A modified regional 1-dimensional velocity model is defined which best predicts Pn and Sn observations at multiple stations

up to 15 degrees. The significance of the regional traveltime models for estimating location is demonstrated for a low magnitude event on or close to the northern island of Novaya Zemlya in March 2014, recorded with a satisfactory signal-to-noise ratio at only 4 stations.

Introduction

The Arctic archipelago of Novaya Zemlya, the Kara Sea, and the eastern Barents Sea are characterized by low seismicity, with fewer than 20 seismic events having been detected in the last 30 years using stations on mainland Europe and on Svalbard. The small-aperture SPITS and ARCES seismic arrays facilitate a seismic detection threshold of around magnitude 2 [*Ringdal*, 1997; *Gibbons et al.*, 2011] but, given the poor azimuthal coverage, the ability to locate low-magnitude events accurately requires accurate travel-time predictions for regional phase arrivals. Calibrating seismic velocity models requires reference events of which there are few, if any, with sufficiently low uncertainty in origin time and location. The era of Soviet nuclear weapons testing on Novaya Zemlya [*Khalturin et al.*, 2005] resulted in many large seismic events for which the source parameters are well known and which were recorded globally. All of these events however predate the installation of the highly sensitive SPITS array and most of the network of 3-component stations. Data from the ARCES array, the KEV station at Kevo in Finland, and a few stations of the Norwegian National Seismic Network (NNSN) does exist for a few of the later nuclear tests. A teleseismically recorded event on August 1, 1986, was determined to be an earthquake due to the observation of clear depth phases [*Marshall et al.*, 1989], but this too predates the regional European Arctic seismic network.

Progress has nevertheless been made in constraining regional seismic velocity models. Using body waves from a number of reasonably well-constrained events, with paths covering the European Arctic and Barents Sea, *Kremenetskaya et al.* [2001] developed a 1-d "Barents" velocity model, modified from the IASP91 model [*Kennett and Engdahl*, 1991], with a deeper Moho and higher velocities in the uppermost mantle. This provided a far better fit to observed seismic traveltimes in the region than the underlying global model and provided improved seismic location estimates for Ground Truth events. The Barents model was evaluated and modified [*Schweitzer and Kennett*, 2007; *Hicks et al.*, 2004] to be based on the more recent AK135 global model [*Kennett et al.*, 1995] and with two alternative 1-dimensional models, *BAREY* and *BAREZ*, differing in the P/S ratio in the upper mantle, being proposed to model optimally different paths from the Kara Sea to the Barents Sea. The problem of lacking path coverage for body waves from sufficiently well-constrained sources can be circumvented by using surface waves for inverting for crustal and upper mantle velocities. This can be performed for layered models [e.g. *McCowan et al.*, 1978] or accommodating lateral variations over extended regions [e.g. *Levshin and Berteussen*, 1979]. In 2003, a project was started to construct a far more detailed model for the crust and upper mantle below the Barents Sea [*Bungum et al.*, 2005], using not only body wave traveltimes for large seismic events but a large number of datasets such as deep seismic reflection profiles and surface waves. Products of this collaboration were the Barents50 model [*Ritzmann et al.*, 2007] and BARMOD 3D [*Levshin et al.*, 2007]. The latter was based on surface wave tomography of an extended region surrounding the Barents Sea and indicated anomalously high S-wave velocities in the upper mantle below the eastern Barents Sea and Kara Sea [see also *Ritzmann and Faleide*, 2009].

Hauser et al. [2011] consider a probablistic seismic model for the region comprising many diverse sets of geophysical data. Rather than specifying a single deterministic velocity at any given latitude, longitude and depth, they consider probability distributions for seismic velocities over a 3-dimensional grid where the uncertainty at any given node is a function of the quality of constraints. A probablistic 3-dimensional velocity model does not result in a single deterministic event location estimate for a given set of phase arrivals, but rather a distribution of hypocenters and corresponding event origin times which fit the distribution of model parameters. The resulting clouds of hypocenters provide the analyst with a more realistic picture of the uncertainty than the classical error ellipses for which all uncertainty is assumed to be normally distributed. The primary disadvantage of this approach is that enormous computational resources are required to calculate the posterior probability distributions of event hypocenters. The event location procedure described by *Hauser et al.* [2011] of course is not the only means of incorporating 3-D structure into event location procedures. The HYPOSAT algorithm and program [*Schweitzer*, 2001] for example facilitates the use of multiple 1-dimensional velocity models for different groups of phases and, even using a single global velocity model, relatively unbiased solutions can be obtained by applying calibrated source specific station corrections [e.g. *Yang et al.*, 2001; *Murphy et al.*, 2005].

Significant progress has been made towards fully 3-dimensional tomographic velocity models [e.g. *Simmons et al.*, 2012, 2015] which have been demonstrated to provide location estimates for seismic events with greatly reduced uncertainty and bias [*Myers et al.*, 2015]. The Regional Seismic Travel Time (RSTT) software package (see Data and Resources) was designed to compute rapidly approximate travel times for crustal and upper mantle phases, accounting for 3-dimensional structure. The techniques for calculating the RSTT travel times, accounting for lateral variations in seismic wave velocity, are described by

Phillips et al. [2007]. An initial tomographic study for regional travel times in Eurasia [described by *Myers et al.*, 2010] formed the basis for RSTT, although the underlying model is revised continually to incorporate the results from regional tomographic studies. At the time of writing, the most recent release of RSTT is from April 2014 although all previous releases of RSTT are still available for download (see Data and Resources) This allows for a systematic comparison between the performance of subsequent releases.

On 11 October 2010, an earthquake exceeding magnitude 4 occurred close to the northern tip of Novaya Zemlya. This was (by a good margin) the largest event on Novaya Zemlya since the cessation of Soviet nuclear testing [*Gibbons et al.*, 2011] and was well recorded at regional distances by the arrays and permanent 3-component stations in northern Fennoscandia and on Spitsbergen, in addition to stations of the Arkhangelsk seismic network [*Morozov and Konechnaya*, 2013] and the network operated by the Kola Regional Seismological Center (KRSC) on the Kola Peninsula. Fig. 1 displays the beams for the 11 October event recorded at the SPITS and ARCES seismic arrays together with the locations of the stations within 15 degrees of the epicenter for which Pn and Sn arrival times could be read with a satisfactory accuracy (Table 1). As is typical for the regional recordings of Novaya Zemlya events, Pn and Sn are the only visible phases; the Lg phases which dominate regional recordings along continental paths are blocked on Barents Sea paths [see *Baumgardt*, 2001].

This earthquake is significant since it was recorded at teleseismic distances with excellent azimuthal coverage. The event is listed in the Reviewed Event Bulletin (REB) of the International Data Center (IDC) for the Comprehensive Nuclear-Test-Ban Treaty

Organization (CTBTO) with the coordinates 76.2640°N, 64.7619°E, and depth fixed to the surface. As is clear from Fig. 1, there is a significant discrepancy between the REB solution (dominated by teleseismic P-phases) and the NORSAR regional reviewed event location (see Data and Resources section) which is constrained exclusively by P and S arrivals at regional and intermediate distances up to 25 degrees: all to the West and South West of the source region. The need to apply station corrections for source-to-receiver paths from the Barents Sea to stations in Fennoscandia has been documented [*Yang et al.*, 2001] and it is clear that an event location estimate that does not take account of 3-dimensional effects will be biased. The bias in the REB solution is likely to be considerably smaller, although it too is constrained to some degree by regional and far-regional phases recorded in Fennoscandia. The solution provided by the International Seismological Center (ISC, see Data and Resources) is indicated in Fig. 1 using an arrow. This solution is also dominated by teleseismic phases but with regional and far regional phases to the West and South West, and is close to the REB solution.

We seek to provide a more accurate location and origin time for the 11 October event using only data recorded at teleseismic distances. Since the data at far-regional distances comes only from a single direction, it is likely that the solution constrained by purely teleseismic arrivals will be less strongly biased. With a high confidence hypocenter and origin time estimate, derived from teleseismic observations with as broad as possible azimuthal range, we can then assess how well different regional velocity models predict the regional arrivals given in Table 1. We seek to modify the best of the 1-dimensional models to better predict the regional arrivals observed from this event and evaluate how the location estimates for this event using only regional phases vary with the different velocity models. Finally, we consider a low magnitude event in or close to the northern island of Novaya Zemlya in March 2014. Without Ground Truth information or teleseismic observations, we examine the variability of the location estimates possible using the limited observations at regional distances.

Locating the 11 October 2010 Novaya Zemlya event Using Teleseismic Data

With a magnitude of between 4 and 5, the 11 October event is not observed universally at the distances for which teleseismic P is anticipated. There is evidence of a signal at many stations for which the phase onset is too poor to be used for the purposes of event location. The seismic network of the International Monitoring System (IMS) for verifying compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) is typically very effective for the detection and location of earthquakes in remote regions given the predominance of array stations. A seismic signal which is right at the background noise level at a single site can be elevated to a clear detection through the stack-and-delay beamforming operation [e.g. *Schweitzer*, 2014]. [The superiority of the IMS seismic arrays over the IMS seismic 3-component stations for contributing to built events is demonstrated by *Kværna and Ringdal*, 2013]. Teleseismic observations from the 11 October event are displayed in Fig. 2 and the locations of stations where these signals are recorded are displayed in Fig. 3. We have specifically tried to focus on the distance range from 23 degrees to 80 degrees, avoiding the far regional distance range in which the global traveltimes are the least reliable [*Myers et al.*, 2015]. This map gives a fairly accurate detectability map for the event; while some regions of course have very few seismic stations, large regions with few symbols indicate that the event was poorly observed overall. This is the case for almost all of Canada for example. The most important selection criterion for stations was that the arrival time of the initial P-phase could be read sufficiently accurately, although maintaining an a reasonably uniform azimuthal distribution was an important consideration. For a region such as Europe, with many satifactory arrival time readings on array beams, no attempt was made to find signals on complementary national 3-component stations since an excess of stations from one azimuth would likely worsen bias in the solution if not addressed by appropriate weighting. For regions with fewer arrays, all data openly available through the Incorporated Research Institutes for Seismology (IRIS) Data Management Center (DMC) was obtained in the hope of finding a few stations with low background noise and/or anomalously high signal-to-noise ratio (SNR). This included temporary deployments of stations such as the Transportable Array of the USArray project [FDSN network code TA, *Levander et al.*, 1999] and NECESSArray in North East China [FDSN network code YP, *Tao et al.*, 2014].

Fig. 2 displays a trace for each station that is in some way optimal for picking the P-wave arrival time. In all cases, a frequency band was selected that optimized the SNR and, for the array stations, a stack-and-delay beam was formed which optimized the alignment of traces in the anticipated direction of arrival. While only a single filter band (1-5 Hz) is displayed, other bands were considered in making the arrival-time picks. The traces are ordered according to the azimuth from the event location. A small azimuthal band, between 345 and 355 degrees, contains waveforms which all have a considerably larger amplitude arrival shortly following the initial P-phase. Most of these stations are temporary sites of the Transportable Array, although this arrival is also observed at the TXAR array and a few sites of the United States National Seismic Network. These stations are displayed with white symbols in Fig. 3. Were this later arrival to be a depth phase, pP - or possibly sP, this would provide a significant constraint on the depth of the event and therefore also the origin time. Closer inspection of a few other stations, e.g. PETK, CMAR, NVAR, and DLBC, also indicates a second pulse of energy which could correspond to a depth phase. Fig. 4 (a) shows VESPA plots [*Davies et al.*, 1971] which indicate two pulses of coherent energy, separated by approximately 5s, propagating in a similar direction and recorded at two different seismic arrays at great distance from each other. In Fig. 4 (b) we demonstrate using three of the Transportable Array stations that the second phase appears to have a polarity reversal relative to the first phase. The time delay from positive peak to negative peak is between 4.3s and 4.4s.

Fig. 5 shows time residual 1-norms as a function of latitude, longitude, and depth for the P-wave arrivals displayed in Fig. 2. This is to say that we have placed a trial hypocenter for our event at every point of a 3-dimensional grid and solved for the origin time which minimizes the 1-norm of the vector of observed minus predicted traveltime residuals, where the traveltime is predicted using the AK135 model of *Kennett et al.* [1995]. The white and the blue stars in Fig. 5 (a) indicate the REB and NORSAR-reviewed location estimates (see Data and Resources) and the grey lines indicate the great circle paths to each of the observing stations. The azimuthal coverage is reasonably good and this is reflected in the high degree of azimuthal symmetry in the residual vector norm contours. Fig. 5 (b) and (c) display the residual norms from this gridsearch procedure as a function of depth for the lines CD and AB displayed in the map. The HYPOSAT program allows the depth to be fixed and a best-fit latitude, longitude and origin time to be found; the small white stars in Fig. 5 (b) and (c) indicate the fixed-depth HYPOSAT solutions and demonstrate that these are consistent with the results of the independent gridsearch procedure. We conclude that, using only the initial teleseismic P-wave arrivals, the epicenter of the earthquake is at approximately 76.28°N and 64.6°E but with the depth of the event being essentially unconstrained. The trade-off is between the depth and the origin time, the teleseismic P arrival times being almost equally consistent with an event at the surface at a time 22:48:26.2 and, for example, an event at depth 50 km at time 22:48.32.9. There is not a significant shift in the epicenter as the depth of the hypocenter changes. *Bondár et al.* [2004] demonstrate a good correspondence between the epicenter location accuracy provided by a given teleseismic network and the azimuthal coverage of the recording stations. For the 66 stations at teleseismic distances used for locating the October 2010 event, the secondary azimuthal gap is estimated at about 70 degrees (see figures 2 and 5). From studies of GT5 events, *Bondár et al.* [2004] estimated a median mislocation of about 7-9 km for events having a secondary azimuthal gap of less than 70 degrees.

The depth of an event is of great significance for both structural studies and, for example, in the context of screening events from potential violations of a nuclear test ban treaty. In the absence of stations in the immediate vicinity of the epicenter, the depth is typically determined by detecting evidence of a surface reflection [e.g. *Bonner et al.*, 2002; *Letort et al.*, 2014, 2015]. As with the 1986 Novaya Zemlya/Kara Sea event [*Marshall et al.*, 1989], this event appears to have clear depth phases visible in the waveforms. Ascribing the identification pP to each of the observed secondary arrivals and solving using HYPOSAT results in a depth of approximately 13.1 km with an origin time of 22:48:28.2. In order to assess how sensitive the location is to our identification of these depth phases, a calculation was also performed in which the phases assumed to be pP were labelled sP. This resulted in a hypocenter with a depth of 9.8 km and an origin time of 22.48.27.6, a very limited change in the source parameters.

The grid search event location estimation procedure as displayed in Fig. 5 for the ak135 model was also repeated using traveltime tables constructed using the 3-dimensional LLNL-Earth3D model and LLNL-G3Dv3 raytracing software [*Simmons et al.*, 2012]. (The data and resources section provides a link to the model and software.) The hypocenter and origin time which minimized the 1-norm traveltime residual for the 3-D model, using both teleseismic P and pP depth phases, was 76.282°N and 64.692°E, with depth 11.3km and origin time 22:48:27.8. This solution is within 2 km in depth and within 5 km laterally of the estimate obtained using the 1-D ak135 model and the origin time is within 0.4s. The 1-norm of the traveltime residual vector was 0.405 for the 3-D calculation compared with 0.524 for the ak135 calculation, a reduction of approximately 20 percent.

Evaluating 1-D velocity models to explain regional arrivals

With a location estimate and origin time based entirely on teleseismic phase picks, we evaluate how well commonly applied velocity models match the observed arrival times for Pn and Sn at the stations displayed in Fig. 1. In addition to the 1-dimensional ak135, BAREY and BAREZ models, we consider also Pn and Sn times predicted using the 3-

dimensional RSTT models. Fig. 6 displays the observed minus predicted travel time residuals for each of the Pn and Sn arrival time picks listed in Table 1 for velocity models as displayed, given an origin time of 2010-284:22.48.28.224, a hypocenter 76.2845°N, 64.6505°E, and depth 13.1 km. The RSTT traveltimes were calculated both for the software releases in April 2014 (labelled RSTT14) and in October 2010 (labelled RSTT10).

The ak135 model overestimates the Pn traveltimes by up to several seconds for the Barents Sea propagation paths (Fig. 6 a). The BAREY and BAREZ models provide as expected a better fit for Pn arrivals (the two models having identical P-velocity profiles) and the Pn predictions from RSTT are very close. RSTT predicts slighly shorter Pn traveltimes for paths from northern Novaya Zemlya to Svalbard than for northern Novaya Zemlya to mainland Fennoscandia. The differences are however very small in comparison with the spread in the data, which is likely to be dominated by uncertainty in the arrival time picks for these largely emergent onsets. The 2014 RSTT Pn traveltime estimates from Novaya Zemlya to Svalbard are not significantly different to the estimates from the 2010 RSTT release. For paths from northern Novaya Zemlya to Fennoscandia, the 2014 RSTT release predicts significantly faster traveltimes than the 2010 RSTT release.

The predictions for Sn vary greatly with almost 20s separating the slowest arrival predictions (ak135) from the fastest (BAREZ) for the stations on mainland Europe (Fig. 6 b). The BAREY and BAREZ S-velocity models differ only between 41 km and 410 km depth with a P:S velocity ratio of 1.72 for the (faster) BAREZ model and 1.77 for the (slower) BAREY model. The Sn phase arrival picks are as expected more spread than the Pn picks, although the 7 to 9 second difference between the BAREY and BAREZ predicted traveltimes is significantly greater than the 2 to 3 second variability in the arrival time estimates. Comparing a linear regression of the BAREZ residual points (3-4s too fast) and a linear regression of the BAREY residual points (5-7s too slow) indicates that a modification of BAREY/BAREZ with a P:S ratio of 1.74 between 41 and 410 km depth would likely fit the observations better. We label this velocity model BS174. The RSTT Sn traveltime predictions from the 2010 release are better than the ak135 predictions but significantly poorer than either BAREY or BAREZ. The predictions from the 2014 RSTT release are similar to the BAREY model estimates: far more consistent with the observations than for the 2010 release.

While the fit for Pn is far better than for Sn, a 0.5 percent increase in the upper mantle P-velocity can be demonstrated to reduce the absolute residuals in Fig. 6 a). We call the velocity model with the S-wave velocity structure of BS174, combined with this marginally increased P-wave velocity profile, NZ2010. The P and S velocity profiles for BAREY and BAREZ, together with the modifications, are displayed in Fig. 7 and tabulated in Table 2.

Traveltime residuals as displayed in Fig. 6 were calculated for a large number of alternative candidate hypocenters and origins which were similarly consistent with the teleseismic observations. Although small perturbations to the latitude, longitude, depth and time of the source resulted in small changes to the traveltime residuals, the patterns displayed in Fig. 6 appear to hold for all likely source locations and origin times.

While we can draw conclusions as to the suitability of velocity models by examining the residuals as displayed in Fig. 6, the true test is the influence the models have on event location. If we attempt to locate the 11 October event ignoring all stations at distances greater than 15 degrees, we are left with the arrival time readings provided in Table 1. Fig. 8 displays location estimates using only these phase arrivals and the velocity models as indicated together with the teleseismic reference location. That the NZ2010 model location comes closest to the reference location is not in itself significant; the modifications to the velocity profiles were chosen specifically to optimize the fit for exactly these arrivals. What is of greatest interest is the geographical bias resulting from applying different velocity models when the observing stations all lie within a 90 degree wide band of azimuth from the event's true location. The faster S-wave velocities in the BAREZ model pull the preferred location almost 50 km to the East. The slower BAREY model S-velocities draw the event a similar distance to the West. In the absence of stations in the wide azimuthal gap, it is the S-wave arrivals that primarily constrain the distance the event appears to be from the observing stations to the West and South West. Fig. 8 gives an impression of the extent to which the event locations are subject to uncertainty in the S-wave velocity models. Note that the spread in the event location estimate for regional stations and different velocity models is over an order of magnitude greater than the anticiapted uncertainty in the event location from the teleseismic observations. A similar observation was made by *Schweitzer and Kennett* [2007].

Consequences for Regional Event Location

On 4 March 2014 a far smaller event occurred on or close to the northern island of Novaya Zemlya. With an approximate magnitude of 3, this event is far more typical of the Novaya Zemlya seismicity which needs to be detected, located, and classified. Signals from this event were only recorded well on a very limited number of stations. The signal on the SPITS array is by far the best observed, although the recordings on ARCES and KBS are sufficient for Pn and Sn arrival times to be read with a sufficient accuracy for use in location procedures. While there are now far more stations than previously in northern Fennoscandia and on Svalbard, the signal-to-noise ratio for an event of this magnitude is still too low on most stations for these recordings to be useful. The monitoring at low magnitudes for the region is still dominated by the SPITS and ARCES arrays and only the very best of the network 3-component stations. This event is interesting from a location perspective since it is also observed on the new station ZFI2 on Franz Josef Land [see *Morozov et al.*, 2015]. Fig. 9 displays traces optimized for the observation of Pn and Sn at the ZFI2, SPITS, ARCES, and KBS stations. Signals on all other available stations were deemed to be of too poor quality for use in the location procedure.

The March 2014 event is about 300 km further south than the 11 October 2010 event and, depending upon the significance of the 3-dimensional velocity structure, the performance of the 1-dimensional models may be significantly different to that observed for the northern tip of Novaya Zemlya. It is important to note that, for this event, we have no ground truth and no independent seismic observations that can constrain the event location. The Pn and Sn phase arrival times listed in Table 3 are the only pieces of information we have to locate the event. For each of the models ak135, BAREY, NZ2010, and BAREZ, we locate the event using HYPOSAT (depth fixed to the surface) using two different networks. We consider the ARCES, SPITS, and KBS network which has recorded most of the low magnitude Novaya Zemlya events over the previous two decades, and then the full set of stations displayed in figures 9 and 10 a).

Fig. 10 b) shows the location estimates for the 3- and 4-station configurations using the models as indicated. The ak135 model places the event at sea. The BAREY and BAREZ models place the event at the West and East coasts of the northern island of Novaya Zemlya respectively. The NZ2010 model with its intermediate upper mantle S-velocity structure places the event on land approximately half way between the East and West coasts. Numerous attempts were made to locate the events using arrival time estimates perturbed slightly from the times provided in Table 3 and this was found to have a negligible result in the location estimates; the S-wave velocity model is far more significant. The time-residual norms for the ak135 model are significantly higher than for the other models, although the minimum time residual alone is not sufficient to favor any one of the BAREY, NZ2010, or BAREZ models over any of the others. If a 1-dimensional velocity model provides reasonable fidelity over the region to which it is supposed to apply, then the location estimate made using the 4-station network should not differ greatly from that made using the 3-station network. While the differences are not large, the solutions using the NZ2010 model are moved less by the addition of the readings from the ZFI2 station than the solutions resulting from the BAREY or BAREZ models.

A grid-search location estimate for the 4 March event using traveltimes calculated from the 2014 release of RSTT results in inland location estimates essentially co-located with the location estimates obtained using the BAREY 1-dimensional model.

Conclusions

The ability to locate low magnitude seismic events in the European Arctic requires excellent models for seismic wave velocities in the crust and upper mantle. This is primarily because we are only able to monitor from the northernmost part of mainland Europe and from Svalbard. The $m_{\mathrm{b}} = 4.5$ earthquake close to the northern tip of Novaya Zemlya on 11 October 2010, is unique among seismic events in this part of the world as it is, to date, the only event that has been recorded both on the regional seismic networks of the European Arctic and globally at teleseismic distances. By careful consideration of teleseismic signals, we estimate the epicenter to be 76.28°N, 64.65°E with a likely uncertainty of only a few kilometers. Clear depth phases are observed on many stations, but are strongest on stations in the southern United States. Assuming these phases to be pP provides a depth estimate of approximately 12 kilometers and a corresponding origin time of 2010-284:22.48.28.2.

Given that this teleseismic location estimate is entirely independent of the many observations at distances of 20 degrees or less, we can use this hypocenter and origin time estimate to evaluate velocity models for predicting regional travel times. We have evaluated a number of commonly applied 1-dimensional velocity models in addition to the 3-dimensional RSTT software. The BAREY/BAREZ and RSTT models predict the Pn arrivals at stations within 15 degrees of the epicenter relatively well although it appears that the traveltimes are slightly overestimated particularly for the paths towards mainland Europe. There is however a very large spread in the time-residuals for the Sn phases. Most of the models predict Sn arrivals that are significantly too late, with the exception of the BAREZ model which slightly underestimates the traveltime. The BAREY and BAREZ models differ only by the P:S velocity ratio in the upper mantle (1.72 for BAREY and 1.77 for BAREZ) and a new 1-dimension model BS174 (identical to BAREY/BAREZ except for a 1.74 P:S velocity ratio) reduces the Sn residuals significantly. A second model, NZ2010, with the same S-velocity profile as BS174, but with a 0.5 percent increase in P-velocities between 41 and 410 km depth in addition minimizes the Pn time-residuals. We hope also that the data presented here will be of use in subsequent 3-dimensional tomographic studies. The scarcity of well-observed events in this region makes the body wave arrival data of great interest.

The increase in the number of stations in the European Arctic in recent years has been of great benefit in providing many regional observations of the 11 October 2010 earthquake. The modifications made to the BAREY/BAREZ velocity models were made on the basis of observing the residuals displayed in Fig. 6. Had we only had three or four stations with satisfactory regional phases, the confidence in the significance of the time residuals would have been substantially lower. However, as the March 2014 event demonstrated, the detection capability for events in the European Arctic at the lowest magnitudes is still controlled by the SPITS and ARCES seismic arrays and the most sensitive of the closest 3-component stations. (Newly deployed instruments such as the ZFI2 station may have significance in future years.) We have reason to believe that the Pn traveltimes predicted by the 1-dimensional BAREY/BAREZ models, and also by the 3-dimensional RSTT model, perform well for events in this region. The failing of the existing models appears to be in the Sn traveltime predictions which appear to be the most significant factor in the location estimate uncertainties. The 2010 release of RSTT appears to overestimate the Sn traveltimes from this region of the European Arctic significantly. The 2014 RSTT release predicts Sn traveltimes that are comparable to those predicted by the BAREY model, providing an improvement on the 2010 release but still based on velocity estimates that are slightly too low. Together with local 1-D models based on, for example, receiver function studies [e.g. *Morozov et al.*, 2015], we hope that the data presented in this paper will contribute to a significant improvement in the coming iterations of the 3-dimensional models for the crust and uppermost mantle.

The teleseismic depth phases were significant for providing an independent constraint on the event depth and, consequently, the origin time. It is important to note that while there was evidence at many stations for depth phases, they were clearest at a very small number of stations with most of the best recordings being on temporary deployments. We would advocate paying greater attention to depth phases, both in applying advanced techniques for their detection [e.g. *Letort et al.*, 2015], and in searching additional waveforms. Events that are well constrained in time and space using teleseismic data may have a greater role than previously assumed in the calibration of regional velocity models in the absence of Ground Truth explosion sources. We have also demonstrated that cross-border collaboration in the sharing and analysis of seismic data has significant benefits in optimizing the exploitation of the available observations.

Data and Resources

Waveform data from the SPITS and ARCES arrays is available openly from `http://www.norsardata.no/NDC/data/autodrm.html` (last accessed March 2016).

The APA, TER, and BRBB stations are operated by the Kola Regional Seismological Center in Apatity, Russia, and the LSK station is operated by the Institute of Environmental Problems of the North of the Ural Branch of the Russian Academy of Sciences, in Arkhangelsk, Russia. The HSPB station is operated by the Institute of Geophysics of the Polish Academy of Sciences, Warzawa, Poland. The stations HOPEN and HAMF are operated by the University of Bergen, Norway, and are part of the Norwegian National Seismic Network. The stations HEF and KIF are part of the Finnish National Seismic Network and operated by the University of Helsinki (data available from `geofon.gfz-potsdam.de/waveform/`, last accessed March 2016). Data from the stations KEV, KBS, and LVZ are obtained from the Incorporated Research Institutes for Seismology Data Management Center at

`http://ds.iris.edu/SeismiQuery/by_station.html`

(last accessed March 2016) from the IU and II networks.

Waveform data from International Monitoring System stations was obtained from the International Data Center in Vienna, Austria.

Waveform data from the Canadian National Seismograph Network (CNSN) was obtained from Natural Resources Canada at

`http://www.earthquakescanada.nrcan.gc.ca/stndon/AutoDRM/autodrm_req-eng.php`

(last accessed March 2016).

All additional waveforms were obtained via the Incorporated Research Institutes for Seismology Data Management Center at

`http://ds.iris.edu/SeismiQuery/by_station.html` (last accessed March 2016). We have utilized data from the networks AK, KN, KR, KZ, RO, TA, and YP and gratefully acknowledge the operators of these networks for making the data available.

The event locations is displayed are taken from the NORSAR Reviewed Regional Event Bulletin available at `http://www.norsardata.no/NDC/bulletins/regional/`. The reviewed location of the 11 October 2010 event is found on (`http://www.norsardata.no/NDC/bulletins/regional/2010/10/1400` (last accessed March 2016).

The LLNL-G3D global 3-dimensional P-wave velocity model and ray-tracing software is available from

`https://missions.llnl.gov/nonproliferation/nuclear-explosion-monitoring/global-3d-seismic-tomography`

(last accessed March 2016).

The Regional Seismic Travel Time (RSTT) software is available openly from `http://www.sandia.gov/rstt/` (last accessed March 2016).

The seismic bulletin of the International Seismological Center is available from `http://www.isc.ac.uk/` (last accessed March 2016).

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Figure 1 caption

Location estimates for the 11 October 2010 Novaya Zemlya event using regional crustal phases only (NORSAR) and using global IMS stations (REB solution). The ISC location estimate uses both IMS and non-IMS stations, at both regional and teleseismic distances. The stations displayed are those within 15 degrees for which satisfactory readings of both Pn and Sn phases were made. The regional array stations are labelled with circles and 3-C stations with triangles. The waveform segments shown have a duration of 10 minutes, starting at a time 2010-284:22.48.25. The beams optimized for the Pn phases use the vertical channels of the arrays and the beams optimized for the Sn phases use the horizontal channels, rotated to be transverse to the great-circle paths indicated by the solid black lines. Please see Data and Resources for event location details.

Figure 2 caption

Waveforms from 66 stations at teleseismic distances centered on the P-phase arrival. This UT arrival time on 11 October 2010 is given on the trace. Various bandpass filters are applied to optimize the signal-to-noise Ratio (SNR). The typical band applied is 1-5 Hz although this varies somewhat from station to station. For array stations, an optimal beam is displayed. Stations obtained from FDSN networks are preceded by the 2 character network code. All stations without a network code are IMS stations. The signals are ordered according to station azimuth. The secondary phase (interpreted as a pP depth phase) is visible on many traces, arriving approximately 5s after P, although these are clearest on the stations between azimuth 345 degrees and 353 degrees.

Figure 3 caption

Locations of arrays (circles) and 3-component stations (triangles) that recorded teleseismic P phases for the 11 October 2010 Novaya Zemlya event with a satisfactory SNR (see Figure 2). The IMS seismic arrays are labelled. The stations at which the clearest depth phases are shown are displayed with white symbols.

Figure 4 caption

Demonstration of presumed depth phases. (a) shows the VESPA procedure [*Davies et al.*, 1971] for two seismic arrays arrays and demonstrates two distinct pulses of energy, separated by approximately 5s, propagating from the same backazimuth. (b) shows waveforms from 3 stations of the US Array Transportable Array in the southern United States for which the amplitude of the presumed depth phase is greater than the amplitude for the first P arrival. Traces have been aligned according to the arrival picks. The lowermost trace is generated by correlating a tapered multichannel 10 second long template (3-channels) with the data stream with the incoming data. A positive peak (the autocorrelation) is followed almost 5s later by a negative peak.

Figure 5 caption

1-norm residuals for the teleseismic P-picks displayed in Figure 2 with respect to the ak135 model for trial hypocenters as a function of (a) latitude and longitude with depth fixed to the surface, (b) longitude and depth with latitude fixed to 76.28 degrees North, and (c) latitude and depth with longitude fixed to 64.65 degrees East. For each trial hypocenter, the origin time is selected which minimizes this 1-norm residual. The grey lines show the directions to the stations displayed in Figure 3. The small white stars in panels (b) and (c) indicate HYPOSAT solutions for fixed depth using only teleseismic P. The indicated stars in panels (b) and (c) indicate the HYPOSAT solution using P and presumed pP arrivals without an imposed depth constraint.

Figure 6 caption

Time residuals with respect to the arrival time picks given in Table 1 using different models using an event origin time of 2010-284:22.48.28.224 and a hypocenter 76.2845°N, 64.6505°E, and depth 13.1 km. The traveltimes computed for the 1-dimensional models ak135, BAREY and BAREZ are not dependent upon the direction whereas those for the RSTT model are calculated point to point using the RSTT software.

Figure 7 caption

Velocity as a function of depth for the ak135, BAREY and BAREZ models together with NZ2010: the modification to BAREY/BAREZ which appears to give the best fit to the regional arrival times listed in Table 1 for the purely teleseismic hypocenter and origin time for the 11 October 2010 event.

Figure 8 caption

Location estimates for the 11 October 2010 Novaya Zemlya event using regional data only (14 stations, Pn and Sn readings listed in Table 1), together with the reference teleseismic location estimate.

Figure 9 caption

Regional waveforms for stations as indicated for the 4 March 2014 Novaya Zemlya event. All Pn traces are vertical components only with the ARCES beam formed using $v_{\mathrm{app}} = 9.1(km/s)$ and backazimuth 54° and the SPITS beam formed using $v_{\mathrm{app}} = 7.4(km/s)$ and backazimuth 107°. All Sn traces are constructed from transverse rotations of horizontal components with the ARCES beam formed using $v_{\mathrm{app}} = 5.1(km/s)$ and backazimuth 54° and the SPITS beam formed using $v_{\mathrm{app}} = 4.7(km/s)$ and backazimuth 107°. All beams are bandpass filtered 4-10 Hz.

Figure 10 caption

(a) Map of regional stations recording the 4 March 2014 Novaya Zemlya event and (b) event location estimates of the event using different velocity models. The location estimates obtained using the 2014 release of RSTT are almost identical to those obtained using the BAREY model.

Table 1. Phase picks at regional distances for the 11 October 2010 Novaya Zemlya event.

Station	Latitude	Longitude	Dist	Azi	Pn pick	SNR	Sn pick	SNR
APA	67.603	32.994	12.9	245	22.51.27.95	4.6	22.53.43.01	1.6
ARCES	69.535	25.506	12.6	257	22.51.28.28	28.6	22.53.43.58	4.5
BRBB	78.059	14.219	10.7	303	22.51.02.36	11.2	22.53.00.00	4.0
HAMF	70.642	23.684	12.7	265	22.51.24.92	7.7	22.53.34.26	7.6
HEF	68.406	23.664	14.4	258	22.51.45.12	11.7	22.54.15.33	11.3
HOPEN	76.508	25.011	9.2	291	22.50.39.46	3.0	22.52.14.03	4.6
HSPB	77.002	15.533	10.7	297	22.51.01.50	65.3	22.52.57.90	30.0
KBS	78.926	11.942	10.9	308	22.51.05.17	5.0	22.53.05.34	3.0
KEV	69.755	27.007	12.1	256	22.51.21.90	10.0	22.53.33.42	15.0
KIF	69.043	20.804	14.6	264	22.51.49.31	3.6	22.54.19.66	3.9
LSK	64.879	45.734	13.0	218	22.51.27.35	5.5	22.53.44.56	4.4
LVZ	67.898	34.651	11.9	240	22.51.18.16	4.0	22.53.25.41	8.0
SPITS	78.178	16.370	10.2	303	22.50.56.35	65.0	22.52.49.00	31.2
TER	69.201	35.108	11.1	246	22.51.03.34	10.9	22.52.59.23	6.2

Table 2. Specification of P- and S-wave velocities for traveltime prediction in the Barents Sea region. From a depth of 410 km and greater, all models are identical to AK135 [*Kennett et al.*, 1995]. All velocities are specified in km/s and the superscripts identify the appropriate velocity models: BAREY (A), BAREZ (B), BS174 (C), and NZ2010 (D).

Depth (km)	$v_P^{A,B,C}$	v_P^D	v_S^A	$v_S^{C,D}$	v_S^B
0.0	6.200	6.200	3.580	3.580	3.580
16.0	6.200	6.200	3.580	3.580	3.580
16.0	6.700	6.700	3.870	3.870	3.870
41.0	6.700	6.700	3.870	3.870	3.870
41.0	8.100	8.141	4.576	4.655	4.709
70.0	8.225	8.266	4.647	4.727	4.782
210.0	8.260	8.301	4.667	4.747	4.802
210.0	8.350	8.392	4.718	4.799	4.810
410.0	9.030	9.030	4.870	4.870	4.870
410.0	9.360	9.360	5.080	5.080	5.080
460.0	9.528	9.528	5.186	5.186	5.186

Table 3. Phase picks for the 4 March 2014, Novaya Zemlya event.

Station	Latitude	Longitude	Dist	Azi	Pn pick	SNR	Sn pick	SNR
ARCES	69.535	25.506	11.0	260	04.45.06.08	2.2	04.47.02.17	5.0
KBS	78.926	11.942	11.0	314	04.45.06.36	1.6	04.47.04.26	4.1
SPITS	78.178	16.370	10.2	310	04.44.55.53	7.5	04.46.42.98	4.6
ZFI2	80.809	47.655	6.7	346	04.44.08.32	3.9	04.45.17.20	3.5

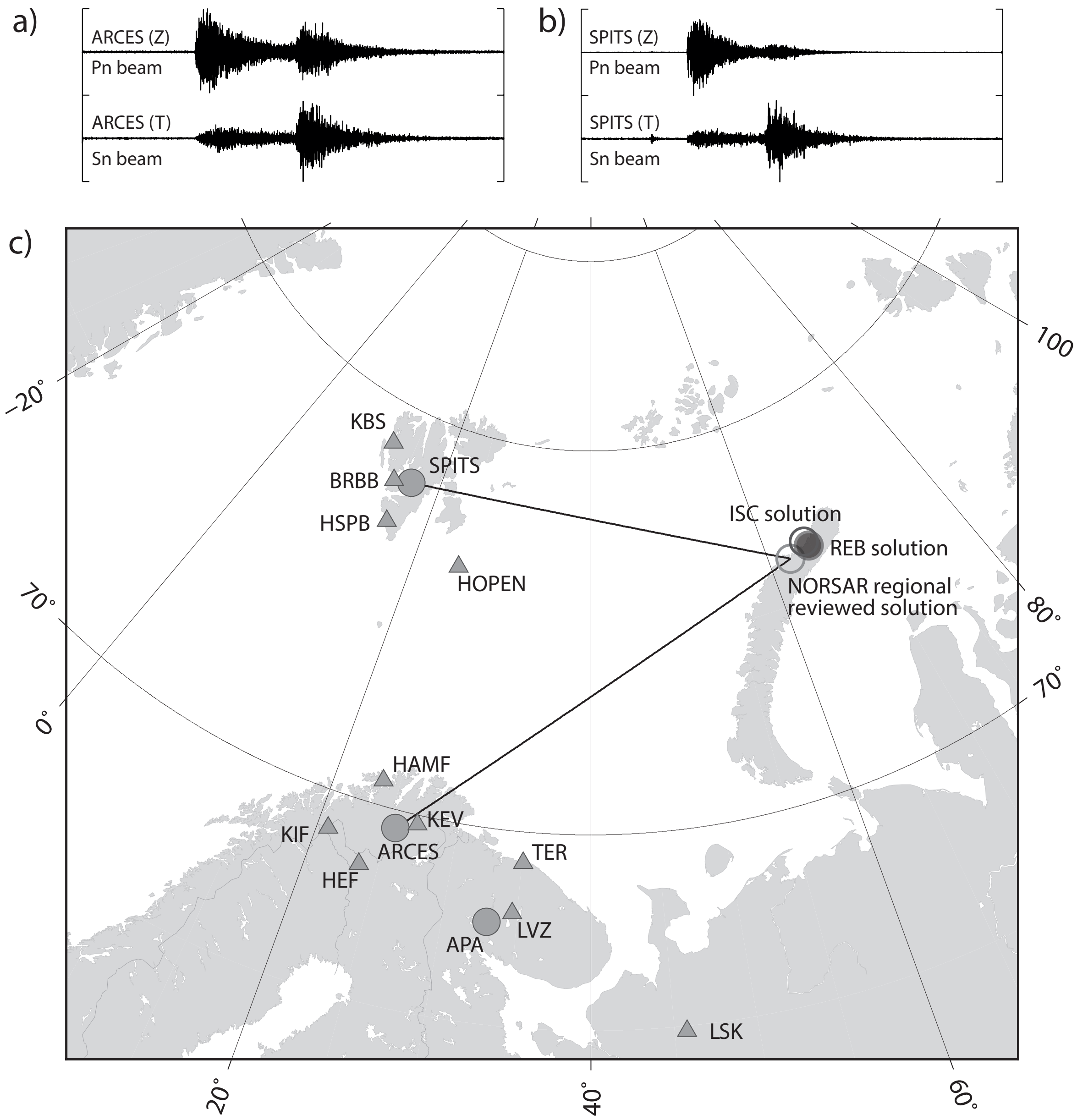


Figure 1. Figure 1 caption.

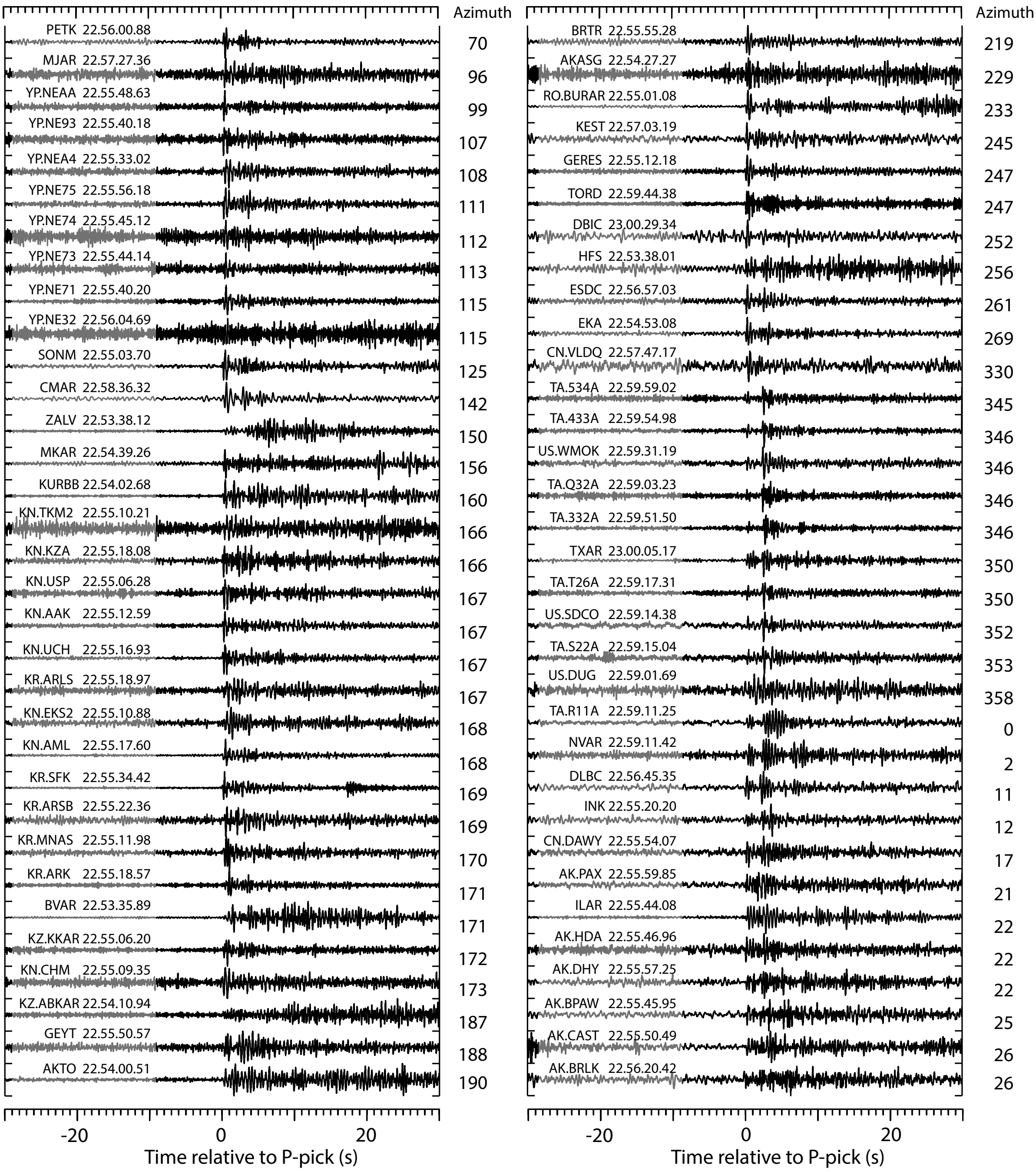


Figure 2. Figure 2 caption.

Figure 3. Figure 3 caption.

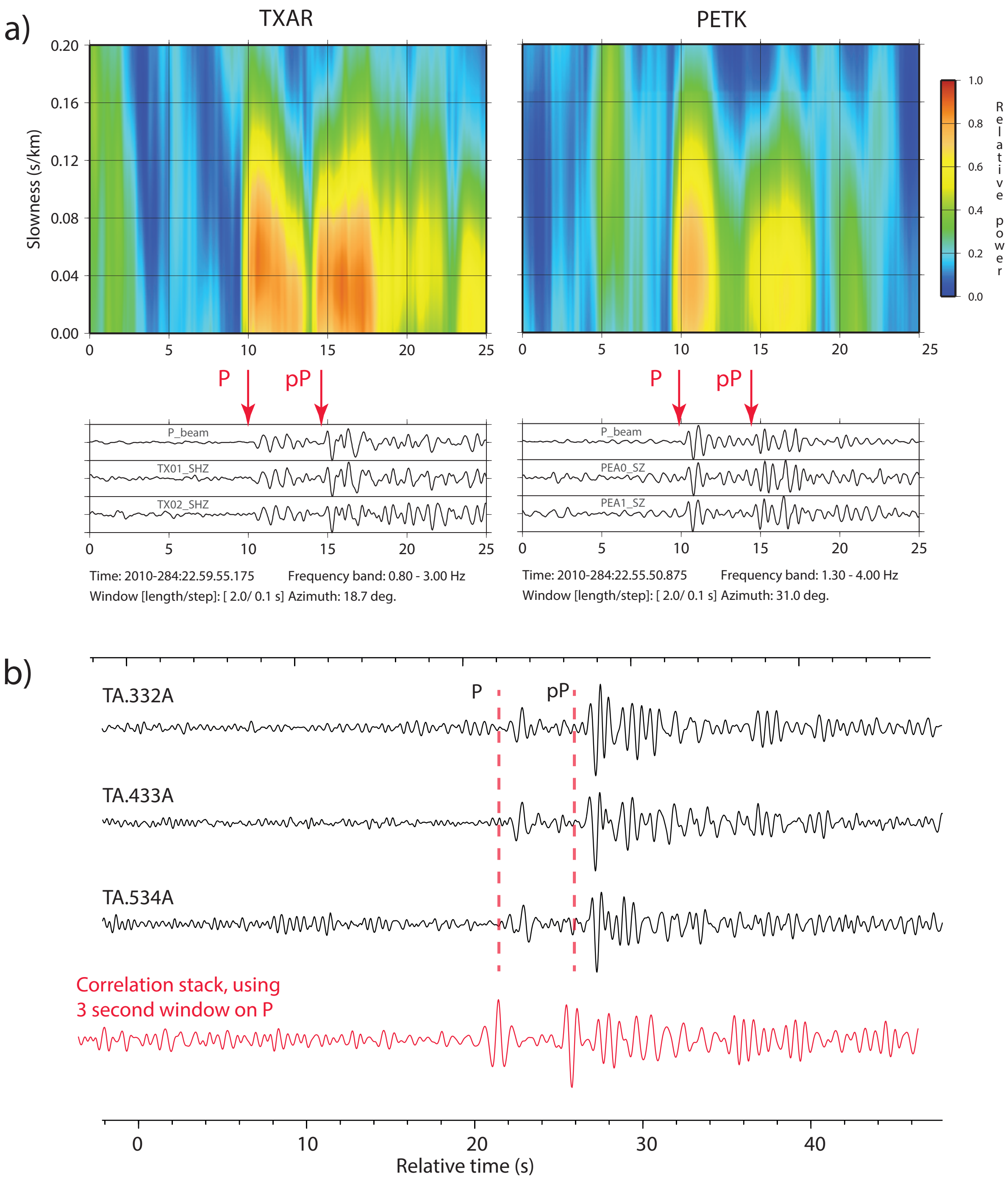
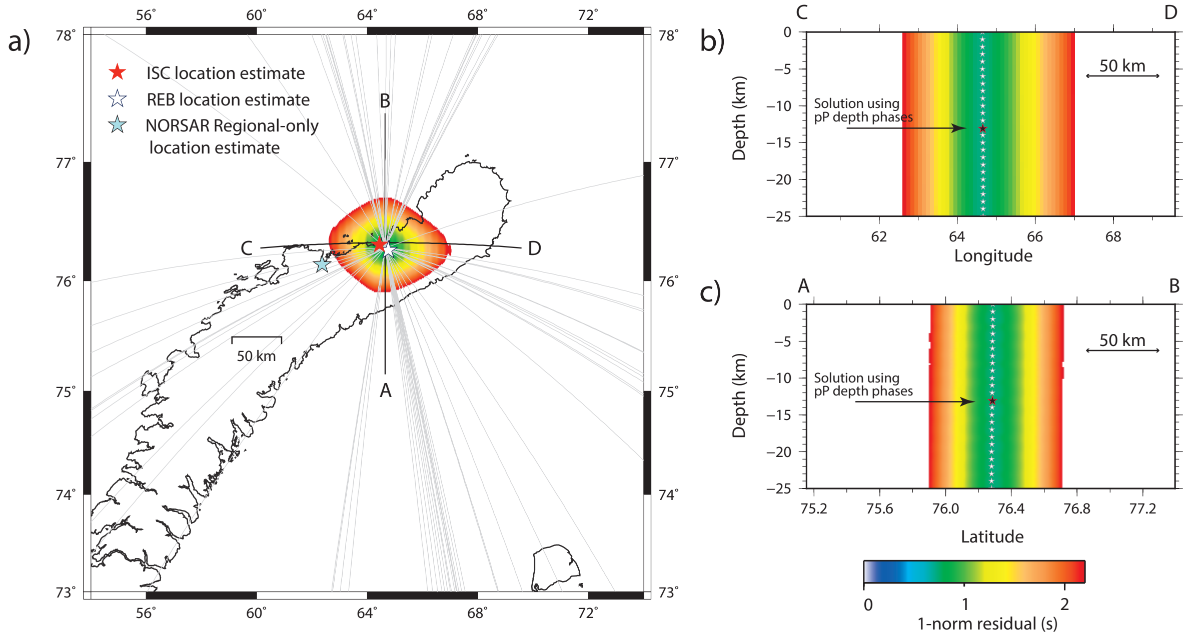


Figure 4. Figure 4 caption.



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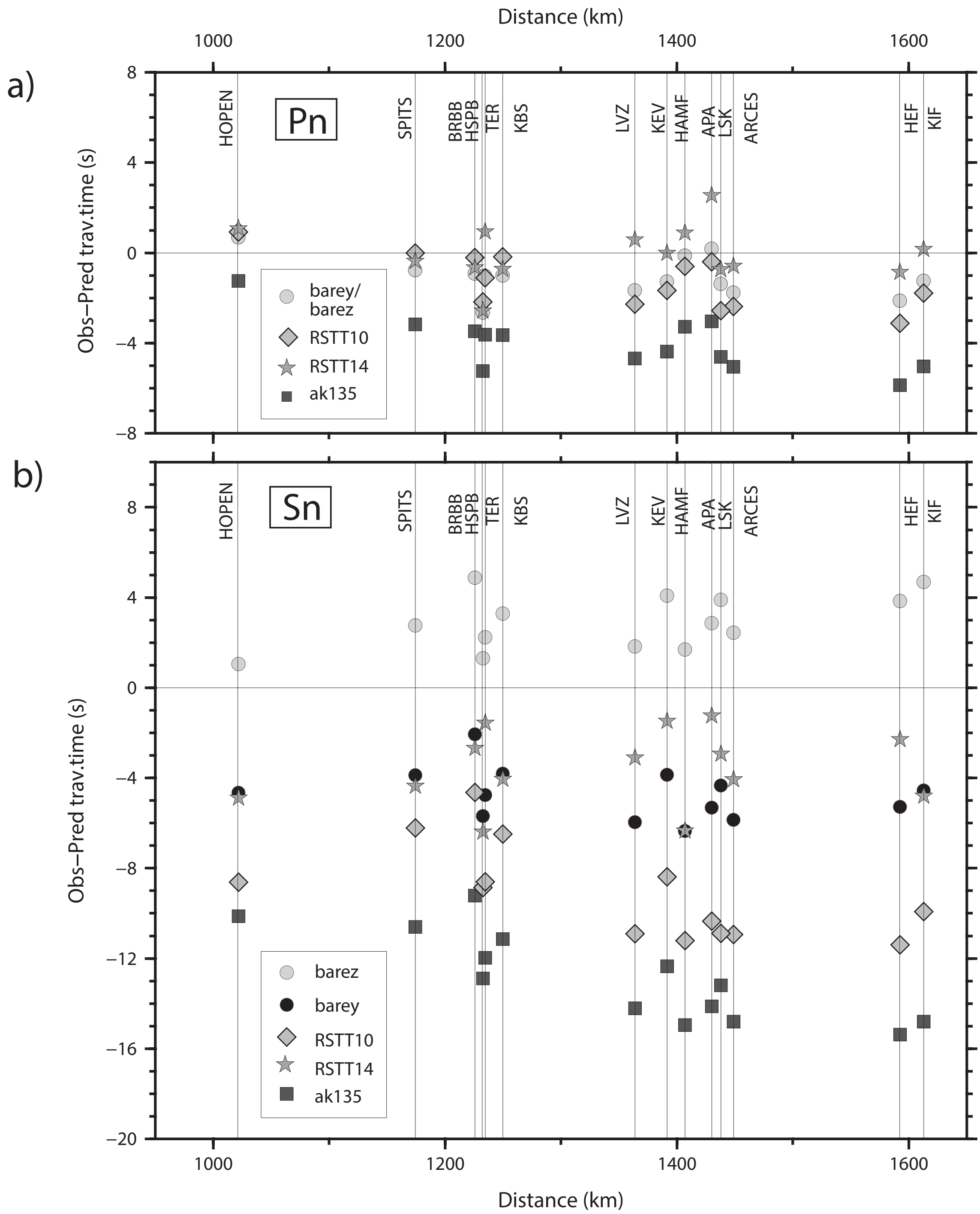

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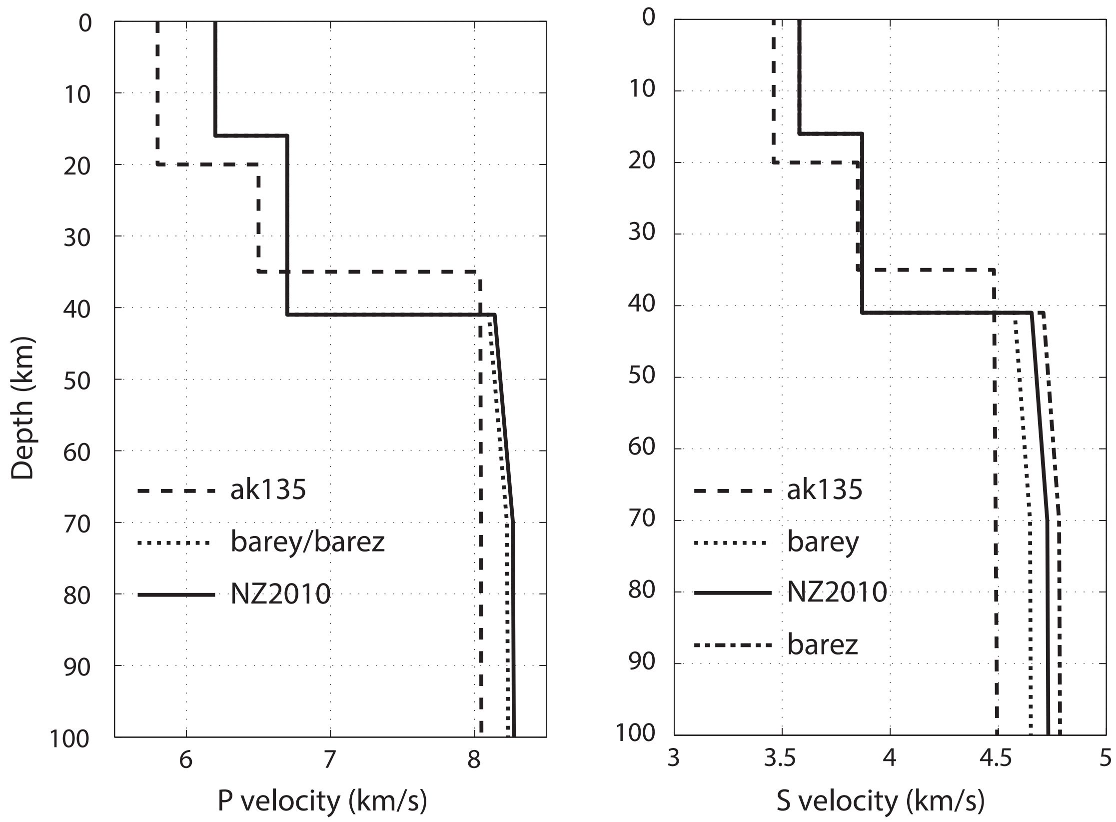

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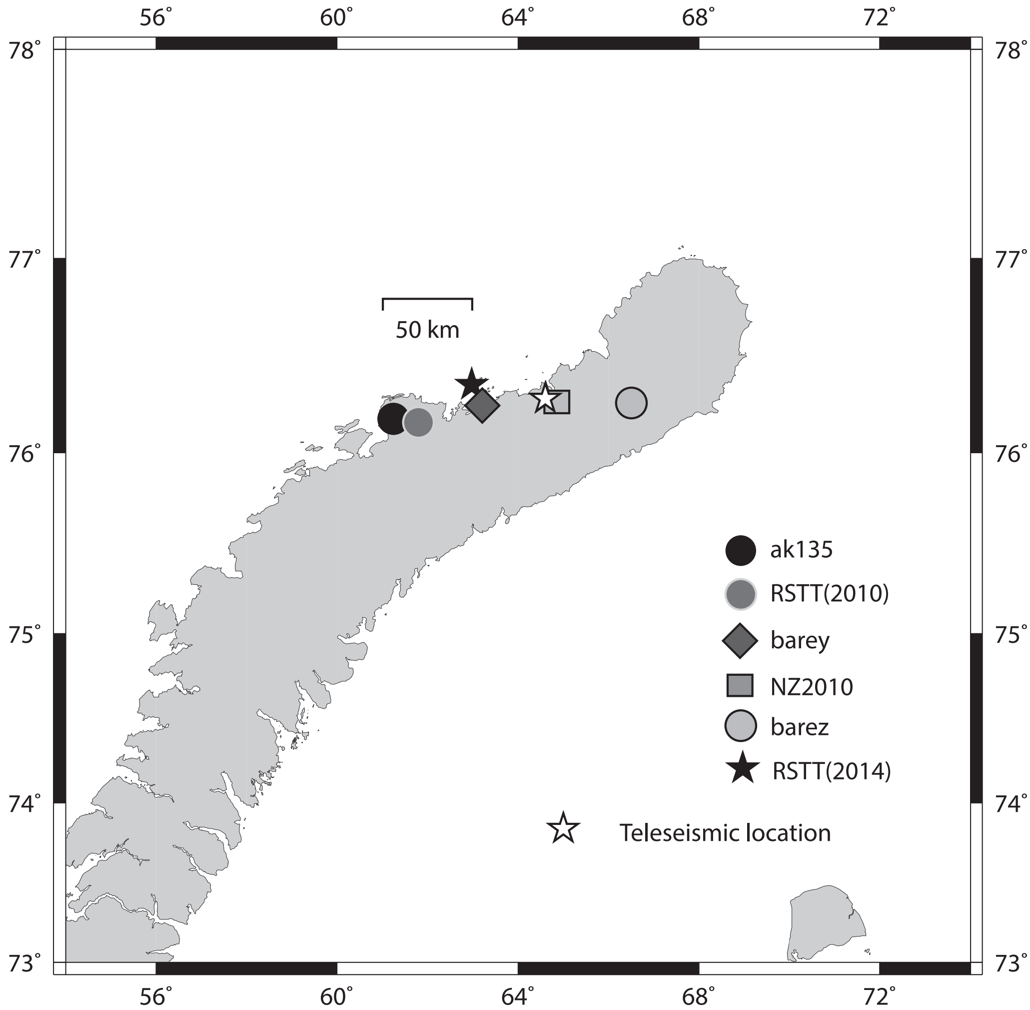

Figure 8. Figure 8 caption.

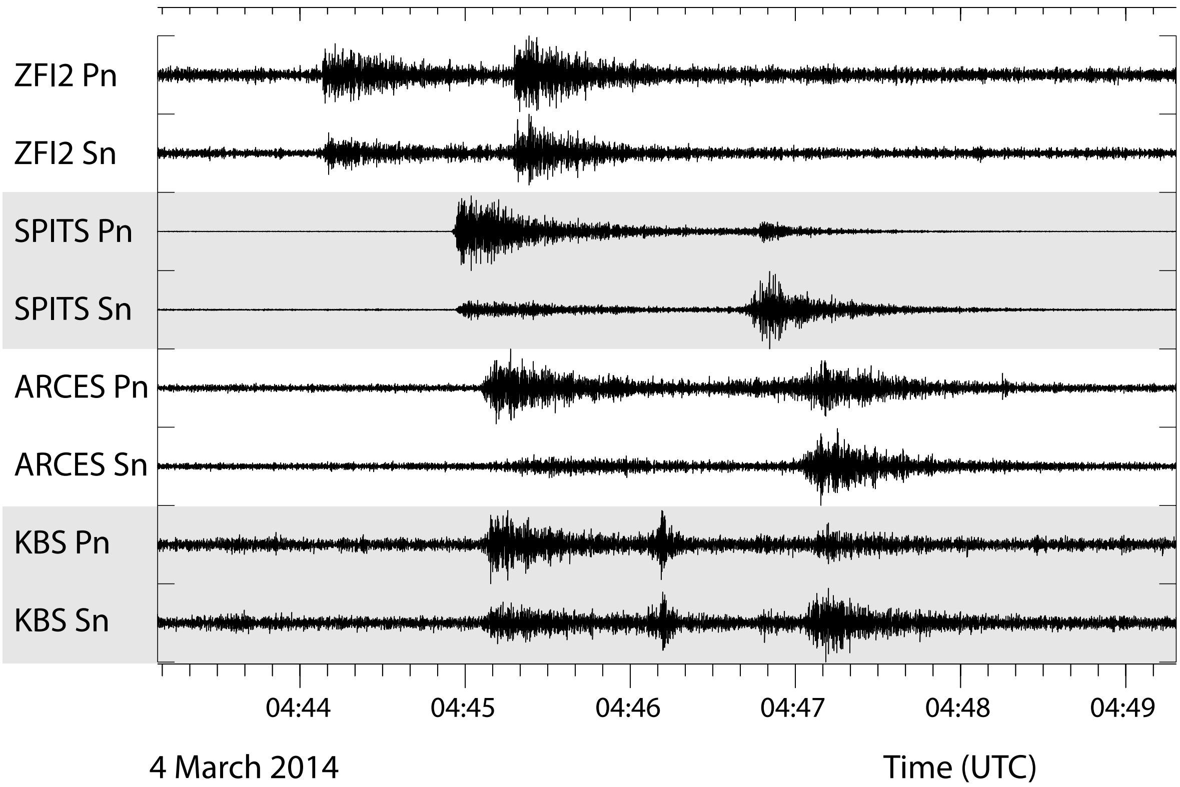

Figure 9. Figure 9 caption.

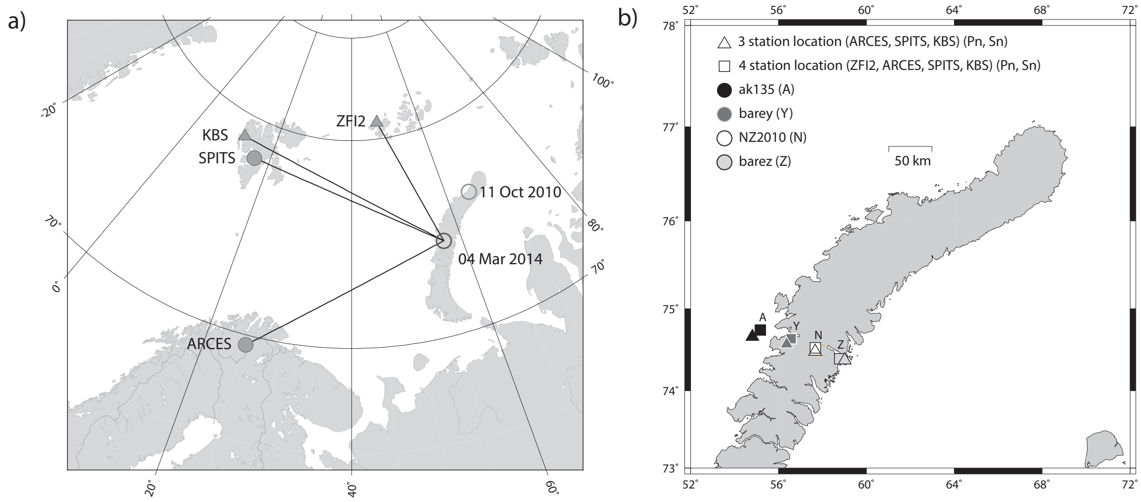

Figure 10. Figure 10 caption.