

# **Reconstructing flood basalt lava flows in 3D using terrestrial laser scanning**

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## **ABSTRACT**

We present a new method for reconstructing flood basalt lava flows from outcrop data, using terrestrial laser scanning (TLS) data to generate virtual outcrops. Case studies are presented from the Faroe Islands and the Isle of Skye (UK), both part of the North Atlantic Igneous Province (NAIP). These were analysed to pick out lava flow tops and bases, as well as dykes, lava tubes and sedimentary layers. 3D surfaces were then generated using the GSI3D software, a modelling package developed by the British Geological Survey (BGS) and Insight GmbH, and 3D geological models constructed. Finally, the models were interrogated to give data on flow thickness and crust to core ratio.

The aim of this research is to obtain quantitative data on the internal heterogeneity of a sequence of flood basalt lava flows, and to provide high resolution information about flow geometries and volcanic facies variations in 3D. Lava flow sequences display complex stacking patterns, and these are difficult to understand from photos or outcrop observations. Laser scanning allows us to study inaccessible outcrops, while avoiding the perspective distortion in conventional photography. The data from this study will form part of larger models of flood basalt provinces, which will be used to improve seismic imaging in areas of basalt cover, and aid our understanding of facies architecture in flood basalts.

## INTRODUCTION

Flood basalt volcanology has developed significantly over recent years, with studies moving from more traditional geochemically-driven research to the development and understanding of emplacement models (e.g. Self et al., 1997), studies looking at the facies architecture of the volcanic units (e.g. Passey and Jolley, 2009; Passey and Bell, 2007; Single and Jerram, 2004), and the types and distributions of volcanic units in offshore environments (e.g. Planke et al., 2000; Jerram et al., 2009). Much of this research has been driven by a realization that the internal architecture of flood basalt provinces is not a simple layer-cake sequence (Jerram and Widdowson, 2005). Moreover, the internal architecture is heterogeneous and complex, with a variety of different stacking patterns. These can be observed at a number of scales, and vary both laterally and vertically. The aim of this work is to identify and quantify the 3D facies variations present in flood basalt outcrops, and this is facilitated by the use of terrestrial laser scanning.

Recent advances in mapping technology have permitted the construction of 3D “virtual outcrops” (McCaffrey et al., 2005; Xu et al., 2000), allowing accurate measurements of an outcrop in a digital environment. These studies use high resolution laser scanning to capture the geological landscape in a format that can be manipulated in 3D, in order to interpret the internal facies and facies variations within the rocks. The term “virtual outcrop” has come to mean a 3D triangulated mesh with a draped photograph, providing an easily interpreted representation of the original outcrop. Such 3D geological models are used in areas such as fluid flow modeling (e.g. Rotevatn et al., 2009) and reservoir modeling (Pringle et al., 2004). Until recently much of the work developing and using virtual outcrops has been aimed at sedimentary problems (e.g. Bellian et al. 2005; Labourdette and Jones, 2007), and

structural problems (McCaffrey et al., 2008), with few examples in the field of volcanology. Previous studies have documented in detail the workflow used to capture and process TLS data (e.g. Buckley et al. 2008; Enge et al. 2007). Our workflow mostly follows that of previous studies with slight site-specific variations highlighted in the text. Strictly, our models are not virtual outcrops in the sense that no triangulated surfaces are made, but they represent the outcrop in a digital format allowing interpretation.

In this study, we construct the first 3D point clouds of flood basalt lava flows from terrestrial laser scanning data, and use the GSI3D software (Kessler et al., 2009) developed by the British Geological Survey (BGS) to construct 3D geological models of lava flows. This allows the accurate measurement of the size and shape of multiple flows, and the reconstruction of flow tops and flow bases between outcrops. Locations of the case studies are shown in Figure 1. We also discuss the potential of this approach for further volcanological studies.

### **3D geological models and facies analysis**

This study is motivated by a need for more accurate characterization of flood basalt lava flows in 3D. Hydrocarbon exploration is increasingly focusing on volcanic rifted margins associated with flood volcanism. In the North Atlantic, many potentially prospective sedimentary basins extend under areas of flood basalt lava flows (e.g. the Faroe-Shetland Basin, Naylor et al., 1999) where seismic imaging provides poor results compared to most other rock types. Much research has focused on optimizing exploration strategies to improve seismic imaging, using methods such as collecting wide-angle or long-offset seismic data, and these have met with some success (e.g. Roberts et al., 2005).

However, seismic imaging is still hampered by the very heterogeneous nature of a basalt sequence, and this is one of the largest challenges to successful imaging. The large difference in rock properties (P-wave velocity or  $V_p$ , density and so on) between the core and crust of a basalt lava flow leads to a very variable velocity profile. This causes scattering and attenuation of the seismic wave, especially at high frequencies, and as a result little energy is returned from below a basalt sequence. Images of sedimentary sequences below the basalt are therefore poor.

The work presented here allows quantification of this heterogeneity by creating detailed 3D geological models which can then be populated accurately with rock properties such as  $V_p$ , density or acoustic impedance. The shape, size and internal structures within flood lavas also provide important information for volcanological research (e.g. Single and Jerram 2004).

Although outcrops provide high resolution data, the scale at which they are exposed is typically in the region of hundreds of metres. Therefore to make outcrop scale observations and models applicable to an entire province (that may be hundreds of kilometres in extent) the use of facies analysis can be employed. A number of volcanic facies have been identified that are found in many flood basalt provinces (Jerram, 2002), and each facies displays common physical characteristics. The two major facies types encountered in this study are compound-braided lava flows and tabular-classic lava flows, both of which occur in large volumes in the NAIP. Compound-braided lava flows are thin (<3m), anastomosing flows of limited lateral extent. Tabular-classic flows are much thicker (up to several tens of metres) and may extend for 10s to 100s of kilometres. They have a simple internal structure of a massive flow core and a vesicular, fractured crust, as shown in Figure 2. Tabular-classic and compound-braided flows are often found close together, either vertically

or laterally, probably related to changes in lava eruption rates and volumes. Other facies types include intrusions, ponded flows and volcaniclastic sediments, all of which are present throughout the NAIP. Volcanic facies are described in more detail in Nelson et al. (2009) and Jerram (2002).

### **Case studies**

In order to test the applicability of TLS to the study of flood basalt facies, and the potential for successful reconstruction of lava sequences, we selected two case studies. Both are located within the North Atlantic Igneous Province, and are taken to be representative of compound-braided flows both onshore and offshore in this province. It was important that the case study areas met certain criteria to make a successful 3D model, including:

- Detailed facies architecture in 3D.
- Composed of typical flood basalt facies.
- Being of a scale that our equipment could cope with, and having good accessibility to enable the heavy laser scanning equipment to be relatively easily deployed.

The first case study, located near Ljosa, Eysturoy, Faroe Islands, is a quarried outcrop approximately 75m by 20m. Its location is shown in Figure 1. It is an extremely well-exposed section through compound-braided lava flows, comprising two flows which extend across the entire outcrop and several more which pinch out within the exposure. It is not a true 3D exposure as the two faces are at right angles, but a 3D model can be built by extending the interpretations laterally. The relative simplicity of the flow geometries and the small number of flows made this an excellent case study for developing the methods used in this work.

The second case study is located in Talisker Bay, Skye, Scotland (Figure 1). Here, two sea stacks and a cliff section display well-exposed sections through a lava sequence. This location had previously been mapped in detail by Single (2004) which aided our interpretations (also see Single and Jerram 2004). We selected this location because the sea stacks and the cliff section contain exposures of the same lava flows, and it is therefore possible to correlate between them. This allowed us to build a comprehensive 3D geological model once the data had been collected. The tidal nature of this location did, unfortunately, limit the amount of data we were able to collect, as well as posing a logistical problem.

### **The GSI3D software**

GSI3D (Geological Surveying and Investigation in 3 Dimensions) has been developed by the BGS and INSIGHT GmbH, and is now used extensively by the BGS for the construction of detailed 3D geological models. GSI3D uses cross-sections, mapped outlines and a digital terrain model to produce a solid model made up of triangulated objects. Its main function is to produce 3D geological models from existing geological maps and borehole data (e.g. Kessler et al., 2009). For example, detailed models of quaternary sediments have been constructed to give information on groundwater flow (Lelliott et al., 2006).

To produce a 3D geological model in GSI3D, the user must first construct cross-sections through the units of interest. Then, the outline extents must be defined in a map view. Once these have been defined, the software triangulates surfaces satisfying the cross-sections and map extents, and the DTM forms the top of the model. All these steps are fully controlled by the user, allowing the user to apply their geological knowledge to construct a realistic final model. This level of control makes the

software potentially ideal for use with TLS data, and one of the additional goals of this study is to test the use of TLS data within the GSI3D environment. The process of constructing the models is described in detail below.

## **GEOLOGICAL SETTING**

In this section, we briefly review the geological setting of the two case studies, putting them into their regional context. Both case studies are located within the North Atlantic Igneous Province (NAIP), a large igneous province with an approximate areal extent of  $1.3 \times 10^6 \text{ km}^2$  (Eldholm and Grue, 1994). Map locations are shown in Figure 1. The NAIP consists of a variety of facies including flood basalt lava flows, thick hyaloclastite sequences, central volcanoes, sills and dykes. The majority of the flood basalt sequences were emplaced between 60.5Ma and 54.5Ma (Jolley and Bell, 2002), however subaerial volcanism continues in the North Atlantic to the present day in Iceland.

### **The Faroe Islands study area**

The Faroe Islands are almost entirely formed of the Faroe Islands Basalt Group (FIBG), part of the NAIP, which was emplaced between approximately 60.6 and 57.5Ma (Ellis et al., 2002). The FIBG is subdivided into four main volcanic formations: from uppermost to lowest, the Enni, Malinstindur, Beinisvorð and Lopra formations (Passey and Jolley, 2009). The formations display a variety of facies: the Enni Formation contains tabular-classic and compound-braided lava flows; the Malinstindur Formation mainly contains compound-braided flows and the Beinisvorð Formation is dominated by tabular-classic flows. The Lopra Formation is known only from the Lopra 1/1A borehole (Berthelsen, 1984; Chalmers and Waagstein, 2006) and

is dominated by hyaloclastites. For a comprehensive description of the FIBG and a discussion of its emplacement mechanisms, see Passey and Bell (2007).

Our case study is located on the island of Eysturoy, within the Malinstindur formation. The quarry near Ljosa cuts through a sequence of thin (up to 3m) compound-braided basaltic lava flows, giving excellent exposure. The flow cores and crusts are easily identified, and the location is an excellent example of the complex flow architecture of the compound-braided facies.

## **Skye**

The Isle of Skye, located off the west coast of Scotland, contains excellent exposures of flood basalt lava flows forming part of the NAIP. The Skye Lava Field covers much of the island, with the main sequence erupted between ~61-59 Ma, and in the west of Skye this can be divided into three sequences based on facies types (Single and Jerram, 2004). These are: lower compound-braided lavas; transitional lavas; and upper tabular lavas.

The Talisker Bay case study is located in the Minginish district on the west coast of Skye, within the lower compound-braided lavas. This area has been mapped in detail by Single (2004) and it is also the basis for a fine-scale facies classification scheme for flood basalt lava flows (Single and Jerram, 2004). In this study, we incorporate these detailed observations into a 3D reconstruction.

## **DATA COLLECTION AND PROCESSING**

Figure 3 summarises the steps followed to produce the 3D geological models. Data collection is followed by interpretation, surface construction and finally model interrogation.



## **TLS data collection**

Terrestrial laser scanning has become increasingly popular amongst geologists, as it allows 3D data to be captured which can be analysed away from a field situation. 3D point clouds thus obtained can be analysed to provide quantitative structural or geological data (e.g. McCaffrey et al. 2005, 2008). The laser scanner measures the XYZ coordinates of points on the outcrop at specified intervals. These points can then be coloured from digital photos to give an accurate representation of the outcrop, which can then be viewed from any angle and features on it can be measured. This is particularly useful for inaccessible parts of outcrops. Multiple scans from different angles are obtained to minimise shadow areas where parts of the outcrop hide other areas from the scanner viewpoint. Reflectors are used to provide common points of reference between scan and photo, and between scans.

Data for this study were collected during fieldwork in June 2007 (Faroe Islands) and September 2008 (Skye) using a Riegl LMS-Z420i terrestrial laser scanner combined with a calibrated Nikon D70 digital camera. The Z420i equipment is capable of an accuracy of up to 10mm and a precision of up to 4mm (<http://www.riegl.com>). The scanning range can be up to 1000m for highly reflective objects, however the maximum range falls as the reflectivity of the target decreases. We found that the dark colour of weathered basalt and the often wet nature of the outcrops reduced the range to less than 200m, suggesting the reflectivity is likely to be 10% or less based on data from <http://www.riegl.com>. The camera has a resolution of 6MP, and lenses with a variety of focal lengths are available to produce the best possible picture.

## **Ljosa quarry**

At this location, three scans were required to collect all the required data. The quarry is extremely well-exposed, and the surfaces are relatively smooth. This means there are few shadow areas to cause problems, and the three scans were required primarily to obtain good photos for interpretation. Figure 4 shows the quarry layout and the scan setup. The three scans collected a total of approximately 8,600,000 points, at an angular resolution of  $0.03^\circ$ , giving a spacing of approximately 10mm between points on the quarry wall. Points were duplicated between scans. A total of 60 digital photos were taken, at focal lengths of either 14mm or 50mm depending on the distance from the scanner to the quarry walls.

### **Talisker Bay**

Five laser scans were acquired here, however many more could have been acquired to provide a more complete coverage of the outcrops. Unfortunately the other locations were inaccessible due to the tidal nature of the site. The five scans obtained provided a good coverage of the outcrops and allowed us to correlate flows between the outcrops. In total, approximately 10,020,000 points were collected at an angular resolution of  $0.05\text{-}0.06^\circ$ . 84 digital photos were taken, again using either the 14mm or 50mm lenses.

### **Data processing**

Once the point clouds and digital photos were collected at each site, a common frame of reference was needed. This was provided by the reflectors, as shown in Figures 4 and 6. These were identified in both the scans and the photos, and an adjustment carried out to establish the relative locations of the scanner and camera, and the relative locations of the various scan positions. A common coordinate system was

thus established for the whole project. The point clouds could then be coloured from the images, and the scans merged to give one point cloud, as shown in Figure 7.

The 3D point clouds at this stage are made up of millions of points, making it difficult for software to handle. Unwanted areas of the outcrop were removed to leave only the areas of interest. The data were then filtered using an Octree filter to leave around 10,000 points, suitable for importing into GOCAD®. In the case of the Ljosa quarry data this was achieved by giving the resulting points a spacing of 20cm spacing; whereas the point spacing for the Talisker Bay data was 50cm.

## **BUILDING AND ANALYSING THE 3D MODELS**

### **Picking key horizons**

At this point, our workflow differs slightly from that of Buckley et al. (2008) and Enge et al. (2007). In their workflows, a triangulated mesh is formed from the point cloud, and the photographs are draped onto this. This allows detailed interpretation not possible on the point cloud itself, as the photograph is at a higher resolution than the point cloud. The process of meshing the point data is extremely time-consuming, and becomes more so when the geometry of the site is complex. The Talisker Bay case study is extremely complex, and attempts to build a triangulated mesh were hampered by the high level of computing power required. Accordingly, a simpler method for interpreting the data was devised.

It was decided to draw interpretations directly onto the digital photographs, and then project the altered photographs onto the point cloud. The point clouds generated are at a resolution of around 50 points/metre, whereas the photographs have 300 or more pixels/metre, so much more detailed interpretation is possible. Lines drawn on the photograph had a width of approximately 10cm when projected onto the point cloud,

covering 4 or 5 points. The lines from the photos are projected into the correct position on the point cloud, and can easily be seen, so 3D lines could be drawn directly onto the point cloud then exported. Figure 2 gives an example of the digital photo and its interpretation.

The purpose of our 3D geological models is to show the different volcanic facies present in the outcrops, and provide data on flow thicknesses and crust to core ratios. The high quality digital photographs, accompanied by detailed field observations, allowed us to identify flow tops, bases and crust/core boundaries, as well as dykes, sills, lava tubes and boles. The loss of 10cm of accuracy is acceptable in this situation, as very high precision is not required, but this workflow would not be suitable for other uses.

### **Extending the horizons laterally**

The .dxf files produced in the previous step were imported into GOCAD®, and the fault modelling package used to produce rough surfaces. In the case of the Talisker data, flows from different outcrops had already been correlated, and their top surfaces were constructed using the interpreted lines as edges. Where each horizon only had one interpreted line, this was extended laterally by treating the line as a fault centre line. The triangulated surfaces were then exported to GSI3D. GSI3D, unlike GOCAD®, places no limitations on where surfaces are constructed. This allowed us to extend surfaces to where no data was available, and to use our geological experience to determine where the surfaces should go. While this introduced a much higher level of uncertainty, it allowed us to extend the surfaces and construct a useful block model. The finished model of Ljosa quarry is shown in Figure 9. Lighter colours are flow crusts and darker colours are flow cores.

For the Talisker Bay case study, two final models were constructed. The first is a palaeoreconstruction of the lava flows between the sea stacks and cliff section, constructed as detailed above. The second uses a GOCAD® surface of the topography, generated from the filtered laser scan point cloud, to display only the present-day flows. The GOCAD® surface is shown in Figure 10. All overhanging areas have been replaced by vertical sections to make it compatible with the GSI3D software. The final models are shown in Figure 11. It has also been possible to include lava tubes, a sill and a dyke in this model, making it possible to determine what proportion of the total volume is made up of these features.

### **Interrogating the block models**

The completed geological models can be analysed in a number of ways. Virtual boreholes and cross-sections can be obtained for any area of the model to give an idea of the heterogeneity, which is useful in showing how complex the stacking patterns of lava flows may be. An example of a synthetic borehole is given in Figure 12.

It is also easy to obtain volumes and map areas for each unit. While the volume is a function of the size of the model, and therefore not useful in determining the original flow volume, it can be used with the flow area to calculate an average thickness. We have calculated average flow thicknesses and crust to core ratios for the Ljosa quarry model, and these are given in Table 1. In the case of the Talisker Bay model, it was not possible to identify crusts for the majority of flows; however volumes and average thicknesses were calculated. These are given in Table 2. The use of these data is described in the next section.

## **DISCUSSION AND CONCLUSIONS**

The 3D geological models presented here accurately capture the heterogeneity present in a complex sequence of compound-braided lava flows. The internal flow structure can be identified, and irregular features such as dykes, sills and lava tubes can be visualized. Quantitative data on lava flow thicknesses, volumes and crust to core ratios can be easily obtained from the final models, and virtual boreholes constructed in any location.

This work builds on previous detailed facies analysis of flood basalt sequences (e.g. Single & Jerram 2004; Passey and Bell 2007). The use of TLS technology and associated software packages provides many advantages over traditional “paper-based” methods, as summarised by Buckley et al. (2008). For our purposes, it is useful to capture 3D data quickly and accurately, allowing for lab-based analysis. Additionally, the level of detail and accuracy provided by TLS makes it possible to correlate lava flows between inaccessible parts of outcrops.

The workflow presented here provides a relatively simple way to construct 3D models, albeit with a slight loss in accuracy. It reduces the computer memory and processing power required compared to workflows such as that of Buckley et al. (2008). The loss of accuracy may make the workflow unsuitable for detailed structural analysis, but it is suitable for facies analysis.

This study forms part of ongoing work to construct realistic geological and geophysical models of flood basalt provinces. The models generated in this study can be used to populate larger sequences where the distribution of such facies is known (e.g. Jerram et al., 2009). The fine-scale modelling is required to capture all the heterogeneity present in a flood basalt sequence, and the models also need to include lateral variations. Future work will also incorporate geophysical data from boreholes

on the Faroe Islands, as well as data on lava flow surface roughness from other laser scans and 3D models of other facies types.

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## REFERENCES

- Bellian, J.A., Kerans, C., and Jennette, D.C., 2005, Digital Outcrop Models: Applications of Terrestrial Scanning Lidar Technology in Stratigraphic Modeling: *Journal of Sedimentary Research*, v. 75, p. 166-176.
- Berthelsen, O., Noe-Nygaard, A. & Rasmussen, J. (eds), 1984, The deep drilling project 1980-1981 in the Faeroe Islands.: *Annales Societatis Scientiarum Faeroensis, Supplementum*, v. IX, p. 158pp.
- Chalmers, J.A., and Waagstein, R., 2006, Scientific results from the deepened Lopra-1 borehole, Faroe Islands. Geological Survey of Denmark and Greenland Bulletin 9.
- Eldholm, O., and Grue, K., 1994, North Atlantic volcanic margins: Dimensions and production rates: *Journal of Geophysical Research*, v. 99, p. 2955-2968.
- Ellis, D., Bell, B.R., Jolley, D.W., and O'Callaghan, M., 2002, The stratigraphy, environment of eruption and age of the Faroes Lava Group, NE Atlantic Ocean, *in* Jolley, D.W., and Bell, B.R., eds., *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*, Volume 197, Geological Society, London, Special Publications, p. 253-269.
- Jerram, D.A., 2002, Volcanology and facies architecture of flood basalts, *in* Menzies, M.A., Klemperer, S.L., Ebinger, C.J., and Baker, J., eds., *Volcanic rifted margins*. Geological Society of America Special Paper, Volume 362, p. 119-132.
- Jerram, D.A., Single, R.T., Hobbs, R.W., and Nelson, C.E., 2009, Understanding the offshore flood basalt sequence using onshore volcanic facies analogues: an example from the Faroe-Shetland basin: *Geological Magazine*, v. 146, p. 353-367.
- Jerram, D.A., and Widdowson, M., 2005, The anatomy of Continental Flood Basalt Provinces: geological constraints on the processes and products of flood volcanism: *Lithos*, v. 79, p. 385-405.
- Jolley, D.W., and Bell, B.R., 2002, The evolution of the North Atlantic Igneous Province and the opening of the NE Atlantic rift, *in* Jolley, D.W., and Bell, B.R., eds., *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*: Geological Society of London Special Publications 197, p. 1-13.

- Kessler, H., Mathers, S., and Sobisch, H.G., 2009, The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology: *Computers & Geosciences*, v. 35, p. 1311-1321.
- Labourdette, R., and Jones, R.R., 2007, Characterization of fluvial architectural elements using a three-dimensional outcrop data set: Escanilla braided system, South-Central Pyrenees, Spain: *Geosphere*, v. 3, p. 422-434.
- Lelliott, M., Bridge, D., Kessler, H., Price, S., and Seymour, K., 2006, The application of 3D geological modelling to aquifer recharge assessments in an urban environment: *Quarterly Journal of Engineering Geology & Hydrogeology*, v. 39, p. 293.
- McCaffrey, K., Feely, M., Hennessy, R., and Thompson, J., 2008, Visualization of folding in marble outcrops, Connemara, western Ireland: An application of virtual outcrop technology: *Geosphere*, v. 4, p. 588.
- McCaffrey, K.J.W., Jones, R.R., Holdsworth, R.E., Wilson, R.W., Clegg, P., Imber, J., Hollman, N., and Trinks, I., 2005, Unlocking the spatial dimension: digital technologies and the future of geoscience fieldwork: *Journal of the Geological Society*, v. 162, p. 927-938.
- Naylor, P.H., Bell, B.R., Jolley, D.W., Durnall, P., and Fredsted, R., 1999, Palaeogene magmatism in the Faeroe-Shetland Basin: influences on uplift history and sedimentation, *in* Fleet, A.J., and Boldy, S.A.R., eds., *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference.*, p. 545-558.
- Nelson, C.E., Jerram, D.A., Single, R.T., and Hobbs, R.W., 2009, Understanding the facies architecture of flood basalts and volcanic rifted margins and its effect on geophysical properties., *in* Varming, T., and Ziska, H., eds., *Faroe Islands Exploration Conference: Proceedings of the 2nd Conference*, *Annales Societatis Scientiarum Faroensis, supplementum, Volume 48*, p. 84-103.
- Passey, S., and Jolley, D., 2009, A revised lithostratigraphic nomenclature for the Palaeogene Faroe Islands Basalt Group, NE Atlantic Ocean: *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, v. 99, p. 127-158.
- Passey, S.R., and Bell, B.R., 2007, Morphologies and emplacement mechanisms of the lava flows of the Faroe Islands Basalt Group, Faroe Islands, NE Atlantic Ocean: *Bulletin of Volcanology*, v. 70, p. 139-156.
- Planke, S., Symonds, P.A., Alvestad, E., and Skogseid, J., 2000, Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins: *Journal of Geophysical Research-Solid Earth*, v. 105, p. 19335-19351.
- Pringle, J.K., Westerman, A.R., Clark, J.D., Drinkwater, N.J., and Gardiner, A.R., 2004, 3D high-resolution digital models of outcrop analogue study sites to constrain reservoir model uncertainty: an example from Alport Castles, Derbyshire, UK: *Petroleum Geoscience*, v. 10, p. 343-352.
- Roberts, A.W., White, R.S., Lunnon, Z.C., Christie, P.A.F., Spitzer, R., and Team, i., 2005, Imaging magmatic rocks on the Faroes Margin, *in* Doré, A.G., and Vining, B.A., eds., *Petroleum Geology: North-West Europe and Global Perspectives - Proceedings of the 6th Petroleum Geology Conference*, p. 755-766.
- Rotevatn, A., Buckley, S.J., Howell, J.A., and Fossen, H., 2009, Overlapping faults and their effect on fluid flow in different reservoir types: A LIDAR-based



- outcrop modeling and flow simulation study: AAPG Bulletin, v. 93, p. 407-427.
- Self, S., Thordarson, T., and Keszthelyi, L., 1997, Emplacement of continental flood basalt lava flows, *in* Mahoney, J.J., and Coffin, M.F., eds., Large Igneous Provinces: Continental, Oceanic and Planetary Flood Volcanism, Volume 100, American Geophysical Union Geophysical Monograph, p. 381-410.
- Single, R.T., 2004, The facies architecture of large igneous provinces: an integrated geological and geophysical approach to the characterisation of volcanic successions in 3-D. [PhD thesis], Durham University.
- Single, R.T., and Jerram, D.A., 2004, The 3D facies architecture of flood basalt provinces and their internal heterogeneity: examples from the Palaeogene Skye Lava Field: Journal of the Geological Society, v. 161, p. 911-926.
- Xu, X., Aiken, C., Bhattacharya, J., Corbeanu, R., Nielsen, K., McMechan, G., and Abdelsalam, M., 2000, Creating virtual 3-D outcrop: The Leading Edge, v. 19, p. 197-202.

**Figure 2** Photo interpretation from Ljosa quarry, Faroe Islands, and schematic geophysical logs. The photo was taken by the scanner-mounted camera. The schematic logs show the large variation between flow crust and core, and the values are based on data from Nelson et al. (2009a).

**Figure 3** Summary of the workflow used in this study.

**Figure 4** Overview photo of Ljosa quarry and map of the scanning setup, showing the scan positions and the reflector positions.

**Figure 5 a)** Overview photo of the Talisker Bay case study, showing the small sea stack, cliff section and wave-cut platform. **b)** The TLS equipment in action. **c)** The large sea stack. **d)** The case study area at high tide, showing the cliff section and both sea stacks.

**Figure 6** Map of the scan setup at Talisker Bay. The complex layout meant several scans were carried out, two on the platform halfway up the large sea stack. Two scans were carried out at one position, one of which was tilted at an angle of 30° to the horizontal, in order to capture the top of the sea stack.

**Figure 7** The completed laser scan point clouds, coloured from the digital photos. Animated versions available.

**Figure 8** Interpreted 3D lines from the Talisker Bay case study.

**Figure 9** The completed 3D model of the Ljosa Quarry case study constructed in GSI3D. Lighter colours are flow crusts and darker colours are flow cores. Animated versions available.

**Figure 10** The GOCAD® surface used to construct the Talisker Bay model.

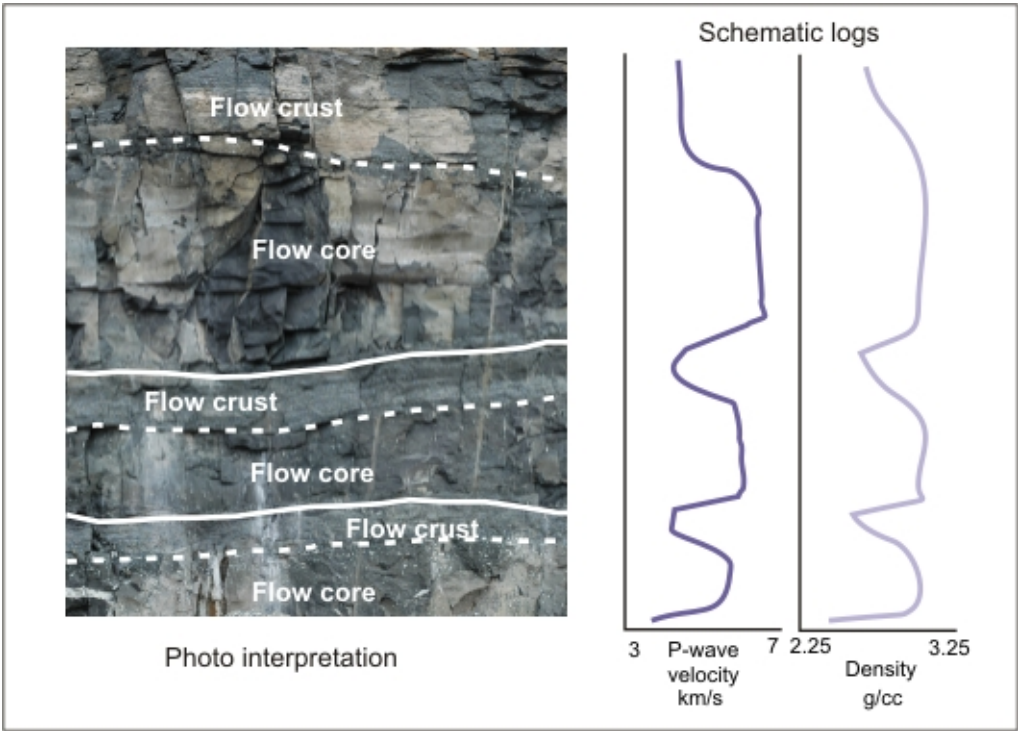
**Figure 11** Completed GSI3D models of the Talisker Bay case study. Animated versions available. **a)** Exploded view of the lava flows and sedimentary units. **b)** The

3D volumes cut to the present day topography. **c)** Transparent view of the entire model highlighting the sill, dyke and lava tubes.

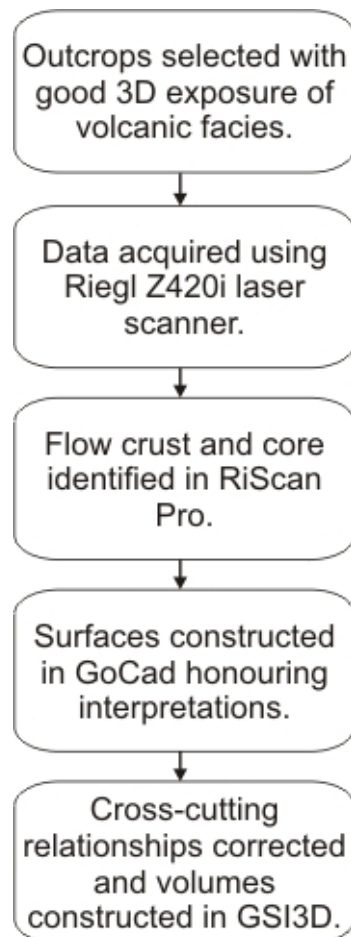
**Figure 12** Synthetic borehole through Ljosa quarry model.

**Table 1** Details of flows from Ljosa quarry model.

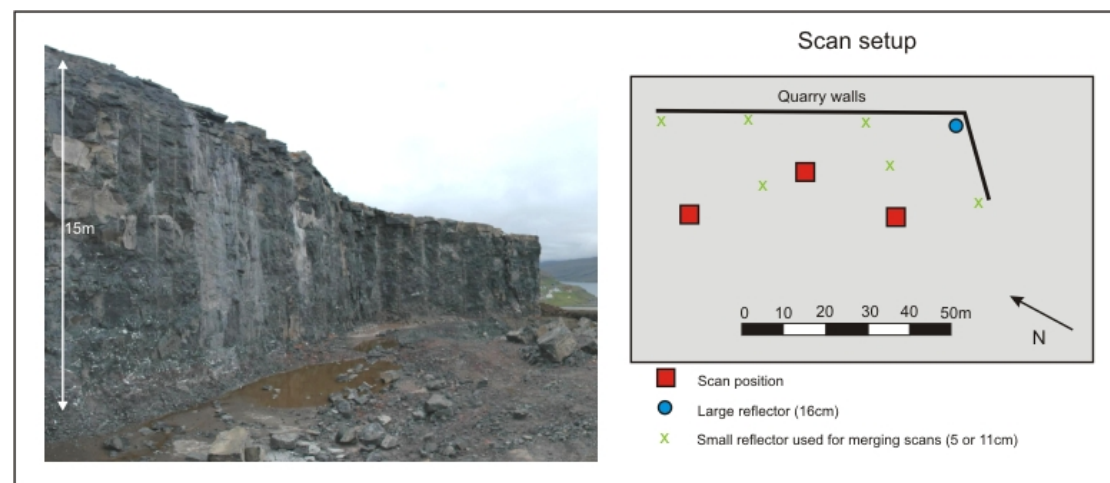
**Table 2** Details of flows from Talisker Bay model.



**Figure 2** Photo interpretation from Ljosa quarry, Faroe Islands, and schematic geophysical logs. The photo was taken by the scanner-mounted camera. The schematic logs show the large variation between flow crust and core, and the values are based on data from Nelson et al. (2009a).



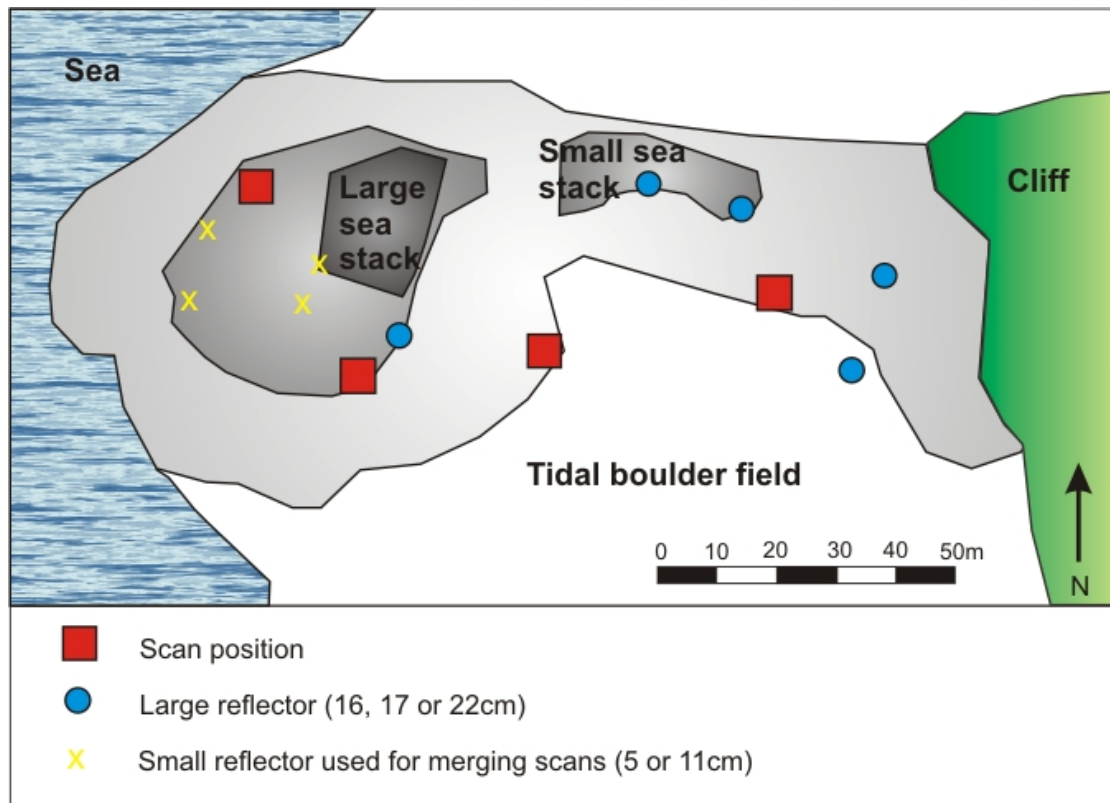
**Figure 3** Summary of the workflow used in this study.



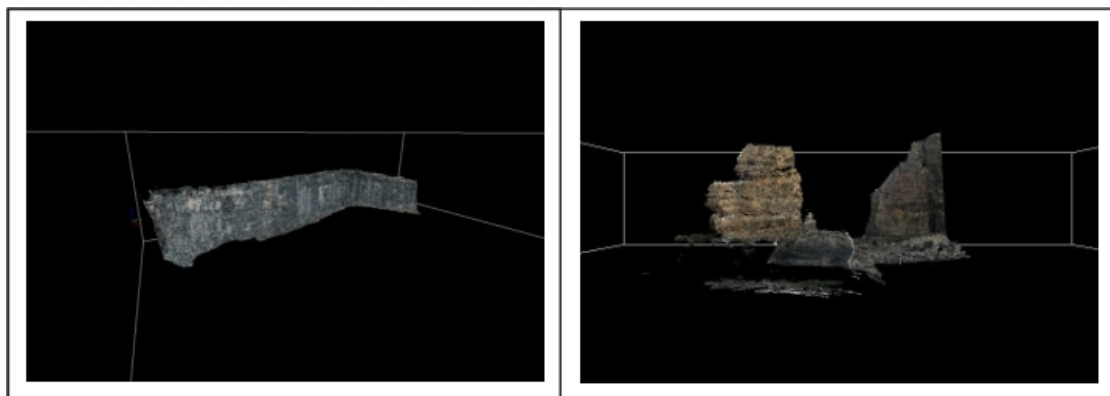
**Figure 4** Overview photo of Ljosa quarry and map of the scanning setup, showing the scan positions and the reflector positions.



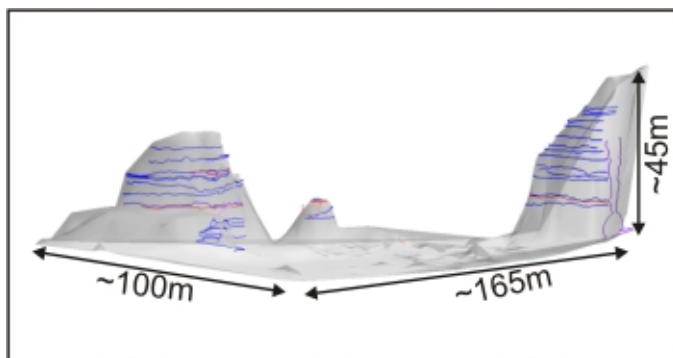
**Figure 5** **a)** Overview photo of the Talisker Bay case study, showing the small sea stack, cliff section and wave-cut platform. **b)** The TLS equipment in action. **c)** The big sea stack. **d)** The case study area at high tide, showing the cliff section and both sea stacks.



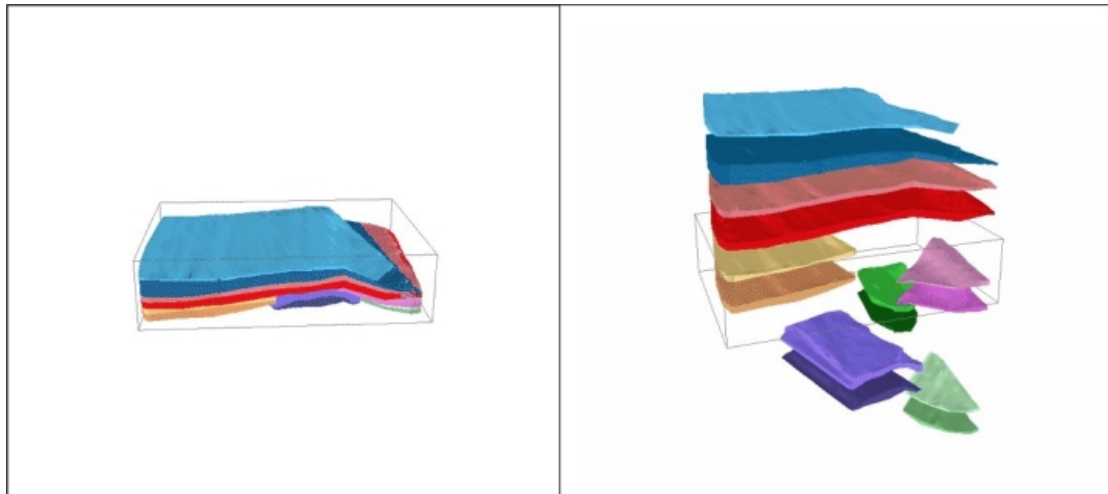
**Figure 6** Map of the scan setup at Talisker Bay. The complex layout meant several scans were carried out, two on the platform halfway up the large sea stack.



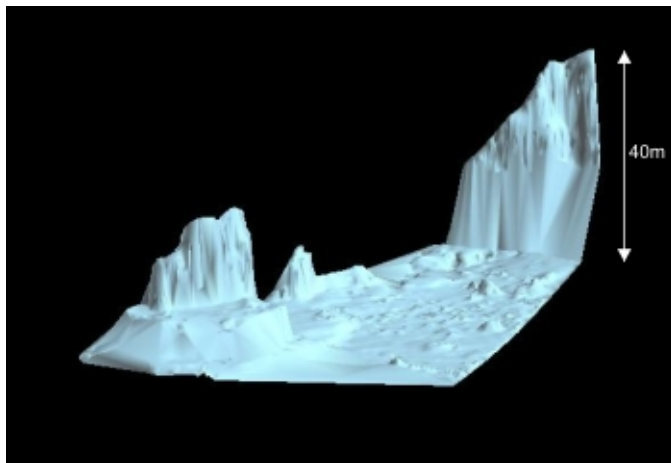
**Figure 7** The completed laser scan point clouds, coloured from the digital photos. Animated versions available.



**Figure 8** Interpreted 3D lines from the Talisker Bay case study.

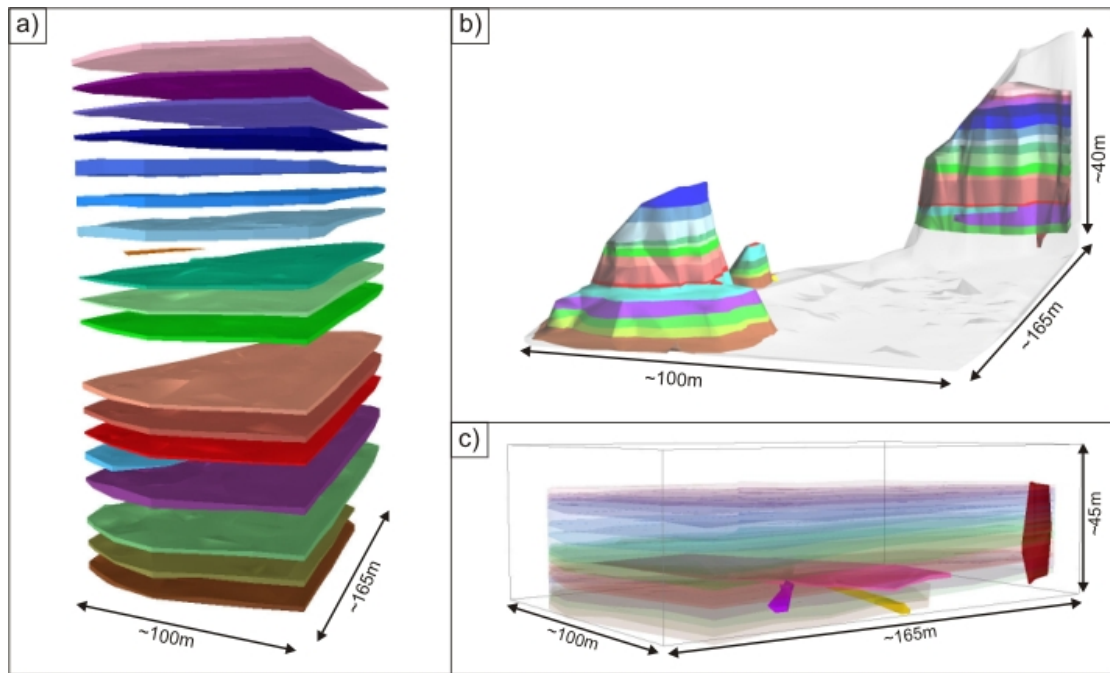


**Figure 9** The completed 3D model of the Ljosa Quarry case study constructed in GSI3D. Lighter colours are flow crusts and darker colours are flow cores. Animated versions available.

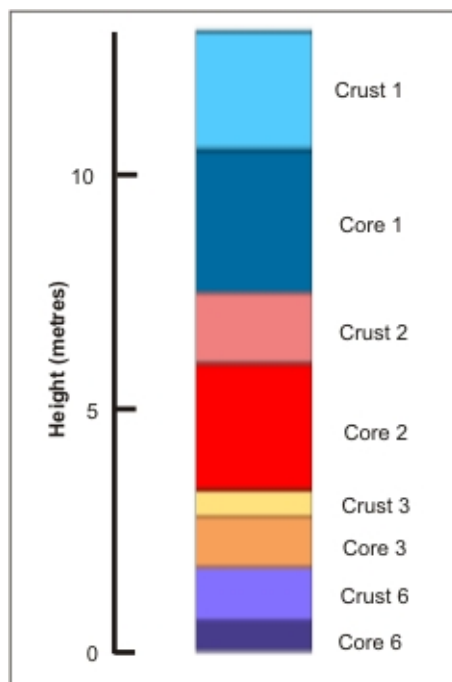


**Figure 10** The Gocad surface used to construct the Talisker Bay model. All overhanging areas have been replaced by vertical surfaces.





**Figure 11** Completed GSI3D models of the Talisker Bay case study. Animated versions available. **a)** Exploded view of the lava flows and sedimentary units. **b)** The 3D volumes cut to the present day topography. **c)** Transparent view of the entire model highlighting the sill, dyke and lava tubes.



**Figure 12** Synthetic borehole through Ljosa quarry model.