

Preliminary results from investigations of seismic and petrophysical properties of Faroes basalts in the SeiFaBa project

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Abstract: The development of methods of seismic imaging beneath basalts is still hindered by a lack of knowledge about the elastic properties of basaltic sequences and the degree of three-dimensional heterogeneity. The SeiFaBa project (2002–2005) is funded by the Sindri Group as part of the programmes for licensees within the Faroese area and will attempt to address these issues.

The Glyvursnes-1 well was drilled by SeiFaBa through the Upper Basalt Formation outside Tórshavn in 2002. A full core and numerous wireline logs were acquired from the 700 m deep well. During the same operations, the existing 660 m deep Vestmanna-1 well drilled mainly into the Middle Basalt Formation was reamed and logged. The two wells are central to a number of closely co-ordinated experiments, which are all targeted at creating models for seismic wave propagation through a succession of basalt by combining detailed analysis at core, log and seismic scales. Data from these two wells, in combination with the data for the Lopra-1 well drilled into the Lower Basalt Formation, will give new stratigraphic and petrophysical control of the Lower, Middle and Upper Basalt formations on the Faroes.

The seismic programme was initiated in 2002 and the main acquisition was carried out during 2003. The well site at Glyvursnes gives optimal conditions for combining VSP, offset-VSP and surface seismic experiments both onshore and offshore and the seismic effects of a nearby near-vertical shear zone can be studied in detail. Preliminary analysis of log data from the Lopra-1 well suggests that the acoustic properties of these basalt flows are mainly controlled by porosity of a stiff matrix filled with clay minerals and water. Further studies will allow for explanations of the sonic response of basalt in terms of physical and compositional properties and a better understanding of the seismic signatures of flood basalt successions.

Keywords: basalts, drill holes, Faroe Islands, petrophysics, seismic methods, sonic waves



DVD: Core display G2 is relevant to this chapter and can be viewed on the accompany DVD.

Flood basalt-covered basins exist world-wide along continental margins and are now targets for future hydrocarbon exploration. One such area is the Northwest European margin covering Norwegian, UK, Irish and Faroese waters, but similar cases include areas offshore Namibia, India, Brazil and West Greenland. Exploration strategies in Faroese waters are largely driven by the nearby British Foinaven Field, which is covered in the western part by basalt entering from the Faroese side (Roberts *et al.* 1999).

Offshore from the Faroe Islands it is generally difficult to image through the basalt cover by conventional seismic reflection methods. Alternative strategies include the use of wide-angle data from super-long offset profiles acquired with two seismic vessels (e.g. White *et al.* 1999, 2003), or, increasingly, with single 12 km long streamers; the use of seismic sources tuned to low

frequencies (White *et al.* 2002; Ziolkowski *et al.* 2003); deployment of ocean bottom receivers (e.g. Scrutton 1970); and the possibility of utilizing converted waves (Purnell 1992) (although the latter seems not to be viable according to work by Hanssen *et al.* 2003).

Surprisingly, it is, however, possible to image through kilometre-thick basalts on some conventional profiles; details of basalt stratigraphy are revealed on old, reprocessed seismic profiles as well as on recently acquired profiles even though the imaging may be unsuccessful on near-by profiles (Fig. 1; e.g. Boldreel & Andersen 1993; Roberts *et al.* 1999). This stresses the need for a better understanding of the acoustic and other physical properties of basalt as well as of the degree of three-dimensional heterogeneity (cf. Kern & Richter 1979). The SeiFaBa project ('Seismic

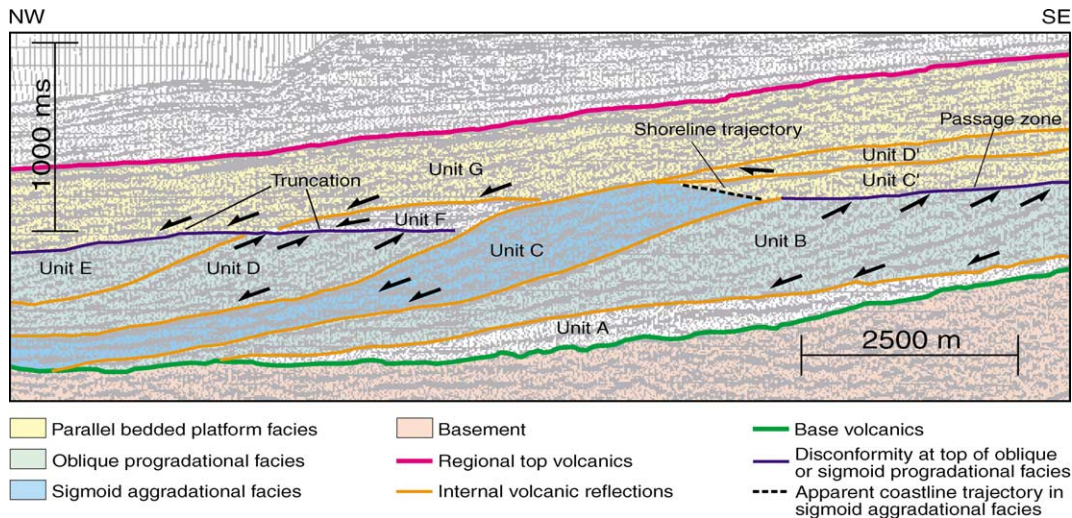


Fig. 1. Multi-channel reflection seismic profile across a basalt succession east of the Faroe Islands. Seismic stratigraphical principles can be applied in reflection seismic interpretation of the basalt succession and various units can be mapped. However, correlation between the seismic profiles of thick basalt offshore and the basalt formations onshore has proven difficult. With permission of BP. Originally published by Musgrove & Mitchener (1996), re-interpretation by M. S. Andersen (GEUS) and K. Hitchen (British Geological Survey).

and petrophysical properties of Faroes Basalt', 2002–2005) is funded by the Sindri Group as part of the programmes for licensees within the Faroese area and will address these issues with special focus on the subaerially extruded flood basalts.

The Glyvursnes-1 well was drilled to 700 m by SeiFaBa outside Tórshavn in 2002 (Fig. 2; Waagstein *et al.* 2003). During the same operations, the existing 660 m deep Vestmanna-1 well was reamed and logged. The purpose of the experiments at these wells is to provide a link from the hand-specimen scale of the core-log, through the slightly larger averaging of borehole logs to seismic scales. The seismic scales will range from high-resolution VSPs

and multi-channel land arrays, to onshore–offshore shooting using wide-band airguns, to the truly long-period response of the basalt flows using teleseismic arrivals recorded by a tight array of broadband (0.03–100 Hz) seismometers. Glyvursnes is suited for combining VSP and surface seismic experiments: the terrain is

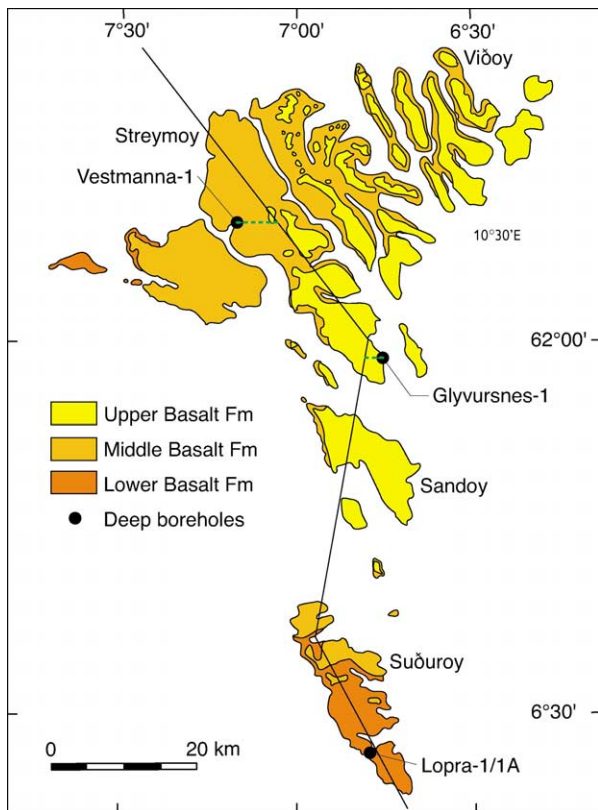


Fig. 2. Geological map of the Faroe Islands showing the location of deep boreholes, distribution of the three Palaeogene basalt formations and the line of section in Fig. 4 (modified after Waagstein 1998).

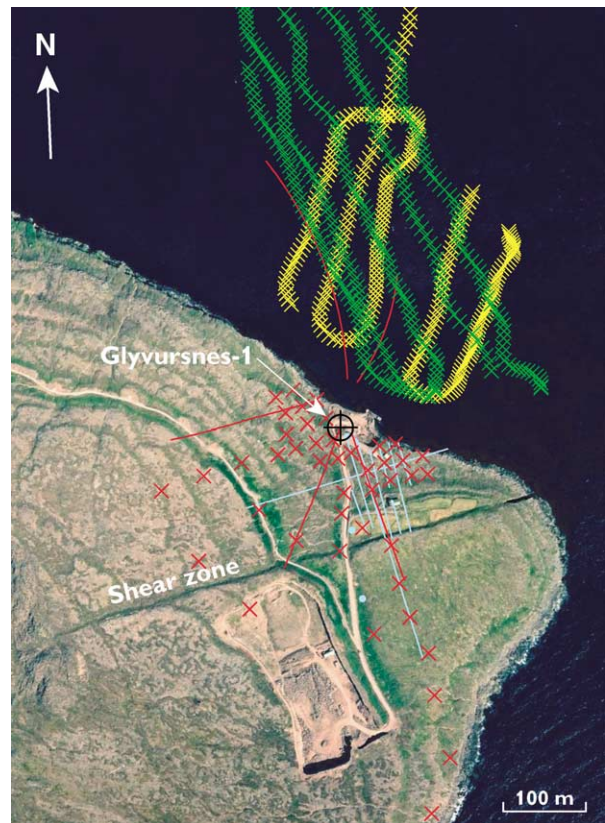


Fig. 3. Airphoto of Glyvursnes with well location and outline of seismic data recording in 2003. Red crosses indicate the locations of permanent seismometers during the experiments. Blue dots mark the positions of the three airgun pits for the VSP experiments. Blue lines mark the locations of the 14 Hz geophone strings used for the onshore reflection profiles. Red lines show the locations of onshore geophone strings and the tethered streamer during the offshore–onshore experiments and marine reflection experiment. Yellow and green crosses mark shotpoints for the marine reflection experiment.

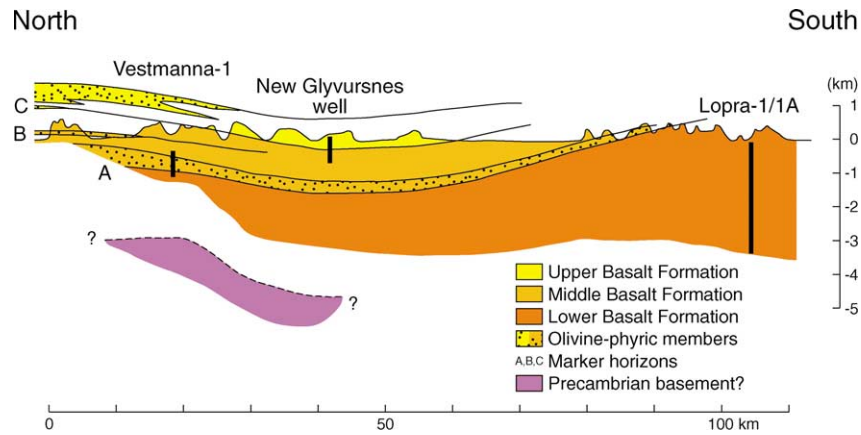


Fig. 4. North–South section through the Faroe Islands along the line in Fig. 2. The strata in the northern Faroes are partly extrapolated from exposures far west and east of the line of section. Projection of exposures and well stratigraphy (dashed lines) is due east–west along the regional dip. The top of the drilled section in the Vestmanna well thus projects below sea level (modified after Waagstein 1988).

relatively flat and the seismic effects of a nearby near-vertical shear zone can be studied in detail (Fig. 3).

The investigations will provide a unique dataset and new understanding of the petrophysical and seismic properties of Faroes basalt. The relations of sonic velocities of basalt to porosity, composition, stress, burial depth and fluid content will be studied through analysis of well logs and core material. This will allow for explanations of the sonic response of basalt in terms of physical and compositional properties and a better understanding of the seismic signatures of flood basalt successions.

Regional outline

Break-up of the North Atlantic in the Palaeogene was accompanied by widespread magmatism caused by interaction of the Iceland mantle plume with lithospheric rifting (White & McKenzie 1989). Massive lava flows extend away from the rifted margin across the hydrocarbon-bearing basins along much of the northern North Atlantic margin (Barton & White 1997). The Faroe Islands comprise a fragment of continental crust capped by up to 7 km of Palaeogene lavas produced during continental break-up and underlain by an underplated or heavily intruded lower-crustal region (Richardson *et al.* 1998, 1999).

Extrusive igneous rocks dominate the northwestern flank of the Faroes–Shetland Basin. Flood basalts created at the time of break-up between the Faroe Islands and East Greenland extend over >200 000 km² (Roberts *et al.* 1984; Andersen 1988; Waagstein 1988; Larsen *et al.* 1999), at least 40 000 km² of which lie in the Faroe–Shetland Basin (Naylor *et al.* 1999). The lavas flowed *c.* 150 km eastward away from the Faroes Islands, feathering out in the Faroes–Shetland Trough (White *et al.* 2003). The lavas are 59–55 Ma old and are divided into the Lower, Middle and Upper Basalt formations (Fig. 4; Rasmussen & Noe-Nygaard 1970; Waagstein 1988; Larsen *et al.* 1999; Waagstein *et al.* 2002).

The extensive cover of basaltic rocks around the Faroes is characterized by densities and seismic velocities that are high compared to sedimentary successions. Seismic facies analysis of a large dataset from the region show that the dominant lithology is parallel-bedded basalts that are comparable to the basalts exposed on the Faroe Islands where two contrasting lava morphologies are dominant (Figs 5 and 6).

- Aa flows are generally thick (10–50 m), with sediments and tuffaceous deposits in between. These thick-bedded basalts are characterized by systematic porosity variations within individual basalt beds and they dominate the Lower Basalt Formation. This lithologic succession is characterized by large,

systematic, internal variations of most physical properties (e.g. Planke & Eldholm 1994; Boldreel 2003).

- Pahoehoe flows are often of compound type, being made up of fairly thin basalt beds (about 2 m on average). The compound flows may be separated by thin beds of tuff. Thin-bedded basalts are dominant in the Middle Basalt Formation and part of the Upper Basalt Formation. The variation of physical properties, such as density and velocity, is moderate in this type of lava flow, but it is still significant compared to that of most sediments (e.g. Nielsen *et al.* 1984).

No systematic studies have been carried out on the elastic properties of thin-bedded basalts in the Faroe region and

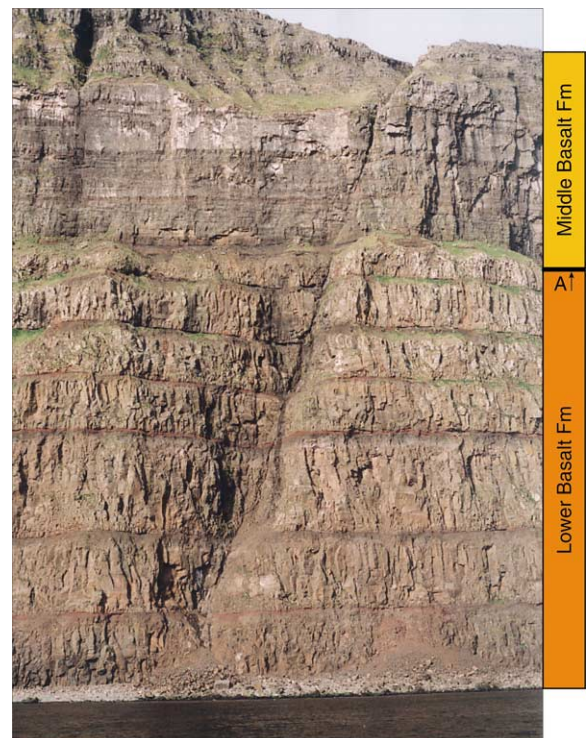


Fig. 5. Photo of contrasting lava morphologies exposed on a 400 m high cliff, Prestfjall, west coast of Suduroy (from Waagstein 1998). Thick simple aa flows (Lower Basalt Formation) overlain by compound thin-bedded pahoehoe flows (Middle Basalt Formation) with the coal-bearing A-horizon in between. The flows of the Lower Basalt Formation have a massive centre or core overlain by a thick purple to red rubbly crust and red tuffaceous clay.

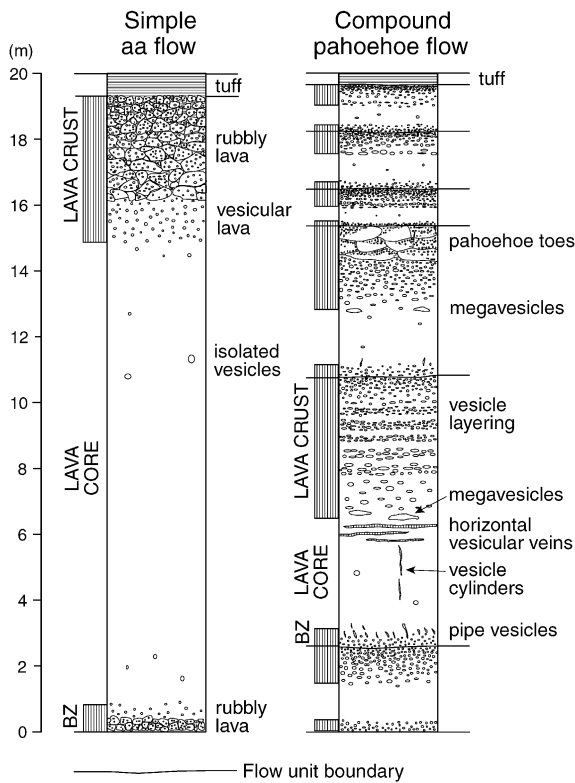


Fig. 6. Sketch of typical lava morphologies of the Faroes (from Waagstein 1998). Thick aa flows have non-vesicular cores grading into a rubbly top and base. Pahoehoe flows have smooth undulating tops and are typically compound, consisting of thin beds of variable thickness, vesicle abundance and mineralization.

understanding of the distribution of elastic properties in thick-bedded basalts is based on only a few studies (e.g. Kern & Richter 1979).

Drilling and logging at Glyvursnes and Vestmanna

The Lower, Middle and Upper Basalt formations are all exposed on the Faroe Islands due to late Cenozoic uplift and erosion (Andersen *et al.* 2002). Thick sections of each formation have been drilled by three deep onshore wells (Figs 2 and 4).

- The Vestmanna-1 well was drilled to 660 m in 1980 (Waagstein & Hald 1984) and re-opened to 590 m in 2002 and logged as part of the SeiFaBa project (Fig. 7). The hole is located 30 km northwest of Glyvursnes-1 in the lower part of the Middle Basalt Formation and extends 100 m into the Lower Basalt Formation. A full core was taken.
- The Lopra-1/1A well was drilled through the Lower Basalt Formation to 2.2 km in 1981 and deepened to 3.6 km in 1996 without reaching the base of the volcanics (Fig. 8) (Hald & Waagstein 1984; Nielsen *et al.* 1984; Kiørboe & Petersen 1995; Christie *et al.* 2002; Boldreel 2003). The upper 2.5 km are flood basalts and the remaining section is dominated by subaqueous hyaloclastites (Waagstein 2002). Six short cores of basalt were taken from this well.
- The Glyvursnes-1 well was drilled to 700 m in autumn 2002 as a slim borehole with wireline coring technique around the boundary between the Middle and Upper Basalt formations on the shore of Glyvursnes (Fig. 9). The drilling was carried out by the Finnish company Suomen Malmi (SMOY). A full core was taken (Fig. 10).

An extensive logging programme was run in the Glyvursnes and Vestmanna boreholes by Robertson Geologging in 2002, comparable to that previously run in the Lopra well (1981, 1996). It included optical televiwer, caliper, natural gamma, resistivity,

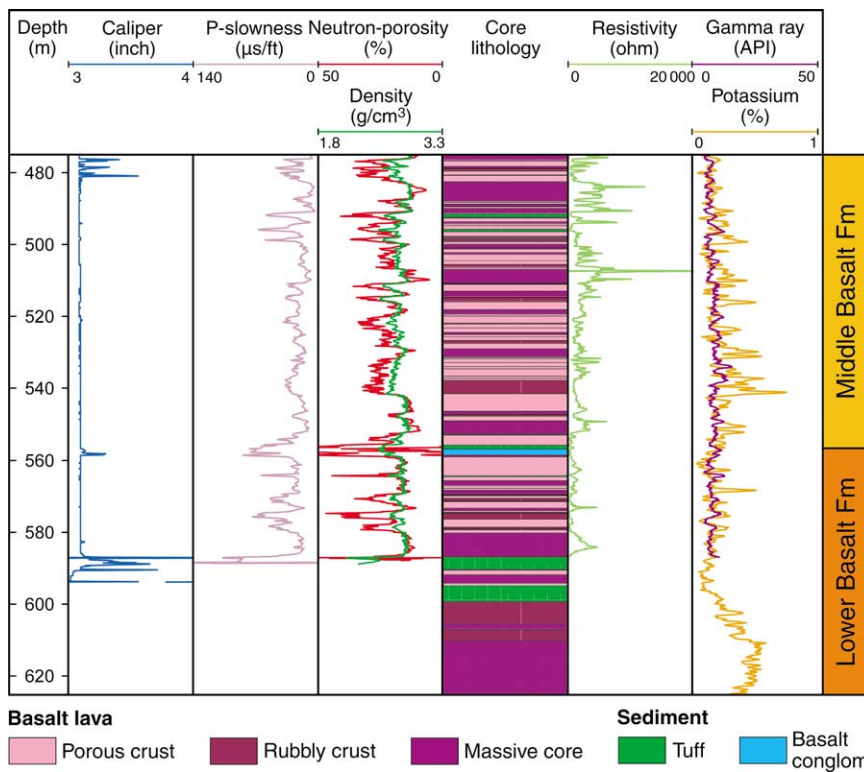


Fig. 7. Composite log from the lowermost part of the Middle Basalt Formation and the uppermost part of the Lower Basalt Formation in the Vestmanna-1 well measured after the re-opening of the well.

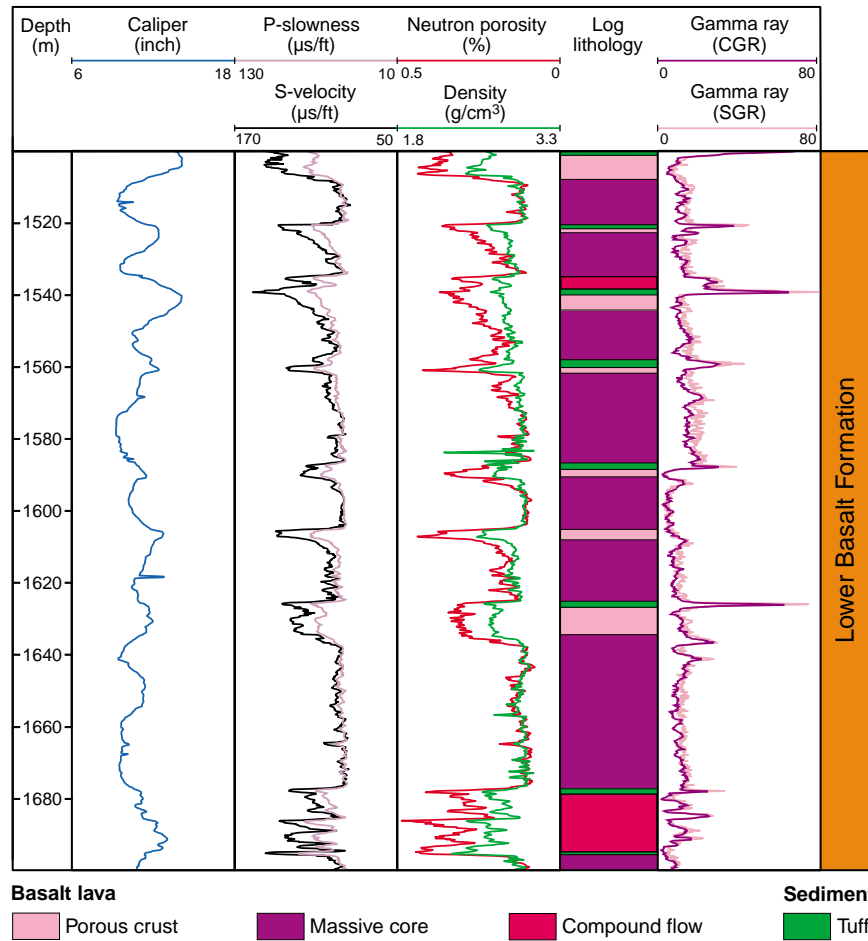


Fig. 8. Composite log from the Lopra-1/1A well. Note the variations in the physical properties within the individual lava flows. CGR, calculated (clay) gamma ray (Th+K); SGR, spectral gamma ray (Th+K+U). After Boldreel (2003).

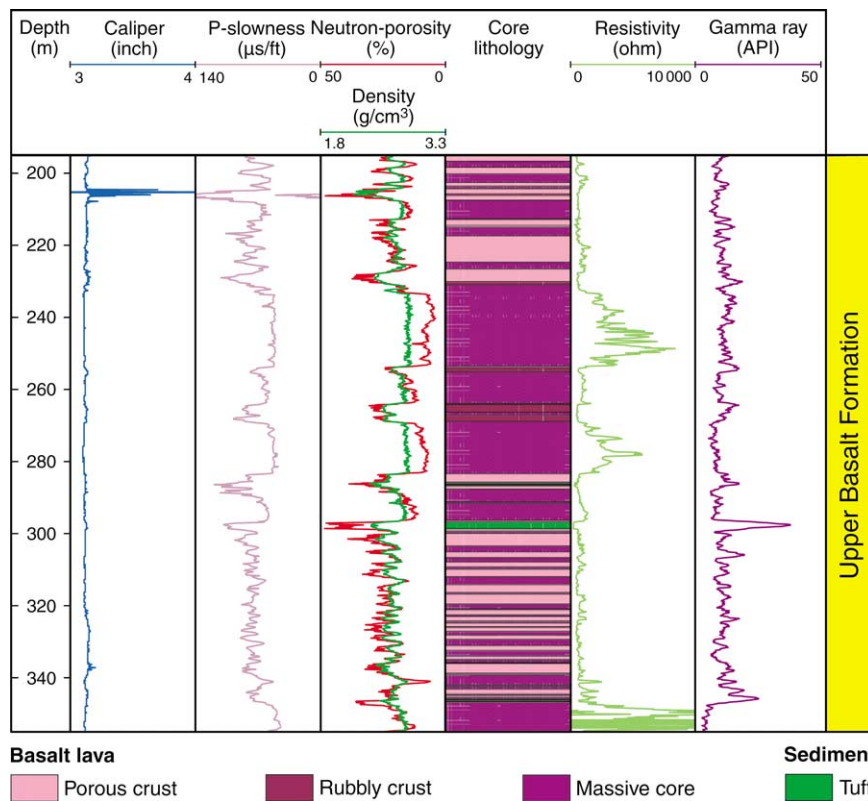


Fig. 9. Composite log from the Glyvursnes-1 well. Note the correlation between P-slowness (P-velocity) and density/neutron porosity that reflects the porosity contrast between the porous crust and the massive core of the basalt flows.

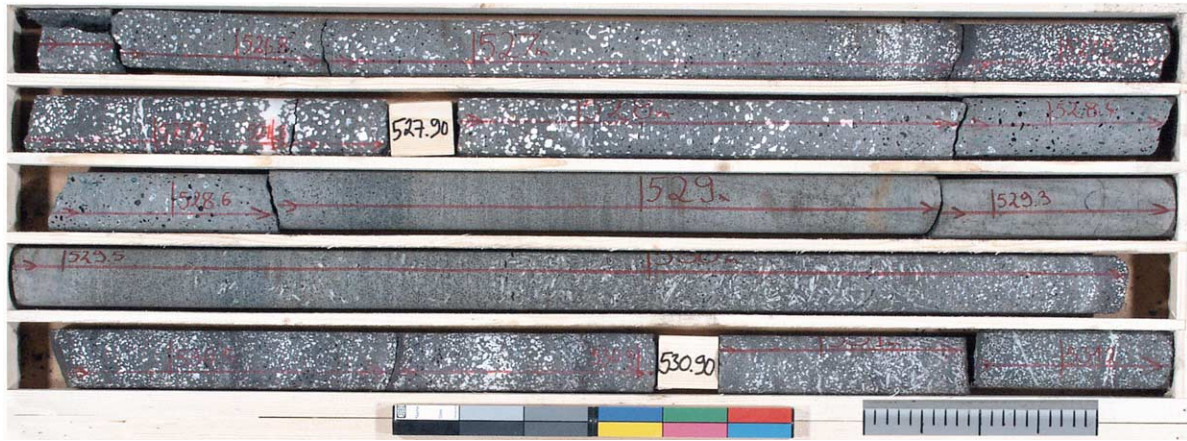


Fig. 10. Photo of the Glyvursnes-1 core in the interval 526.64–531.29 m (box 115), displaying strong variations in vesicularity and mineralogy of the lava flows. 526.64–527.41 m: vesicular, aphyric basalt (almost one complete flow-unit); 527.41–528.63 m: lava crust of vesicular, aphyric basalt with 1 cm thick dark top of altered glass (chill); 528.63–530.25 m: lava core of massive (i.e. non-vesicular), aphyric to plagioclase-phyric basalt; 530.25–530.69 m: basal zone of vesicular, sparsely plagioclase-phyric to aphyric basalt; 530.69–530.85 m, 530.85–531.12 m and 531.12–534.39 m: three vesicular flow-units of aphyric to plagioclase-phyric basalt, with 1 cm thick dark tops of altered glass (only 0.17 m of the lower unit shown). The vesicles are mainly filled with zeolites.

neutron porosity, density, full wave sonic, spectral gamma (of poor quality) and temperature/conductivity.

The Vestmanna and Glyvursnes boreholes penetrate the lowermost 550 m and the uppermost 450 m of the 1400 m thick Middle Basalt Formation, respectively. In both sections the Middle Basalt Formation is characterized by the presence of plagioclase-phyric compound flows composed of thin flow-units of variable porosity and by rare thin beds of tuff. The lowermost part of the Middle Basalt Formation in Vestmanna (Fig. 7) and the lowermost 70 m of the Upper Basalt Formation in the Glyvursnes borehole are very similar (Fig. 9). The overlying section between 230 and 285 m in Glyvursnes-1 consists of a few relatively thick plagioclase-phyric flow-units forming two (?) compound flows (the Tórshavn flows), which are morphologically more similar to the flows of the Lower Basalt Formation, although the latter are near-aphyric.

The Glyvursnes, Vestmanna and Lopra boreholes represent sections of increasing age and depth of burial. The Glyvursnes core displays variable degrees of mineralization of vesicles and voids, while the Vestmanna core is more completely mineralized (Jørgensen 1984). The depth of burial is clearly reflected by increasing palaeotemperatures as estimated from the zeolite parageneses found in Vestmanna and Lopra (Jørgensen 1984; Waagstein *et al.* 2002).

Rock physics properties of Faroes basalts

A preliminary investigation of the rock physics properties of flood basalt on the Faroes has been carried out based on the extensive logging data from the Lopra-1/1A well. A detailed stratigraphy of basalt flows, sediment/tuff layers and dolerite dykes was established for the hole drilled in 1981 based on drill cuttings and cores and compared with the density, porosity, resistivity and gamma-ray log-response (Hald & Waagstein 1984; Nielsen *et al.* 1984).

A more extensive logging programme, including a full wave sonic log was run in the deepened hole from 200 m to TD. The new logs have been used to establish a detailed stratigraphy for the flood basalt sequence between 200 m and 2500 m by dividing the lava flows into massive and porous parts (Boldreel 2003). The porous upper part of a flow is characterized by high values of the neutron porosity log, low values of density, low P- and S-velocities and intermediate values of the caliper. This, in contrast, to the rather massive part characterized by high values of density, high P- and S-wave velocities and low values of the neutron porosity. The basal zone is seldom identified due to the small vertical extent of the zone. In addition, 52 intervals with >1% potassium were

mapped at the flow boundaries and interpreted as altered basalt or tuffaceous sediments. These intervals were also identified from the high values of neutron porosity and caliper, in combination with low values of density, P- and S-velocity. Two dolerite dykes intruding the basalt column were identified by having the highest values of density, P- and S-velocities and lowest values of the neutron porosity. The logs show that large differences exist in acoustic properties within the basalt column and these are attributed to significant variations in porosity – both in the form of vesicles and fractures – across each flow unit.

The gamma-ray log for flood basalts in the Lopra-1 well reveals intermediate values for the porous crust (red curve in Fig. 11) and the massive basalt facies (blue). Systematically lower values are observed for the dolerite (magenta) and higher values for the tuffaceous sediments (green) in accordance with how this unit was defined. The bulk density log shows large fluctuations ($1.2\text{--}3.1\text{ g cm}^{-3}$), but the high-density limit of the curve increases only slightly with depth, while the low-density values are wildly fluctuating. It is believed that the high bulk densities are asymptotically approaching the mineral density as the porosity approaches zero, while the low density values vary with porosity, as well as caliper anomalies. The P-wave velocities have wide fluctuations ($3\text{--}7\text{ km s}^{-1}$), though there are systematic differences among the various facies: the tuffaceous sediments have the lowest velocities; the porous crusts have slightly higher velocities, the massive basalts are higher still, and the dolerites have the highest velocities.

P-velocities increase consistently with bulk density (and, therefore, decreasing porosity), with all four facies falling roughly along the same trend (Fig. 12). The sediments and crusts, being most porous, have the lowest velocities and densities. The massive basalts span a large range of velocity and density, while the dolerites seismically resemble the lowest porosity basalts. Superimposed on Figure 12 are empirical upper bounds on density and velocity (black lines), which are taken as estimates of the mineral properties. These values are consistent with a mineral having properties similar to a mixture of plagioclase and pyroxene (Table 1). Note that the upper density limit for the dolerite is slightly below the limit for the massive basalt. This is in agreement with the relatively low iron content of the dolerite observed from rock chemistry of cuttings from the well (Hald & Waagstein 1984).

P-velocities decrease consistently with increasing neutron porosity, with all four facies falling approximately along the same trend (Fig. 13). This supports the idea that porosity is the dominant parameter controlling the velocity, even though neutron porosity depends on both the free water in the pore space and the

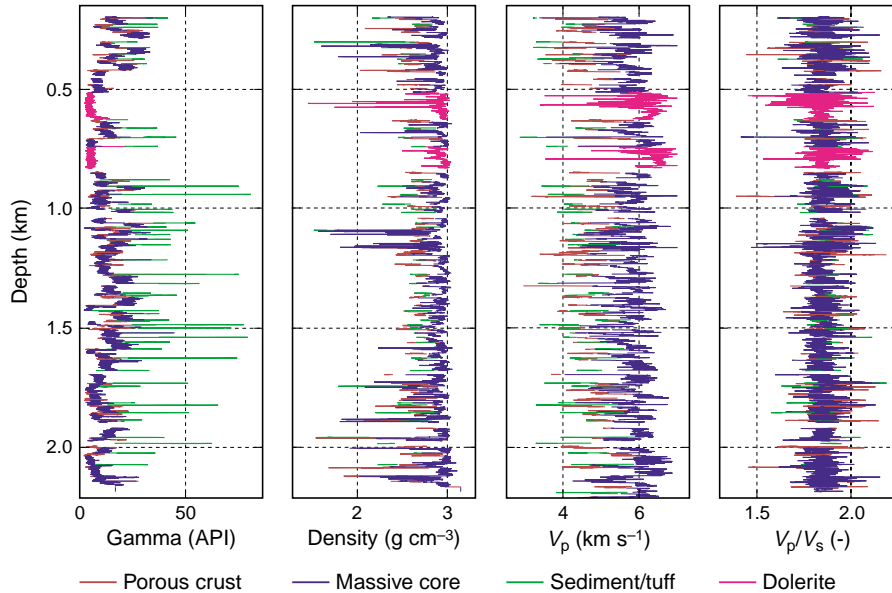


Fig. 11. Log data for the flood basalt sequence in well Lopra-1 above 2.2 km. The colour-coded lithological facies were interpreted by integrated log analysis (after Boldreel 2003). Sediment/tuff interbeds are intervals with > 1% potassium.

water bound in clay minerals. The Lopra-1 data can be compared with effective medium models for velocity vs. porosity, computed using Berryman’s (1980) formulation of the self-consistent approximation where the pores are assumed to take the shape of oblate spheroids, having varying aspect ratios. While spheroidal inclusion models are idealized, the trends of decreasing pore stiffness with decreasing aspect ratio make physical sense. The overall trends of the various facies can be represented with pores that are nearly spherical (aspect ratio 1) or slightly flattened (aspect ratio 0.3), as one might expect for vesicular basalts. Those data that fall at velocities significantly below these trends are consistent with the occurrence of fractures, which can be represented with very low aspect ratios.

V_p and V_s are highly correlated as one would expect for a fixed mineral composition and it is observed that all four facies fall along the same narrow trend (nearly constant Poisson’s ratio of 0.3; Fig. 14). High-velocity points lying to the upper right are dominated by the mineralogy, while porosity increases along the trend to the lower left, where the low-velocity points are dominated by the pore fluid.

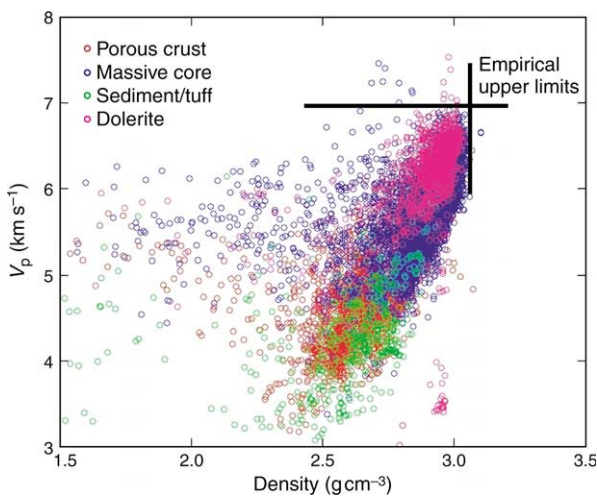


Fig. 12. Cross-plot of V_p vs. density for flood basalts in well Lopra-1. The black lines are empirical upper limits which are taken as rough estimates of the mineral properties (cf. Fig. 14; Table 1).

The seismic experiments at Glyvursnes

Although the extrusive basalt flows in the Faroes–Shetland Basin are generally sub-horizontal on a large scale, there are often large physical property variations (largely governed by porosity) within individual flows and sometimes locally rugged small-scale relief on the tops of flows. The strong layering and local rugged relief may cause some or all of the following: internal multiples, forward-and backscattering of the incident energy, multiple mode conversion, anisotropy, absorption and geometric spreading and low-pass filtering of the energy that propagates through a stacked layer of basalt flows.

Since flow thicknesses are an order of magnitude or more smaller than the seismic wavelength, reflections are rarely seen from individual flows: the seismic response depends on the complex interactions of reflections off multiple flow units (e.g. Planke & Eldholm 1994; Smallwood *et al.* 1998). In the specific case of the Faroe basalts, synthetic sections representing multiple flows show that the reflectivity pattern and average velocities vary between the Lower, Middle and Upper Basalt formations, which each have distinctively different average flow thicknesses and properties. To study these effects, three experiments were carried out around the Glyvursnes-1 borehole in 2003.

- (1) Three VSP surveys with source offsets of 14 m, 242 m and 415 m. The source was a 150 in³ (2.46 l) air gun deployed in water-filled pits. The two offset locations were on either side of a well-defined dyke/fracture zone.

Table 1. Physical properties of typical rock-forming minerals and empirical upper limit for flood basalts estimated from log data, Lopra-1 well (Figs 12 and 14; Mavko *et al.* 1998)

	Density (g cm ⁻³)	V_p (km s ⁻¹)	V_s (km s ⁻¹)	Bulk modulus (GPa)	Shear modulus (GPa)
Pyroxene (Augite)	3.26	7.22	4.18	94	57
Plagioclase (Albite)	2.63	6.46	3.12	76	26
Olivine	3.32	8.45	0.49	130	80
Flood basalts, Lopra-1	3.07	6.95	3.75	91	43

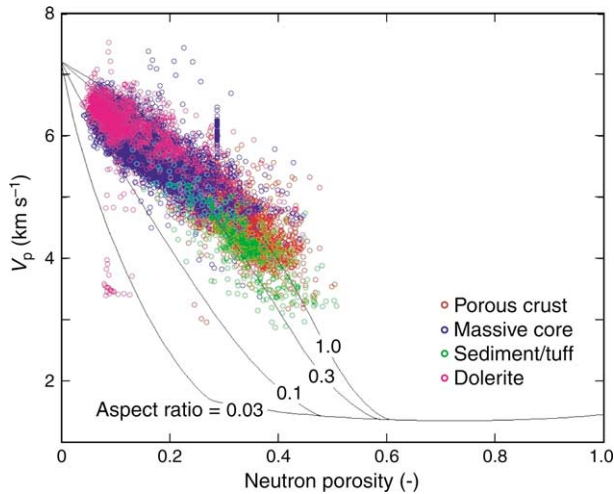


Fig. 13. Cross-plot of V_p vs. neutron porosity for flood basalts in Lopra-1 well. The overall trend of the lithological facies can be represented by pores that are nearly spherical (aspect ratio 1) or slightly flattened (aspect ratio 0.3). Solid black curves are effective medium models assuming ellipsoidal inclusions of four different aspect ratios based on mineral properties similar to pyroxene (Table 1; Berryman 1980).

- (2) Onshore and offshore high-resolution reflection data acquisition along the lines shown in Figure 3 (0.5 ms sample interval and 3 s recording length). All of the onshore reflection seismic data were acquired with 10 m shot spacing (250 g charges) and 5 m geophone spacing using 14 Hz 1-component geophones. The two 625 m lines were shot with the charges along the line, while the short profiles were acquired with the source displaced laterally with 25 m, 50 m or 75 m offset relative to the geophone string. The marine seismic reflection data were acquired on a tethered streamer using a moving 160 in³ (2.62 l) air-gun cluster. Additional data were acquired at longer offsets, using both the 160 in³ (2.62 l) source and a 860 in³ (14.09 l) source.
- (3) A dense array of 45 autonomous Guralp (6TD) seismometers was deployed for a six-month period around the site of the borehole. During the periods of controlled source seismic shooting, all sites maintained a sampling rate of 200 samples s⁻¹. For intervening periods when they were recording earthquakes, a sampling rate of 100 samples s⁻¹ was used. In addition, three

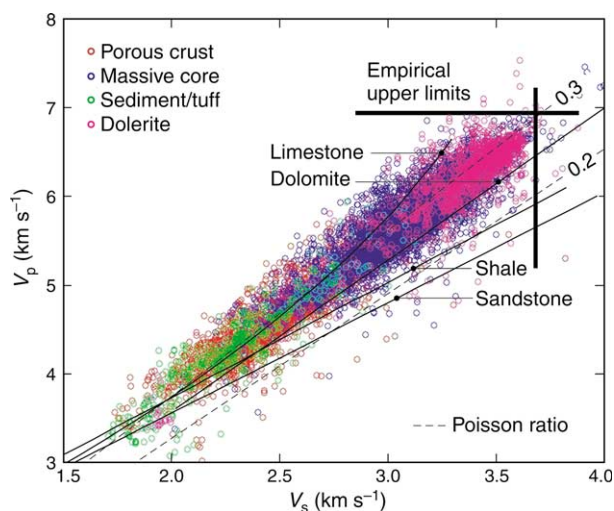


Fig. 14. Cross-plot of V_p vs. V_s for flood basalts in Lopra-1 well. Empirical lines for different sediments are shown for reference (solid lines; Greenberg & Castagna 1992). Dashed lines represent constant Poisson's ratio. Thick lines are empirical upper limits which are estimates of the mineral properties (cf. Fig. 12; Table 1).

400 m long (120 channel) independent temporary land arrays were set up in September 2003 using a mixture of one- and three-component geophones.

Throughout acquisition of the marine reflection seismic and the offshore–onshore, wide-angle seismic data, a three-component borehole seismometer was held clamped at 400 m in the Middle Basalt Formation in the Glyvursnes borehole.

The three experiments are closely integrated. During analysis, it will be possible to combine data recorded by the three-component borehole seismometer with sub-critical reflection gathers, measured by the streamer, and post-critical events, measured by both the temporary and autonomous array. The characteristics of wave propagation, including P- and S-wave response, anisotropy, absorption and scattering may be investigated in detail and at different scales. Recording of teleseismic phases by the autonomous array will make it possible to explore the response of the layered basalt flows to a wider spectrum of frequencies than that provided by the air-gun sources alone. It will thus potentially be possible to measure the crustal thickness and evaluate evidence for underplating from receiver function analysis.

Future work

Ultrasonic velocities and other parameters will be measured on core samples from drill holes in the Faroe Islands. The samples will be investigated under varying pressure for both dry and saturated samples. The investigations of the velocity–porosity relations of basalts will focus on matrix properties but will also take into account variations in magma type, secondary mineralization, pore shapes and fractures.

Lithostratigraphic interpretation of logs will be carried out and the results correlated with petrography, rock chemistry and rock physical lab measurements of core samples for scaling of the core and log data to a seismic scale for data from flood basalts of all three formations. Well log data will be examined to find how magma type and secondary mineralization influence the relation between velocity and porosity of basalt. Supplementary analysis of well logs from commercial wells in the Faroe–Shetland Basin will be carried out to provide additional data concerning the distribution of elastic properties of the basalts around the Faroes.

Future work on seismic field data will include:

- VSP data processing to extract up and downgoing wave fields at both sites and matching with synthetic seismograms derived from log data;
- analysis of offset VSP data at the sites of Glyvursnes-1 and Vestmanna-1 to investigate evidence for velocity and attenuation anisotropy;
- investigation of causes of noise and aberrations in the images;
- investigation of causes of P- to S-mode conversion, anisotropy and shear wave imaging at both sites;
- specific investigation of causes of seismic attenuation (intrinsic, scattering) in core, log and VSP data;
- investigation of seismic characteristics of a well-defined fracture zone exposed at the Glyvursnes locality in VSP and surface seismic data. Reflection, transmission, attenuation and scattering as a function of azimuth and incidence angle;
- seismic modelling of attenuation and the seismic signatures of flood basalt successions for typical variations in thickness and internal structure of individual lava flows and volcaniclastic beds.

Summary

Drilling of the new borehole at Glyvursnes and re-logging of Vestmanna-1, in combination with the extensive dataset for the Lopra-1 well, will give valuable new stratigraphic and petrophysical control of the Lower, Middle and Upper Basalt formations on the Faroes.

Preliminary analysis of log data from the flood basalts in the Lopra-1 well suggests that the acoustic properties of these basalt flows are mainly controlled by porosity and the high correlation between P- and S-velocities may be indicative of a constant mineralogical composition for the Lower Basalt Formation. The new data acquired for the Upper and Middle Basalt formations may reveal how the acoustic properties of these formations differ from those of the Lower Basalt Formation.

The planned experiments will provide a link from the hand-specimen scale, through the slightly larger averaging of borehole logs, to seismic scales ranging from high-resolution VSPs and multi-channel land arrays, to onshore–offshore shooting using wide-band air guns, to the truly long-period response of the basalt flows using teleseismic arrivals.

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