LOAN 843: SCIENTIFIC REPORT on GlyVeST:
Glyvursnes-Vestmanna Seismic Tie, a Land and Marine Seismic Profile

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Abstract

Combined marine and land controlled-source seismic data acquisition was carried out in the Faroe Islands in July 2007, for which 20 Güralp 6TDs were supplied by SEIS-UK. These seismometers recorded visible refraction first arrivals to offsets of 7.5−10 km. Observed P-wave velocities of 4.4−5.4 km/s lie within the expected range for flood basalts, as do calculated V_P/V_S ratios of 1.83−1.92. A range in seismic velocities from data picks indicates the presence of structural dip. A preliminary 'best fit' is a two-layer model incorporating our refraction picks and velocities from vertical seismic profiling (VSP) in the Glyvursnes and Vestmanna boreholes, and imposing vertical and horizontal velocity gradients as well as interface depths consistent with a previously published geologic cross-section.

Background and site map

The primary aim of this project was to make a joint marine and land seismic survey to tie the two borehole locations, Glyvursnes-1 and Vestmanna-1, on Streymoy, Faroe Islands. A line from Vestmanna to Glyvursnes closely follows the west coast of Streymoy, providing the opportunity of tying the two points with both onshore and offshore profiles (Figure 1). Our main reasons for proposing also the land line were to provide: (1) multicomponent data for studies of inhomogeneity and anisotropy in the basalts and the intercalated sediments; (2) long-offset data (not available from the 600-metre marine streamers), and (3) greater velocity control in processing the marine reflection data; also (4) to take advantage of the airgun sources being fired for the marine acquisition, and (5) to

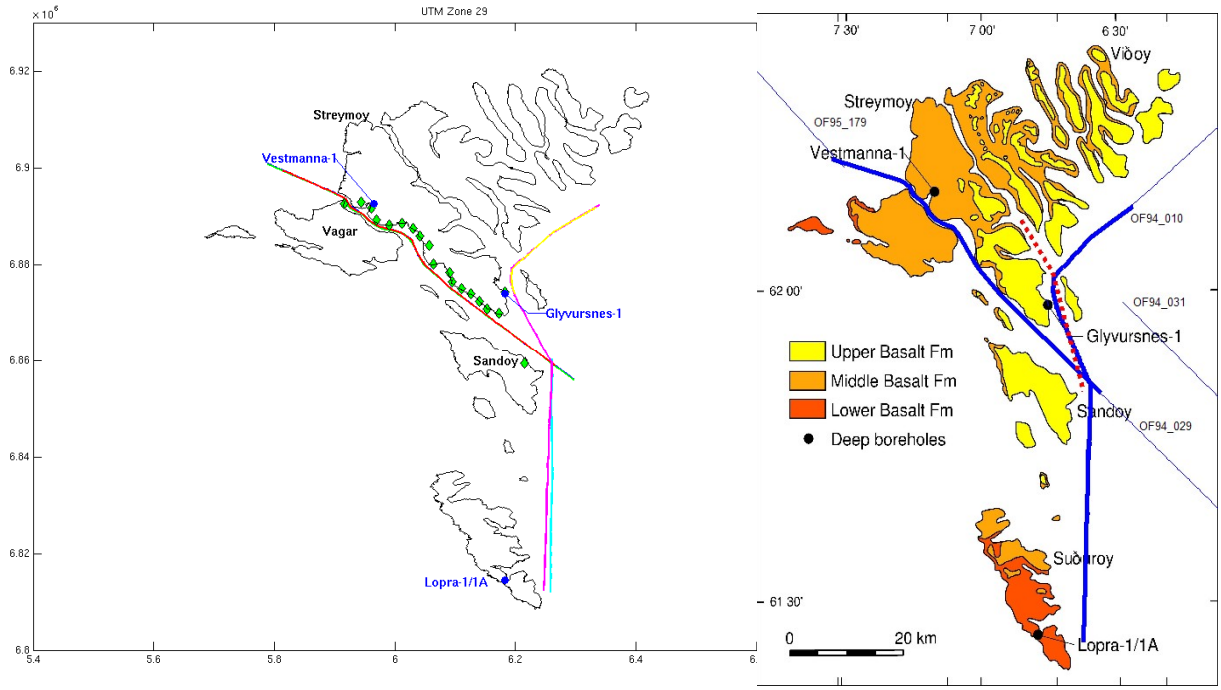

Figure 1. (left) Positions of Güralp seismometer (green diamonds), three boreholes (blue) and GlyVeST marine-acquisition lines (different colours) sailed by the R/V Magnus Heinason. **(right)** Geologic map of the Faroes with GlyVeST sailing lines (blue) and some industry lines (labelled **OF9...**).

capitalize on the observation of Petersen et al. (2006) that a combination of airgun sources and geophone receivers was superior to either an airgun-streamer or dynamite-geophone combination.

Survey procedure

We installed 19 Güralp 6TD seismometers in June-July, 2007 (one could not be deployed due to a bad GPS cable). The seismometers occupied sites covering the critical stretch between Glyvursnes and Vestmanna at intervals of approximately 2 km, with some sites beyond as well (Figure 1). Suitable sites were identified based on the presence of bedrock and good drainage, and considering potential noise sources. Permission was obtained from land owners at all sites. Where possible, we maintained a distance of at least 50 m from such features. Appropriate care was taken on steep slopes to avoid loss or damage to equipment and personnel. Due to rough and steep terrain it often was a challenge to find good sites for the instruments. This, coupled with indirect driving routes and poor roads to some remote sites, meant that on most days we installed only two instruments – never more than four.

Each seismometer was buried in a hole roughly 50-80 cm deep. Ideally, sensors were placed on a level base of quick-drying cement in contact with bedrock, levelled and aligned to magnetic north. In cases where no bedrock was encountered, the soil was compacted as much as possible but no cement was used. The sampling rate was set to 200 samples/second. Each seismometer was then covered with a plastic bucket before burial. The GPS antenna was elevated on a 180-cm vertical wooden pole for better reception in this area of high topography, and to keep it out of reach of grazing livestock. A separate hole was dug for a 12-V car battery and the breakout box. Cables and connections were double-checked before connecting battery power. The sensor was initialized using Shout 2.81 software on a hand-held Palm, and the GPS receiver checked for acceptable readings of o/s and drift.

Marine acquisition equipment from Aarhus University was installed on the R/V Magnus Heinason. During July 8–11 we acquired data with round-the-clock work. Each profile (blue lines in Figure 1) was shot at least twice, in opposite directions, with some acquisition parameters varied for test purposes. The ~50-km profile through Vestmannasund [Figure 1 (left), red segment], close to the seismometer line, was shot four times (Lines 1 to 4). The 210-in^3 Sercel GI airgun source had a generator chamber (G, 105 in^3) and an injector chamber (I, 105 in^3). Each profile was shot with GG mode (G and I fired simultaneously) and with GI mode (for bubble-pulse reduction; I fired 15 or 35 ms after G). The source and streamer tow depths were nearly equal, 8−10 m for most of the lines, but ~3 m for a couple, for test purposes. Shot intervals were mostly 25 m, though 50 m (sufficient for the land experiment) and 12.5 m were also tested. The strength and direction of currents in the fjords was monitored closely to minimize feathering of the streamer.

Data quality

Data samples shown below (Figures 2−5) include examples of a few instrument problems, e.g., missed shots (Figure 2) and weak arrivals (Figure 3). Both GLYV (Glyvursnes; offset ~6 km on east coast; Figures 1 & 3; Table 1) and GJAR (Gjarbotnur; 9th station from NW end of line, at 300 m elevation; Figure 1) were faint. Figure 4 shows some typical good data and Figure 5 some S waves that are clear on Line 2 but not Line 4.

Julia Kingsbury (Cambridge U) picked P-wave arrivals on the vertical component of Line 4 for each receiver to offsets of up to 10 km, and S arrivals on components and shooting lines where they were best defined. Line 4 had suitable shot spacing (50 m) and optimal streamer depth (10 m). Line 2 was not included in this first study due to airgun problems (missed shots; Figure 2). But, if S arrivals were more obvious on Line 2, these picks were used instead (Figure 5). Good seismic profiles were obtained for 15 of the 19 instruments on Line 4. Strong first arrivals are visible to offsets of 7 to 10 km (e.g. Figure 4). These arrivals were picked on the receiver gathers at suitable reduction velocities (e.g. Figure 3).

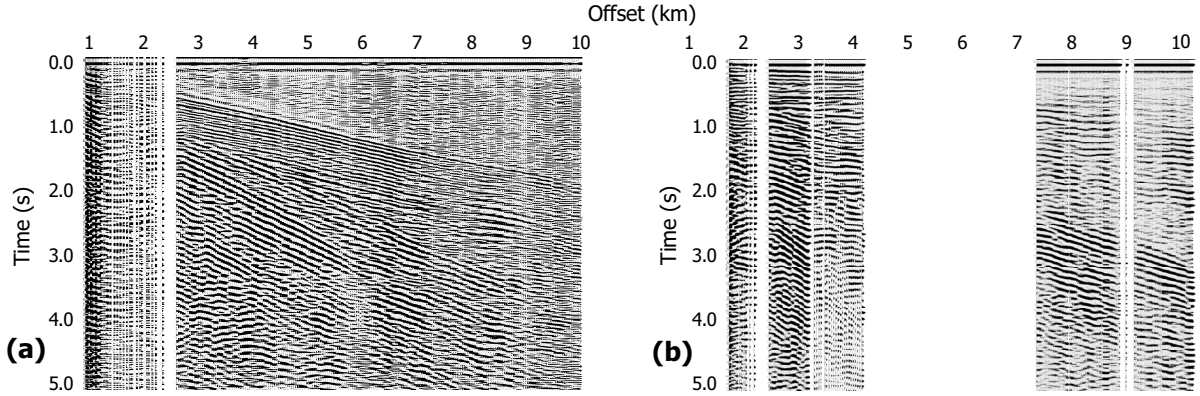

Figure 2. Vertical-component receiver gathers for Line 2 from KVIV and STYK (Table 1): **(a)** 2KVIVzS, shots south of KVIV; **(b)** 2STYKzN, shots north of STYK; showing large gaps of missed shots.

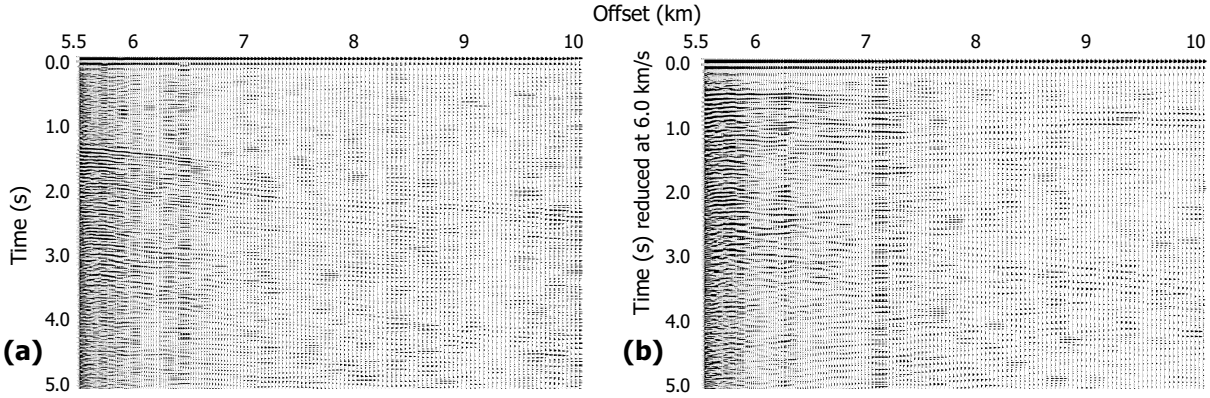

Figure 3. Vertical-component receiver gathers for Line 4 from GLYV showing weak arrivals; **(a)** 4GLYVzN with unreduced traveltime and **(b)** 4GLYVzN with traveltime reduced at 6.0 km/s.

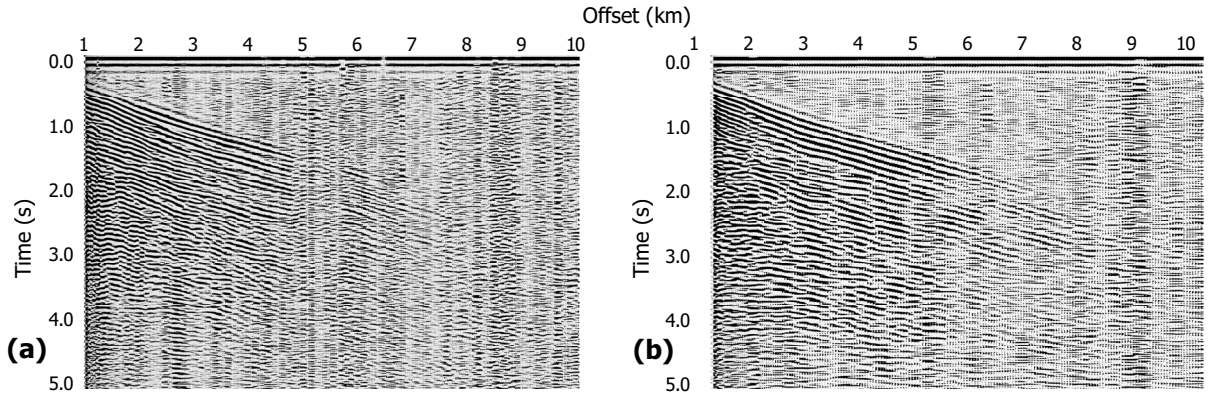

Figure 4. Gathers for GMLT comparing **(a)** Line 2 and **(b)** Line 4; for shots from the north.

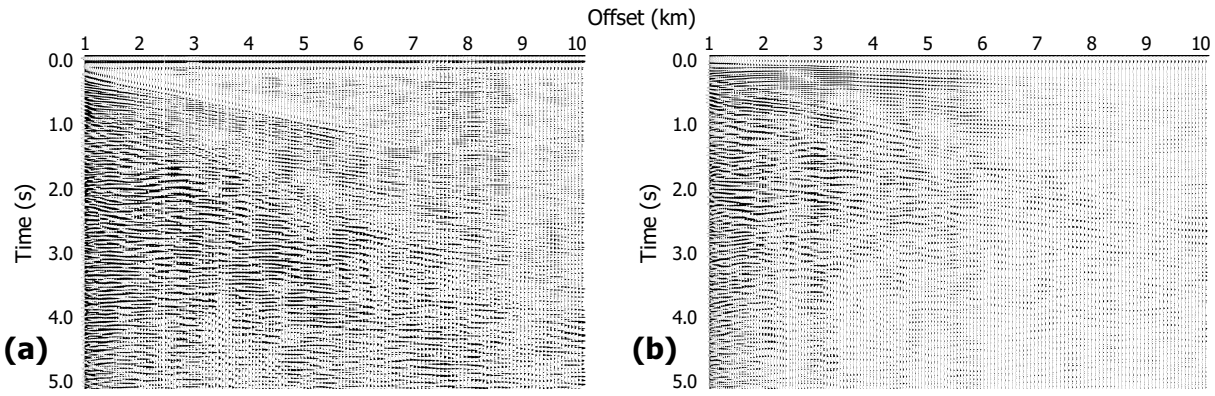

Figure 5. Gathers for KKJB comparing **(a)** 2KKJBzN with distinct S waves and **(b)** 4KKJBzN with unclear S.

Processing and modelling

The raw data were downloaded to Lacie disks, mostly at SEIS-UK. Copies were made to the SEIS-UK server, and then to the server at Bullard Labs. The raw data were converted to SEG-Y receiver gathers, created for the three components of each instrument and copies made to DVD. The SEG-Y files were first converted to Seismic Unix (SU) format and SU used to create displays of receiver gathers, from which the first arrivals were picked. These were visible up to offsets of 10 km. Wiggle traces were plotted and various values of filter parameters, clipping levels and data gain were tested and displayed. A bandpass filter of 12-15–50-60 Hz was chosen and data were displayed with traveltime reduction at an appropriate velocity: 5.0 or 6.0 km/s for P and 3.0 km/s for S arrivals, respectively.

Table 1. Seismic velocities (km/s) calculated from picks on vertical component, Line 4, unless stated otherwise. Profiles to north and south of each site were displayed, and velocities picked separately.

	Seismic velocities to north			Seismic velocities to south		
Site Code	**P**	**S**	**Vp/Vs**	**P**	**S**	**Vp/Vs**
SLAE	6.15	2.14	2.87	5.78	4.30	1.34
VSTM	6.27			5.54		
VALR	4.52			5.37		
VSTV	5.02	3.07	1.63	5.08	2.99	1.70
KVIV	5.11	2.79	1.83	4.97	2.59	1.92
STYK	5.19	2.81	1.84	5.08	2.71	1.87
LEYN	5.28			5.19	2.84	1.83
GJAR	5.29	2.86	1.85	5.02	2.83	1.78
NRDR	5.04	3.01	1.67	4.96	2.40*	2.07
SYDR	5.36	2.85	1.89	4.88	2.69	1.81
KFLD	5.13			4.72	2.81	1.68
CTGR	5.07	2.87	1.77	4.74	2.84	1.67
VELB	5.17	3.02	1.71	4.65	2.32	2.00
GMLT	4.90			4.66		
GLYV	5.49			4.65	2.99	1.56
KKJB**	4.47	2.35	1.90	4.56	2.48	1.84

*S arrival picked on north component

Before picking arrivals, the receiver positions were projected onto the line so that separate profiles could be made for shots to the north and to the south of the receiver. In developing a two-dimensional model of the study area, the shots and receivers are assumed to lie along a straight line, so the receiver positions relative to the line had to be taken into account. Picks were plotted in Gnuplot by fitting a least-squares straight line to the first-arrival data. A number of iterations were carried out to determine best-fit slopes (thus velocities) and intercepts. Simple one-dimensional modelling was carried out in Excel for preliminary analysis of the pick data assuming uniform velocity in a one-layer model.

Water depth and source locations for Line 4 were extracted from the SEG-D headers of sgd files by Khanh Nguyen. Once receiver locations were projected onto the line, the corresponding traveltimes from each shot had to be corrected for the new raypath in order to create a suitable velocity model. This is achieved by assuming a vertical raypath beneath the receiver; subtracting the traveltime through basalt (estimated with $V \approx 5000$ m/s) and adding the traveltime through water (using $V \approx 1480$ m/s). The equivalent offsets were more difficult to correct for. Julia Kingsbury adopted the procedure of projecting the receiver onto the line and migrating shots to their actual offsets along the line.

Interpretation to date

Observed P velocities varied among receivers: ranging from 4.47 km/s to the south to 6.27 km/s in the north of Streymoy. For each receiver, seismic velocities from shots to the north of the receiver tended to be higher than from shots to the south. Good S arrivals on a number of profiles allow reasonable V_P/V_S calculation. S-wave velocities ranged from 2.14 to 3.07, and V_P/V_S ratios from 1.83–1.92. Disagreement in the values of V_P and V_S between shots from the north and from the south at first suggested the possibility of dipping structure. Ray tracing and forward modelling indicated also that a

horizontal velocity gradient would be consistent with the observed difference in velocities between the north and south of Streymoy. Using V_P values from VSPs at Vestmanna and Glyvursnes, a suitable model was created, its boundary depths consistent with the Middle–Lower Basalt Formation (MBF-LBF) boundary in the geologic cross section of Waagstein (1988) or Japsen et al. (2005) (Figure 6).

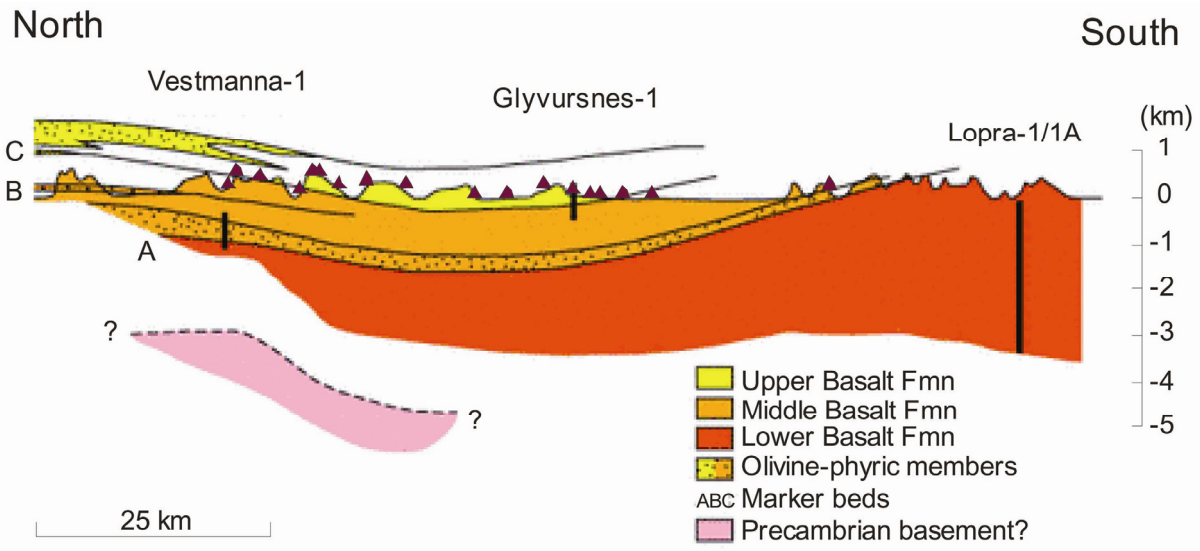

Figure 6. North-south section of the Faroe Islands showing the location of deep boreholes and seismometers (after Japsen et al., 2005; modified after Waagstein, 1988).

Ray tracing and forward modelling were carried out in Rayinvr, a forward traveltime modelling package, with an inversion component developed by Zelt and Smith (1992). The traveltimes for the wide-angle first arrivals from each seismic section were input to the model, which is parameterized by a series of layers described by boundaries at a user-defined number of nodes. The velocity of each layer is defined at the top and bottom, in order to impose a gradient. Raypaths were modelled as turning and head waves. Traveltimes were calculated for rays propagating through this model and the differences between the calculated and observed traveltimes were determined.

Preliminary findings

Rayinvr was run to test different velocity models: (a) a one-layer model with vertical velocity variation from 5.0 km/s at the top 5.25 at the base; (b) a one-layer model with a horizontal velocity gradient: 5.5 km/s down to 6.25 on the left, and 4.5 km/s down to 5.25 on the right; and (c) a two-layer model using VSP velocities (Shaw, 2008): 5.12 to 5.50 km/s at Vestmanna and 4.50 to 4.70 km/s at Glyvursnes; using published estimates of depths of the MBF-LBF. Figure 7 shows results for the two-layer model.

Conclusions and recommendations

Forward modelling and ray tracing indicate a velocity structure involving vertical and horizontal velocity gradients across uneven geological surfaces. One of the best-fitting models uses seismic velocities from VSP data for Glyvursnes and Vestmanna, imposing a vertical and horizontal velocity gradient and MBF-LBF boundary depths consistent with the geologic cross section of Waagstein (1988) or Japsen et al. (2005).

Reflection data is currently being processed by Hilmar Simonsen and Khanh Nguyen, and we will incorporate results from this work to provide better control on the velocities of the sediments as well as the basalts. Improvements to the seismic imaging are also foreseen. S-wave data will be included in the forward modelling of Vestmannasund to better constrain the models. Anisotropy analysis will also be carried out to investigate the possibility of azimuthal anisotropy related to preferred orientation of approximately vertical cracks or transverse isotropy due to horizontal lamination.

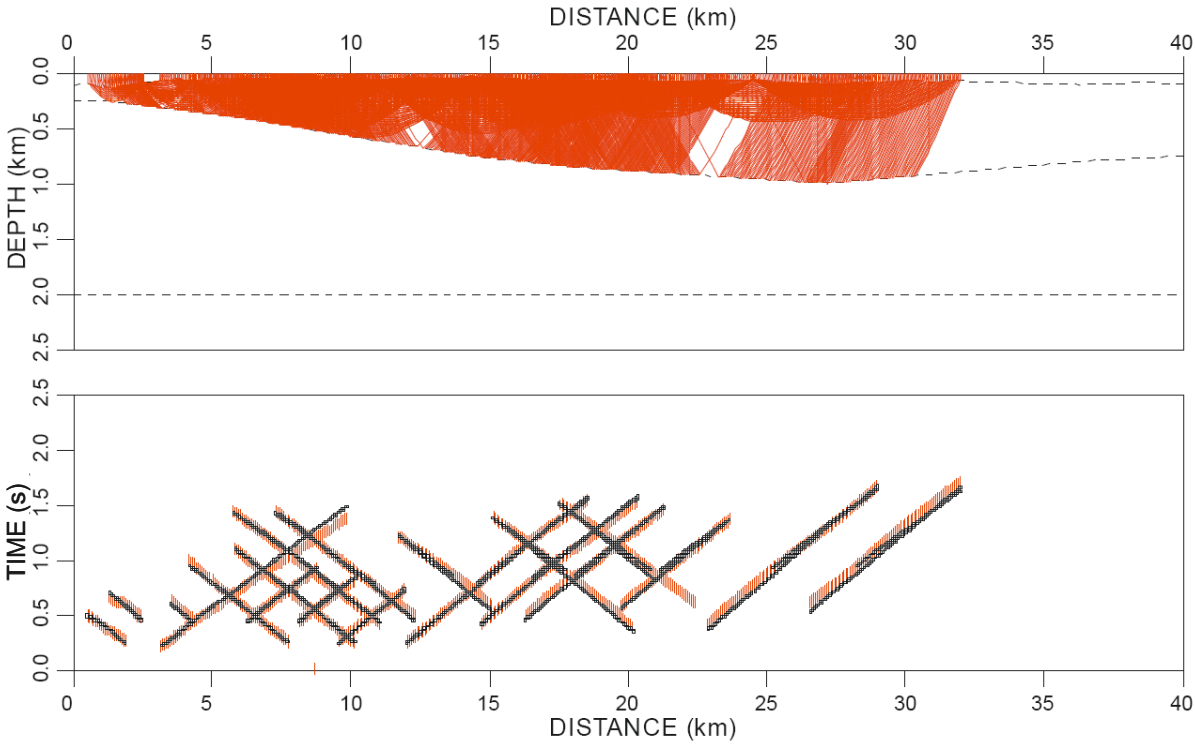

Figure 7. Graphical output from Rayinvr velocity models showing raypaths in red in the depth-vs-distance plot for a two-layer model using VSP velocities from Shaw et al. (2008) and interface depths from Japsen et al. (2005). Calculated traveltimes are plotted as black lines, observed (picked) times as red lines. Error bars showing accuracy of picks are estimated as ±50 ms. See Appendix for fits to individual receivers.

Publications

Kingsbury, J.L., White R.S., Simonsen, H., Nguyen, K.D., Brown, R.J., Andersen, M.S. and Petersen, U.K., 2007. Three-component wide-angle seismometer acquisition on the Glyvursnes-Vestmanna Seismic Tie (GlyVeST): 1st Jóannes Rasmussen Conference, 29–30 August 2007 (poster presentation).

Simonsen, H., Brown, R.J., Petersen, U.K., Andersen, M.S., Kingsbury, J.L. and White R.S., 2007. Hydrophone data acquisition along the Glyvursnes-Vestmanna Seismic Tie (GlyVeST): 1st Jóannes Rasmussen Conference, 29–30 August 2007 (poster presentation).

Kingsbury, Julia, 2007. Wide-angle seismic profiling of basalts, The Færøe Islands: University of Cambridge, M. Res. Report.

In preparation: A paper on processing and interpretation of wide-angle refraction-seismic profiling between the Glyvursnes and Vestmanna boreholes in the Faroe Islands

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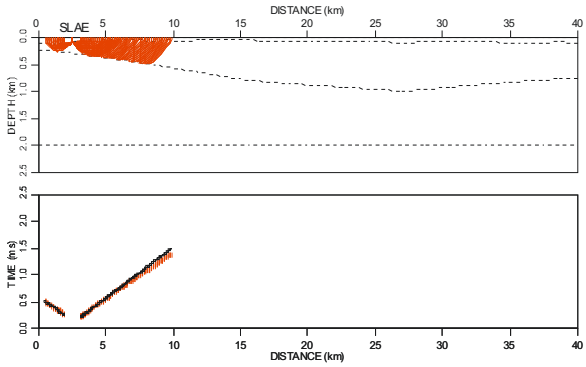
Appendix

Plots of Rayinvr output from individual receivers, showing the coverage and fit to the data for each one separately.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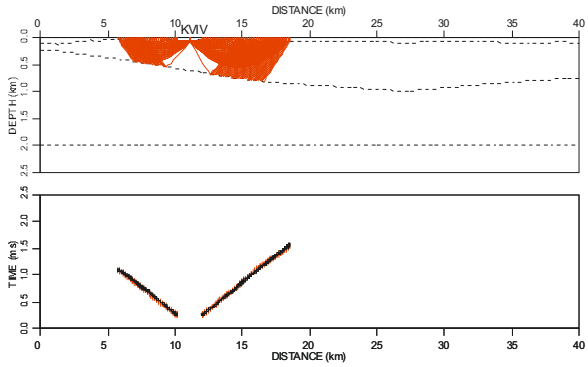
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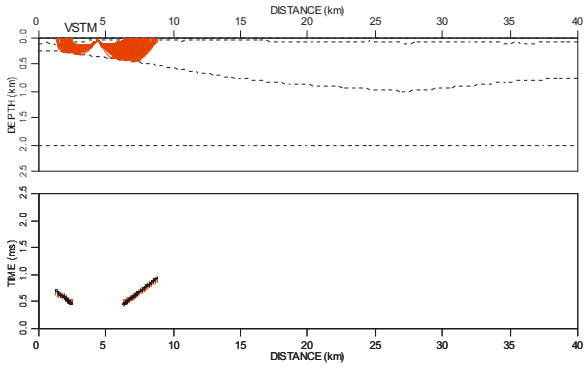
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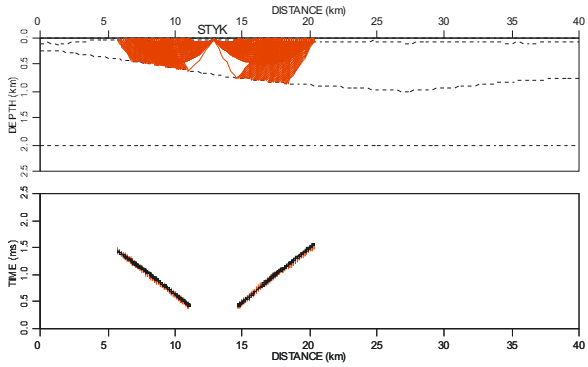
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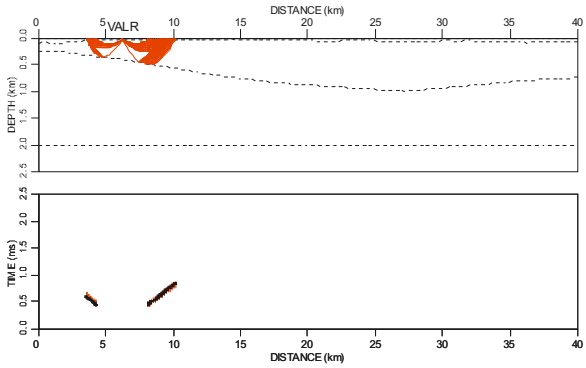
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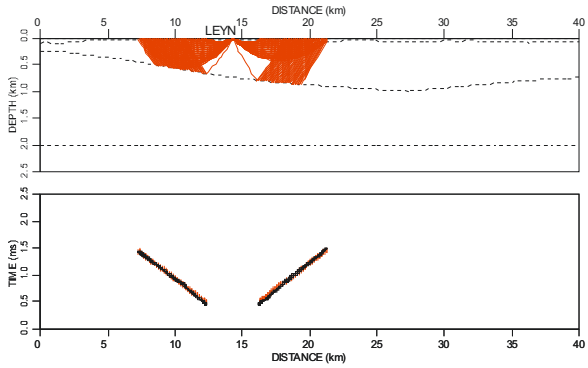
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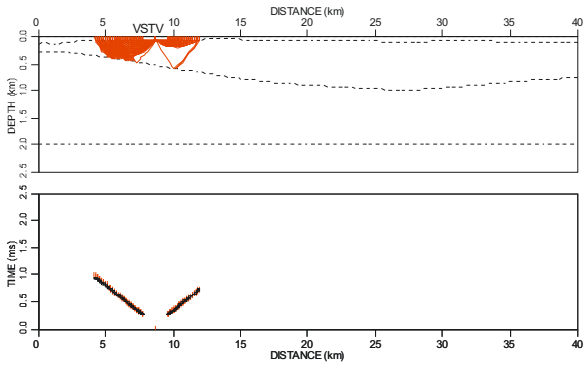
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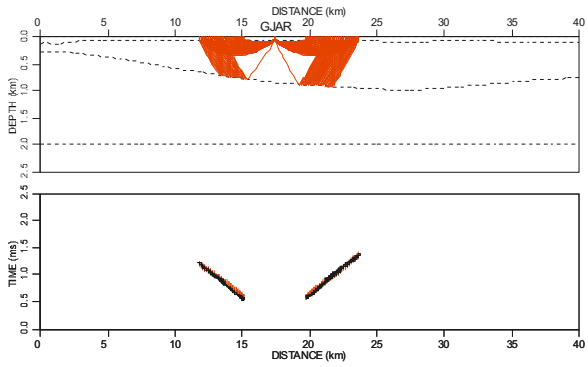
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