Geophysical Equipment Facility loan 783

Neogene Uplift of Scandinavia

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Abstract: GEF broadband seismometers were deployed as an array in southern Norway and along a profile crossing central Norway and Sweden. The deployments were very successful with nearly 90% recovery of good quality data. An investigation of the relationship between deployment methods and noise levels along the profile crossing Norway and Sweden indicate that optimum recording conditions are achieved by burial of the instrument placed on a tile concreted to bedrock. The data are being used as part of ongoing investigations into the relationship between crust and upper mantle structure and pre-glacial uplift in Scandinavia. Delay time analysis of data from Southern Norway indicate the region is underlain by cold high velocity mantle. The Receiver-function analysis of records from central Norway and Sweden indicate a shallow or missing crustal root beneath the highest topography. Further investigations are in progress to recover physical properties of the crust which will improve understanding of the relationship between density, crustal structure and uplift.

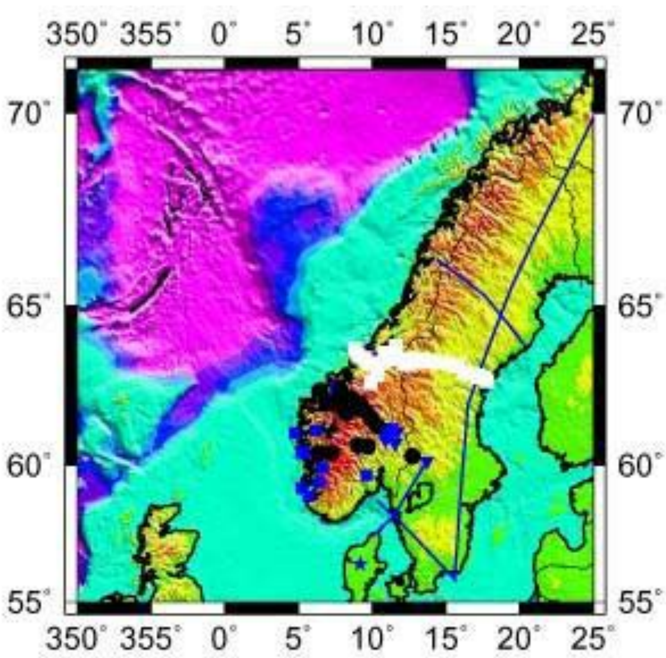

Fig. 1. Locations of the 6T instruments used in the SCANLIPS experiment indicated in white. Black dots are the CENMOVE array GEF 3T instruments were used in the final deployment of this array.

Background: Conventional plate tectonic theory does not explain why parts of the continental crust significant distances from plate margins should move vertically, sometimes by substantial amounts (> 1 km). Intraplate stress, dynamic support, and mantle upwelling have been invoked to account for such 'Epeirogenic' events but few quantitative observations exist which distinguish between competing theories. A substantial body of stratigraphic and geo-chronological evidence [1] suggests the Scandinavian mountains formed a high plateau region, at an altitude of c. 2 km above mean sea-level, during the last 12 Ma, before the onset of Quaternary glaciation. The presence of an uplifted Scandinavian plateau would have accelerated growth of the Northern European ice-sheet during glacial periods. Paleogene uplift of northern Europe is attributed to North Atlantic opening and associated magmatic underplating but this cannot explain the more recent Neogene uplift. Magmatic underplating; tectonic uplift; Eustasy; mantle delamination; and flexure due to intraplate stresses have all been proposed to account for the uplift of Scandinavia [1]. With the exception of Eustasy, which cannot account for all the observed uplift, quantifying the contribution of these processes requires knowledge of the velocity/density structure of the crust and mantle lithosphere in order to determine its isostatic balance. Detailed knowledge of velocity structure will indicate the presence, or absence, of magmatic underplating (characterised by $V_p > 7.2$ km/s). Measured variations in crustal thickness will indicate the extent of crustal thinning associated with continental breakup and/or the magnitude of the crustal load supported by intraplate stress, and can be used to determine the correlation between topography on the surface and the Moho [2]. This will be achieved by using seismology to recover the physical properties and structure of the crust and upper mantle beneath Scandinavia; to correlate variations in these properties of the crust with the observed pattern of uplift.

Fieldwork, data processing and data quality: Loan 783 provided 33 6TD instruments for 6 months (April to October 2006) recording of teleseismic arrivals at c. 30 km intervals along a profile across central Norway and Sweden (phase 1 of the SCANLIPS experiment) (Fig. 1) and 5 3T instruments for broadband recording which supplemented the CENMOVE array in southern Norway (between June 2005 and May 2007) (Fig. 1). Data recovery from the 3T instruments was 100% while data recovery from the 6T instruments was c. 90% with losses due to equipment failure and noisy sites

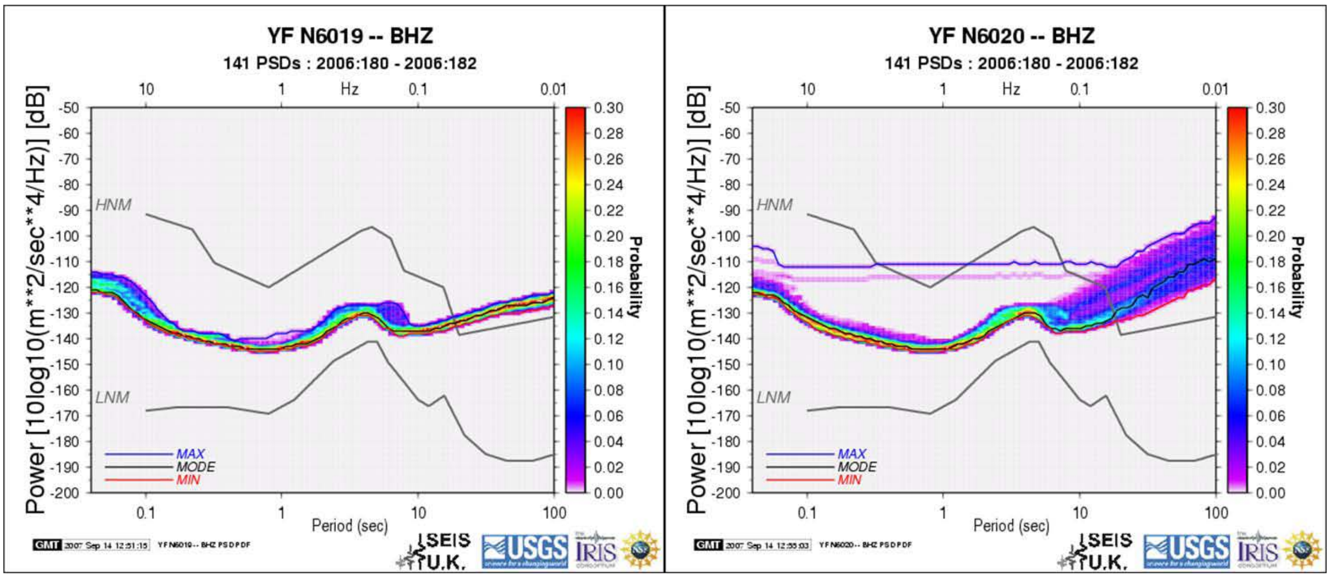

Fig. 2. Left, noise plot (power spectral density vs period/frequency) for site 19 at which the sensor was placed on a tile concreted to bedrock and buried. Right, noise plot for site 20 at which the sensor was placed on bedrock and surrounded by a concrete pipe. Note the significantly higher noise levels at long periods which is due to a combination of temperature variations and tree movement.

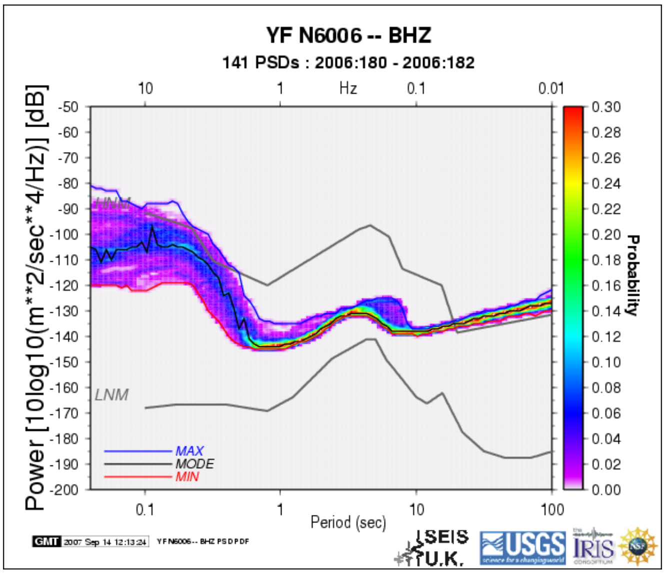

Fig. 3. Noise plot for site 6 at which the sensor was deployed by burial in soil on a tile resting on tamped sand. Note the overall elevated noise levels and high noise levels at short periods. This site was on a working farm.

(the duration of recording for 6Ts being dependent upon noise levels). All data were transcribed into miniSEED and have been archived with IRIS, where it is under a moratorium until May 2010. Event lists for each phase of the deployments were created and events extracted using WEED and written in SAC format for further processing and interpretation, described below.

Instruments in the SCANLIPS array were deployed in a variety of environments and by a variety of methods. All the sites in Norway (1 to 10 and 131 and 133) consisted of burial of the instrument in soil in a 1 m deep pit with a tile bedded into packed sand. The majority of the instruments deployed in Sweden were placed directly onto bedrock and surrounded by a concrete pipe with a lid. Two stations (17 and 19) were buried in soil but placed on a tile concreted onto bedrock. Analysis of noise from the stations showed the lowest levels of noise were recorded at those stations that were deployed on bedrock but buried (Fig. 2). The stations in Sweden that were placed on bedrock at the surface and surrounded by a pipe were generally slightly quieter than the instruments in Norway that were buried but they suffered from low frequency noise which needed to be filtered from the final data (Fig. 2). The exact cause of this noise had not been determined but it is considered to be largely thermally induced, although many of the sites were (unavoidably in Sweden) close to tress and a component of the noise may be induced by the movement of the trees in the wind. Many of the sites in Norway, while acceptable, were close to areas of habitation and consequently were not as quiet (Fig. 3). In addition, absolute amplitudes from sites buried in soil were generally 10% less than those for instruments placed on bedrock and then buried.

Conclusions from fieldwork and data analysis: The optimum deployment configuration is one in which an instrument is placed on a tile concreted to bedrock at the bottom of a pit which is then backfilled; the burial providing the necessary thermal insulation. Alternatively, the instrument should be placed directly on bedrock but then it needs to be thermally insulated. Due to water ingress at a number of sites, which led to some equipment failures, it is also recommended that whenever possible or practical batteries, regulators and data loggers should not be buried but placed on the surface and adequately covered with insulation and waterproofing rather than being buried.

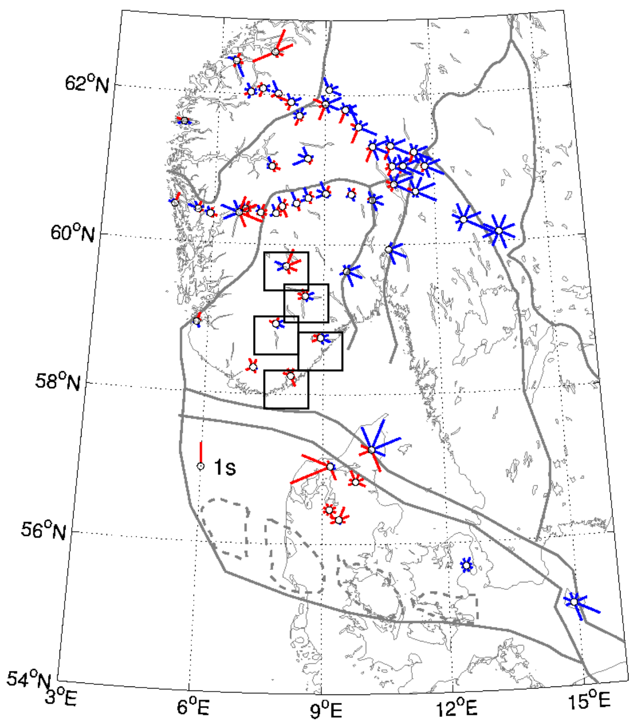

Fig. 4. Plot of delay times in 45° wide bins showing the azimuthal variation in delay times recorded across the array. Line length is proportional to relative arrival time. Red is slow/late and blue is fast/early relative to the IASPEI-91 model. SEIS-UK instruments are surrounded by squares. From Bondo et al. (in review).

Preliminary Scientific Results: The data from southern Norway have been used to complement the CENMOVE Receiver-Function profile [3] and have also been used to undertake a study of delay times as a precursor to a study of upper mantle surface tomography to be undertaken at Aarhus. The results of the delay time study are shown in Fig. 4. This image illustrates the P-wave arrival times relative to those predicted by the IASPEI-91 model [4]. Arrival times of up to 32 events per station were picked, crustal corrections applied and delay times calculated before the data were binned into 45° bins in order to investigate azimuthal variation in arrival times (Fig. 4.). With some notable exceptions toward the coast of Norway, the majority of stations record ‘early’ events from North-easterly azimuths and late events from azimuths to the south-west. Back projection of the events reveals that the ‘early’ events have travelled through the thick high-velocity lithosphere of the Baltic shield and the ‘late’ events have travelled through the thinner lithosphere of north-western Europe. The overall simplicity of this picture, which is entirely consistent with previous knowledge of the upper mantle structure in this region provides little indication of the cause of the uplift. Further work, using surface wave data from the 3T instruments will be used to constrain the thickness and properties of the lithosphere. Once this is constrained and combined with Receiver-Function data a more detailed picture of the relationship between the pattern of uplift and crust and upper mantle structure may lead to a better understanding of the cause of the uplift.

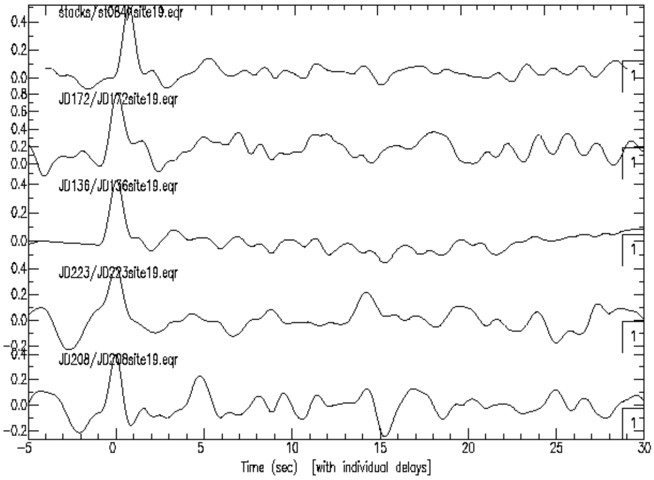

Fig. 5. Example Receiver-Functions from the SCANLIPS array. At the top of the Fig. is a stacked function for events from a single station. Lower 4 traces are individual Functions calculated from different events recorded at station 19.

Receiver-Functions have been calculated from teleseismic arrivals from between 30° and 90° offset for 28 events of $M_b > 6.0$ recorded on the SCANLIPS profile across central Norway and Sweden, following the method of [5]. An example of these together with a stacked Receiver-Function for a single station are given in Fig. 5. In general, events recorded at the stations in Sweden are quieter than those recorded in Norway for reasons given above, but signal to noise ratio was sufficiently high to determine at least 10 Receiver-Functions at all stations. These events are from a range of back-azimuths but there are large gaps with few events from the south and west (Fig. 6). Two approaches have been taken with these data so far. The first was to use the unpublished wide-angle seismic profile of [6] to provide a-priori constraints for simple 1-D inversions for velocity structure, from the better Receiver-Functions. This proved successful and supported the conclusion that there is a velocity inversion within a few km of the surface along the central and eastern part of the profile. A low signal to noise ratio for the data from Norway has prevented an unambiguous velocity model being determined for this part of the line. Secondly, the data have been migrated using the velocity model of [3] (Fig. 7). This allows direct comparison of the crustal structure beneath central Norway and Sweden with the CENMOVE profiles crossing southern Norway. Once again, poor signal to noise ratios and/or 3 dimensional heterogeneity have prevented an unambiguous resolution of the crustal structure beneath Norway. However, a Moho conversion can be imaged at c. 40 km across the profile beneath Sweden (Fig. 7). The velocity model derived from the 1-D inversion suggests that the simple 2 layer velocity structure used to migrate the new data and the CENMOVE data is too simplified and the migration programme has been modified to use a more complex velocity structure; further migrations of the data using a multilayer velocity model are planned. This may remove some of the irregularity in the depth of the Moho and enable better resolution of the structure beneath Norway.

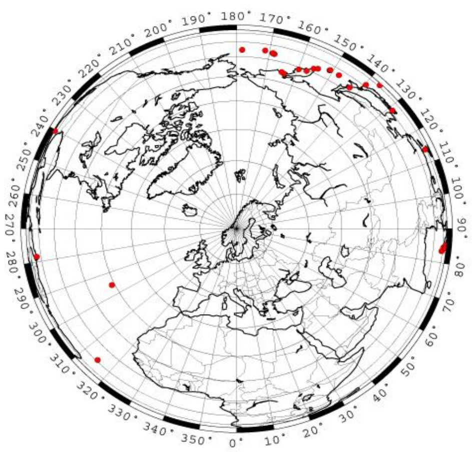

Fig. 6. Red dots indicate the location of events used for calculating Receiver-Functions.

Interpretation and conclusions: The results are currently being integrated into a suite of experiments aimed at determining the velocity structure of Scandinavia. The CENMOVE profiles and array have focussed on southern Norway. The SCANLIPS array data described here have focussed on central Norway and Sweden. A further profile SCANLIPS2 has been deployed in northern Norway and Sweden in the summer of 2008. The intention is that the four profiles and combined array data will be used to identify lateral variations in crustal velocity structure which may then be compared with observed patterns of vertical uplift. In addition delay time and surface wave analysis will be used to study upper mantle structure.

The preliminary results of the delay-time study from the array data suggest that the mountains of southern Norway are underlain by a broad transition from old-cold mantle of the Baltic shield to ‘normal’ temperature north-western European mantle, and that there is little evidence of dynamic

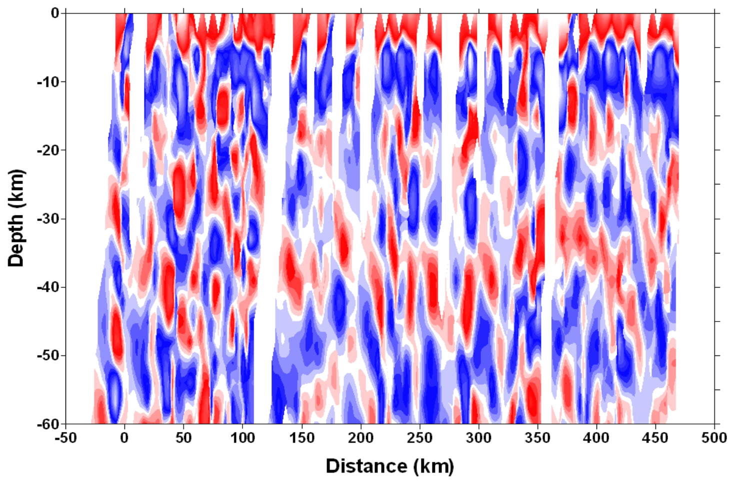

Fig. 7. Migrated Receiver function profile for the SCANLIPS array. 0 km is at the Norwegian coastline. Locations of recording stations is shown in Fig. 1. The migration method follows the technique described in [7] and uses the same velocity model used to migrate the CENMOVE profiles [3] so that a direct comparison may be made between the data.

support of the mountains or uplift as a result of flow of anomalously hot mantle material beneath the region. This study will be developed through analysis of surface-wave data recorded by the 3T instruments and the delay time study is being extended to the SCANLIPS profile data in central Norway and Sweden. This is being undertaken by a research student at the University of Aarhus in Denmark.

Preliminary migrations and 1-D inversions for velocity structure from the SCANLIPS Receiver-Function data suggest thick high velocity crust underlying Sweden which thins underneath Norway toward the continental margin. There is little evidence for a deep crustal root providing buoyant support for the mountain range which has its highest point (c. 1000 m) at100 km along the profile. This is consistent with the most recent reinterpretations of the CENMOVE profiles. It is suggested that the apparent thickening of the crust beneath southern Norway is the result of extension and thinning of the crust beneath the Oslo Graben and the North Atlantic margins rather than thickening by magmatic addition or tectonic shortening beneath the mountain range. A considerable amount of further work is needed, including development of a more sophisticated velocity model for migration and application of the H-κ stacking method [8] to recover more details of the crustal properties before these preliminary conclusions can be verified. This study needs to be replicated for the CENMOVE arrays so that a detailed comparison can be made of these profiles with the 4th profile (SCANLIPS2) which is currently being acquired. This work will be undertaken by the PI at Leicester.

References

[1] Doré, A., Cartwright, J., Stoker, M., Turner, J., & White, N. (eds) 2002. *Exhumation of the North Atlantic Margin: Timing, mechanisms and implications for petroleum exploration*. Geological Society London, Special Publications, 196. Refs therein.

[2] Balling, N. 1984. Gravity and isostasy in the Baltic Shield. *In*: Galson, D. & Mueller, St. (eds) *First EGT workshop: The northern segment*, 53-68. European Science Foundation, Strasbourg.

[3] Svenningsen, L., Balling, N., Jacobsen, B. H., Kind, R.,Wylegalla, K. & Schweitzer, J. 2007. Crustal root beneath the highlands of southern Norway resolved by teleseismic receiver functions. *Geophysical Journal International*. Doi: 10.1111/j.1365-246X.2007.03402.x.

[4] Kennet, B. L. N. 1991. *IASPEI 1991 Seismological tables*. Research School of Earth Sciences, Australian National University.

[5] Ammon, C. 1991. The isolation of receiver effects from teleseismic P-waveforms. *Bulletin of the Seismological Society of America*, 81, 2,504-2,510.

[6] Schmidt, J. *A seismic refraction study of the central Scandes*. Unpublished PhD thesis, University of Uppsala.

[7] Kosarev, G., Kind, R., Sobolev, S. V., Yuan, X., Hanka, W. & Oreshin, S. 1999. Seismic evidence for a detached Indian lithospheric mantle beneath Tibet. *Science*, 283, 1306-1309.

[8] Zhu, L. & Kanamori, H. 2000. Moho depth variation in southern California from teleseismic receiver functions. *Journal of Geophysical Research*, 105 (B2), 2,969-2,980.

Presentations arising from this work:

England, R. W. and Ebbing, J. SCANLIPS – A study of Epeirogenic uplift of Scandinavia. T13D-1582. *American Geophysical Union Fall Meeting, San Francisco, USA, December 2007*

England, R. W. and Ebbing, J. SCANLIPS – A study of Epeirogenic uplift of Scandinavia. *Danish Geological Society Annual Meeting, Alborg, Denmark, January 2008*

England, R. and Ebbing, J.A seismological study of Epeirogenic Uplift of Scandinavia. *European Geological Union, Vienna, Austria, April 2008*

Jacobsen, B.H. Svenningsen, L. Hetényi, G. England, R. Ritter, J. Olsen, K. Roberts, R. Dahl-Jensen, T. Thybo, H. and Kind, R. 1-D receiver function model construction and resolution analysis: New insights and remaining issues. *European Geological Union, Vienna, Austria, April 2008.*

England, R. and Ebbing, J. The relationship between deep crustal structure and surface uplift. *33rd International Geological Congress, Oslo, Norway, 2008.*

Publications arsing from this work:

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In preparation – for submission January 31st 2009.

England, R. W. & Ebbing, J. Crustal structure beneath the central and northern Scandes and its relationship to topography. Tectonophysics.