JARÐFEINGI
FAROESE GEOLOGICAL SURVEY

THE VESTMANNA TUNNEL

GEOLOGICAL OVERVIEW OF THE VESTMANNA-KVÍVÍK AREA, STREYMOY, FAROE ISLANDS

Report to LANDSVERK

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Written and compiled by: Turid Madsen

Modelling made by: Turid Madsen

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Introduction

Jarðfeingi has been commissioned by Landsverk to carry out a geological survey of the Vestmanna-Kvívík Area, Faroe Islands (Fig. 1) in connection with the plans of constructing a new road tunnel, the Vestmanna Tunnel between Kvívík and Vestmanna. The survey includes inhouse examinations of existing data, reports and literature from previous studies and identification of fracture zones and other lineaments from aerial photographs. This has been combined with new geological fieldwork along several streams in the area where the stratigraphy has been logged and joints and fracture zones identified, and their orientation measured. Furthermore, two project-specific boreholes were drilled and logged with an optical televiewer. Based on the overall observations, an idealized geological profile is presented, and some preliminary thoughts are given on possible implications by the known geological conditions for the tunnel construction.

Geology of the Faroe Islands

The Faroe Islands represent the exposed uppermost > 3 km remnant of the Faroe Islands Basalt Group (FIBG) that has a gross stratigraphic thickness of at least 6.6 km (Fig. 2; Rasmussen & Noe-Nygaard 1969, 1970; Passey & Jolley 2009). The FIBG is dominated by subaerial compound and simple basalt lava flows with individual thicknesses of less than one meter up to several tens of meters, which are generally separated by minor (<1-2 m) and a few major (2->30 m) volcaniclastic units. The three main basalt-dominated formations exposed on the Faroe Islands are from oldest to youngest: Beinisvørð (formerly the *lower basalt series*), Malinstindur (formerly the *middle basalt series*) and Enni (formerly the *upper basalt series*) formations (Rasmussen & Noe-Nygaard 1969, 1970; Passey & Jolley 2009).

The morphology and internal structure of the two main lava flow types are shown in Fig. 3. The Beinisvørð Formation is chiefly composed of relatively thick (typically > 10 m) simple lava flows with a characteristic stepped topography. This contrasts with the Malinstindur Formation that is made up of compound lava flows that consist of numerous thin (generally < 1 m up to a few m thick) overlapping and meandering flow lobes and form a continuous topographic profile (Fig. 4). The Enni Formation is a mixture of simple and compound flows and has a complex interfingering stratigraphy.

Intrusive basaltic sills, dykes and more irregular features are frequently found throughout the stratigraphic section where especially the dykes may or may not be associated with minor and major fracture zones with weakened and partly crushed material including abundant secondary minerals such as zeolites and clays.

The stratigraphy of the Vestmanna-Kvívík Area

The stratigraphy of the area is quite well known due to the already constructed Vágar Tunnel (Heinesen 1987, Madsen 2006). In Fig. 2, the Vestmanna-Kvívík area is marked with the inset blue boxes – on the map and in the stratigraphic column. A detailed geological map of the area is shown in Fig. 5.

The tunnel area lies within the central part of the Malinstindur Formation and contains the so-called B Horizon lava flow and the Kvívík beds, which represent a recognisable and laterally extensive volcaniclastic sequence well suited for correlation purposes. As shown on the stratigraphic column in Fig. 2, the planned tunnel will drill through a stratigraphic interval from ca 300 m below to ca 70 m above the Kvívík beds.

A number of basaltic sills are present in the area (Fig. 5; Rasmussen & Noe-Nygaard 1969) and the Vestmanna tunnel will probably drill through one or more such intrusive bodies close to the tunnel entrance at the Kvívík side.

Lithology of the Vestmanna-Kvívík area

A correlation panel is presented in Fig. 6 for the area between Vestmanna and Kvívík. It consists of field logs and logged boreholes (Fig. 7 and appendix 1) from this study combined with logs and drill holes from previous work in the area (Heinesen, 1987, Passey (pers. com.), Waagstein, 1977 and Waagstein & Hald, 1984).

There are in general three types of volcanic rocks dominating this area:

1. Brown weathering compound basalt flows
2. Pale weathering compound basalt flows
3. Volcaniclastic sandstones

These will be described below based on field observations and observations in the two boreholes drilled in connection with this project (B2 Válur and B4 Frammi í Keldum, see Fig. 7).

Brown weathering compound basalt flows

The brown weathering compound basalt flows are presented with a light brown color in the logs (Fig. 6). Their brown field appearance is due to their content of the iron-rich mineral olivine, which turns brownish ('rusty') by exposure and weathering. Examples of these brown flows are exposed along a prominent crag (fo: hamari; Fig. 8A), consisting of numerous lava flow units. This crag coincides with the 80-120 m thick interval in the correlation panel (Fig. 6), where the brown flows dominate.

These olivine-bearing flows occasionally are porphyritic containing 1-2 mm large olivine phenocrysts. They exhibit all the typical features of compound flows (Fig. 3) such as well-developed vesicular bands, pipe vesicles, ropy lava surfaces and lava toes. They are layered with individual lava flow lobes or units that are between 0.1 and 4 m thick (Fig. 8B). Each of the lava flow units typically has a massive core and a vesicular crust. This can also be seen in the boreholes.

Pale weathering compound basalt flows

The grey colors on the correlation panel (Fig. 6) represent pale (whitish grey) weathering flows that are aphyric to highly feldspar-porphyritic basalts. The size of the feldspar phenocrysts varies between fine (<3 mm), medium (0.3-1.0 cm) and coarse (>1 cm). The feldspar phenocrysts are typically lath shaped and sometimes appear in flower like *glomerophyric* clusters (Fig. 9A). The content of feldspar phenocrysts varies from almost 0% to 30%. This variation can also be seen within lava flow units, where the lower part frequently is highly porphyritic, and the upper part is nearly aphyric. The pale weathering flows are also compound in nature, which typically can be seen in the numerous streams in the region (see e.g. Fig. 9B).

Volcaniclastic sandstones

Volcaniclastic sandstones are illustrated with red lines on the correlation panel (Fig. 6). They represent only a very small proportion of the total thickness of rocks. The thickness in cm of the volcaniclastic beds is noted with red numbers next to the logs. In general, the thickness is 1- 50 cm with an average of 10-20 cm. The Kvívík Beds (orange), though, are up to 400 cm thick and will be described in a separate paragraph below.

The volcaniclastic sandstones (Fig. 10C & 10D) are brick red to red brown and often occur at the base of a "step" in the stream (Fig. 4). They are massive to weakly banded, fragile and do often weather out of rock faces and are often hidden in lows and cracks and not exposed in the present landscape.

Kvívík beds

The Kvívík beds are are marked with orange lines on the correlation panel (Fig. 6). In the field, they are red brown to brownish red volcaniclastic sandstones and often well cemented and hard and may be exposed in the middle of a crag (hamari) as opposed to other volcaniclastic units that typically are easily eroded. The Kvívík beds are strongly banded with 1-5 cm thick bands (Fig. 10A & 10B). The thickness is typically ca 1 m although varying between 50 and 400 cm. On Fig. 10A, the Kvívík Beds can be seen to infill a depression in the underlying flow.

The Kvívík beds are mostly composed of one single unit although in a few places, the sediments are separated into two beds with an intercalated lava flow. This is seen e.g. in the Stórá stream where a lower 60 cm thick and an upper 40 cm thick sandstone bed are separated by a brown weathering basalt flow. In the stream this flow is thinning to the East (Fig. 11C & 11D), and in the borehole, B4, only 200 m away, the Kvívík beds consist of one single 100 cm thick unit (Fig. 10B).

Fig. 11 demonstrates the stratigraphic section in the stream of Stórá (log L8 in fig. 6), near the planned tunnel entrance on the Kvívík side. Here, the Kvívík beds overlie AND are overlain by pale (greyish white) weathering, plagioclase-phyric compound flows with large (1-2 cm) plagioclase phenocrysts, which are followed upwards by a series of brown weathering, aphyric compound olivin-bearing flows with an overall thickness of ~20 m and consisting of flow lobes with individual thicknesses of <2 m. The lower boundary of these olivine bearing flowscorrespond to the so-called B horizon of Rasmussen & Noe-Nygaard (1969; 1970). The overlying rocks consist of pale weathering fine plagioclase porphyritic compound flows.

Fracture zones, faults and related features

Fracture zones and faults

In addition to the general rock nature and stratigraphy, as described above, fracture zones and faults may impact on the rock quality and the process of the tunnel drilling. The term 'fracture zones' is used to indicate lineaments where some movements of undefined magnitude have occurred in the subsoil causing some extent of crushing of the basalt material and subsequent infilling of generally weak secondary minerals along such lineaments. The term 'faults' indicates lineaments along which there is a recognizable offset (vertical and/or horizontal) between the two blocks to each side of the fault, respectively. Consequently, faults may be seen to represent a subset of fracture zones.

Due to erosion of the weakened material, fracture and fault zones can usually be recognized as semi-linear depressions in the landscape, as for example a gully or a gorge. The degree of exposure in a gully or gorge is usually quite poor, but one can get an impression of the width of the fracture zone.

Rasmussen (1970) describes fracture zones associated with gorges to consist of "*a frequently large number of parallel basalt lamellae with intervening crushed material and mineralized veins. Not infrequently thin bands of fuller's earth (montmorillonite) can be seen between the basalt lamellae.*" … and they are … "*often a considerable nuisance during blasting work, since they can be very loose.*"

Rasmussen and Noe-Nygaard (1969, 1970) mapped a number of fracture zones and faults in the area (Fig. 5). Aerial photographs (Fig. 1B) reveal further lineaments, which most likely also represent fracture zones – with or without recognizable offsets (faults). Measured vertical throws along faults in the study area vary between 1 to 13 m.

The dominant direction of fractures, faults and unspecified lineaments in the study area is ca 85° (measured clockwise from North). Another common direction is ca 60°. Secondary, more random directions are also observed to some extent (Fig. 12, central rose diagram).

Dykes

Dykes represent basaltic rock material, which frequently is intruded along fracture and fault zones. Other such zones may not contain dyke material, and some dykes may not express any considerable amount of fracturing or faulting.

A large number of dykes is seen throughout most parts of the Faroe Islands. Individual dyke widths vary between < 1 to several meters (exceptionally several tens of meters) and their lateral extent may amount to several kilometers (and even several tens of km) although the extent of individual exposures is often more restricted. Dykes are frequently columnar jointed at a right angle to their strike direction, and they are commonly also jointed along-strike due to movements along the fracture zones.

A few dykes have been observed in the study area. They range in thickness from 10-15 cm to several meters. As indicated in Fig. 5 and 12, the observed dykes' direction in the tunnel area typically follow the main strike of fracture and fault zones although a few dykes have different orientations. Their dip is typically close to vertical. An example of a dyke exposures is demonstrated in Fig. 13A.

Joints and veins

Joints and veins are relatively small features, compared to fracture zones and dykes, and they are omnipresent as indicated e.g. in the numerous stream exposures in the study area. Whereas individual fracture zones and dykes may influence upon the tunnel construction and long-term rock stability in the tunnel, the relevance of joints and veins is more related to their bulk intensity and general direction.

Examples of joints from the tunnel area are shown in Fig. 13 The distance between individual joints varies from just a few decimeters (Fig. 13C), to a few meters (Fig. 13B) and occasionally up to more than 10 meters. There are frequently two and sometimes up to three sets of joints observed in a particular location. Most of the joints are near vertical, although some bedding planes (flow boundaries) have associated joints, which are near horizontal.

In addition to joints, numerous mineralized veins are observed in parts of the tunnel area (Fig. 13D). Individual vein thicknesses vary between 2-10 mm and their shapes are often quite irregular.

Around 230 joints and veins have been registered in the tunnel region, and their location has been noted along with their strike and dip orientation. Two subsets of the observed joints and veins are indicated in Fig. 12 in the regions of the two planned tunnel entrances near Vestmanna (annotated 1 on the figure) and Kvívík (2), respectively. Interestingly, these observations show a clear NNW-SSE oriented trend of the joints, which differ somewhat from the general directions of the fracture zones.

Fractures in the logged boreholes

The B2 and the B4 boreholes from Válur and Frammi í Keldum, Kvívík have been drilled in connection with this project. They have been logged with an optical televiewer and the description is in appendix 1. An overview of the boreholes is presented in fig. 7.

Usually the distance between fractures is usually between 1 and several metres which indicates good to extremely good rock mass. In places e.g. B4 at depth 9-18 metres there are up to 5 fractures pr metre, but this still gives an RQD (Rock Quality Designation) of 100 and indicates good rock (Løset, 1997).

Geological profile of the proposed tunnel

A structure contour map of the Kvívík beds is presented in Fig. 14 showing the idealized height of these beds above sea level. As indicated by the orientation of the individual contours, the general strike direction is seen to be northerly with an average dip of 3.4° toward East.

An idealized geological profile has been constructed to demonstrate, in general terms, the likely stratigraphy together with possible fracture zones and dykes along the planned tunnel section (Fig. 15).

From the entrance at the Vestmanna side ('Station 0') to the Kvívík side ('Station c. 4,3 km'), the first approximately half of the tunnel section is composed of relatively homogeneous basalt with fine grained feldspar phenocrysts, whereas the remaining part seems to vary between sections of more coarsely porphyritic feldspar basalt and sections of olivine basalt.

Several intercalated volcaniclastic sandstone beds are likely to occur throughout the tunnel section. Individual sandstone beds seem to be generally thinner to the Vestmanna side (1-15 cm) than to the Kvívík side (6-30 cm), with the profound Kvívík beds (c. 100 cm?) occurring in the vicinity of 'Station 3.5 km').

In addition, a several m thick basaltic sill (with some thinner subsidiary sills?) is likely to occur close to the tunnel entrance at the Kvívík side.

Approximately 20 recognizable fracture zones and dykes have been projected from the different field observations onto the idealized geological profile (Fig. 15). The exact location and nature of these features in the tunnel section is difficult to predict as both their widths and degree of crushing and secondary mineralization may vary considerably along each of these individual features.

As demonstrated in Fig. 12, the observed fracture zones and dykes in the gross study area seem generally to be oriented relatively perpendicular to the tunnel direction, while joints and veins in the two entrance regions appear quite consistently to be oriented semi-parallel to the tunnel direction.

Possible implications for the tunnel construction

Like most of the almost twenty existing road tunnels in the Faroe Islands, the Vestmanna Tunnel will locate in the Malinstindur Formation, which geologically – in general terms – has shown relatively well suited for tunnel construction. One main reason for this relates to the relatively homogeneous stratigraphy with compound basaltic flows, which may change somewhat, although rarely drastically, in character from one flow to another and the flows are usually separated only by very thin (up to a few tens of cm) volcaniclastic sandstones.

The stratigraphy in the tunnel region between Vestmanna and Kvívík does not differ considerably from the general Malinstindur Formation elsewhere in the islands and no signs of great concern have been observed in the stratigraphic section in the area.

One particular lithological unit is the several meters thick sill, with potential subsidiary sills close to the planned tunnel entrance at the Kvívik side. The sill material is generally much harder and solid compared to the surrounding lava flows, and this may call for some special attention in the tunnel construction.

Structural elements such as fracture zones, faults, dykes, and related features are relatively abundant in the tunnel area. The nature of such features may vary considerably from one location to another and their impact on the tunnel construction will depend on the nature of these features in the specific tunnel locations. Whereas the larger features, i.e. fracture zones, faults, and dykes, seem to have a relatively favorable general direction to the tunnel, the general direction of joints and veins seems less advantageous.

Further work

Based on the observations made during the current study, the following recommendations for further work are suggested:

1. Structural mapping, especially field work to examen the nature and lateral variation of the specific fracture zones and other structural elements in the entire region.
2. Core drilling in the vicinity (above) the planned tunnel entrance in Kvívík to examen the rock quality of the stratigraphic section, in particular the nature of the sill(s).

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Figure 1 Overview of the Vestmanna-Kvívík area. The suggested tunnel is shown with a black and a yellow line in the two figures, respectively. The location of the map is shown in figure 2. **A** Topographic map **B** Aerial photo

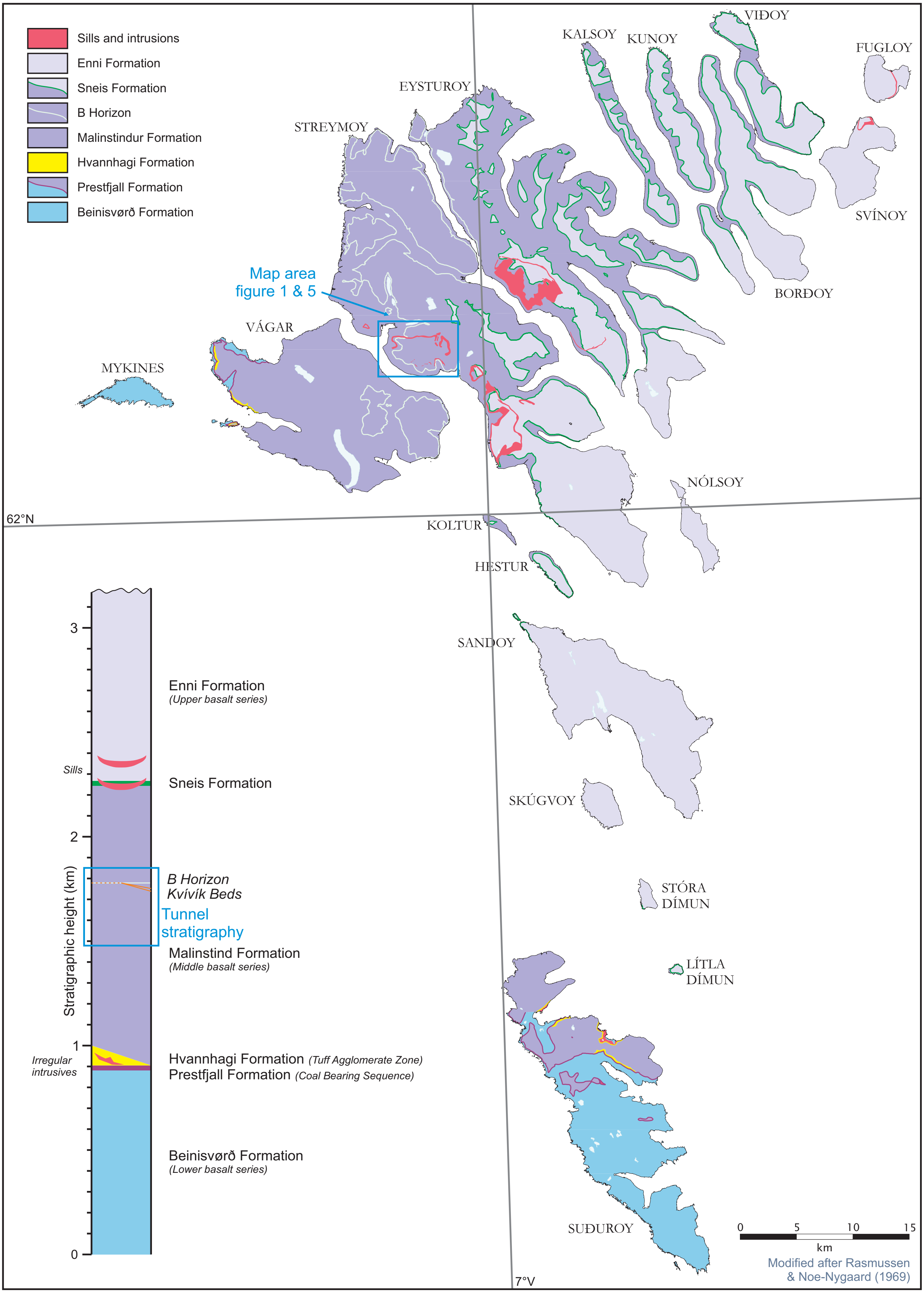

Figure 2 Geology of the Faroe Islands. The blue box on the map is field work area and the blue box on the stratigraphic column shows the stratigraphic interval the planned tunnel will drill through.

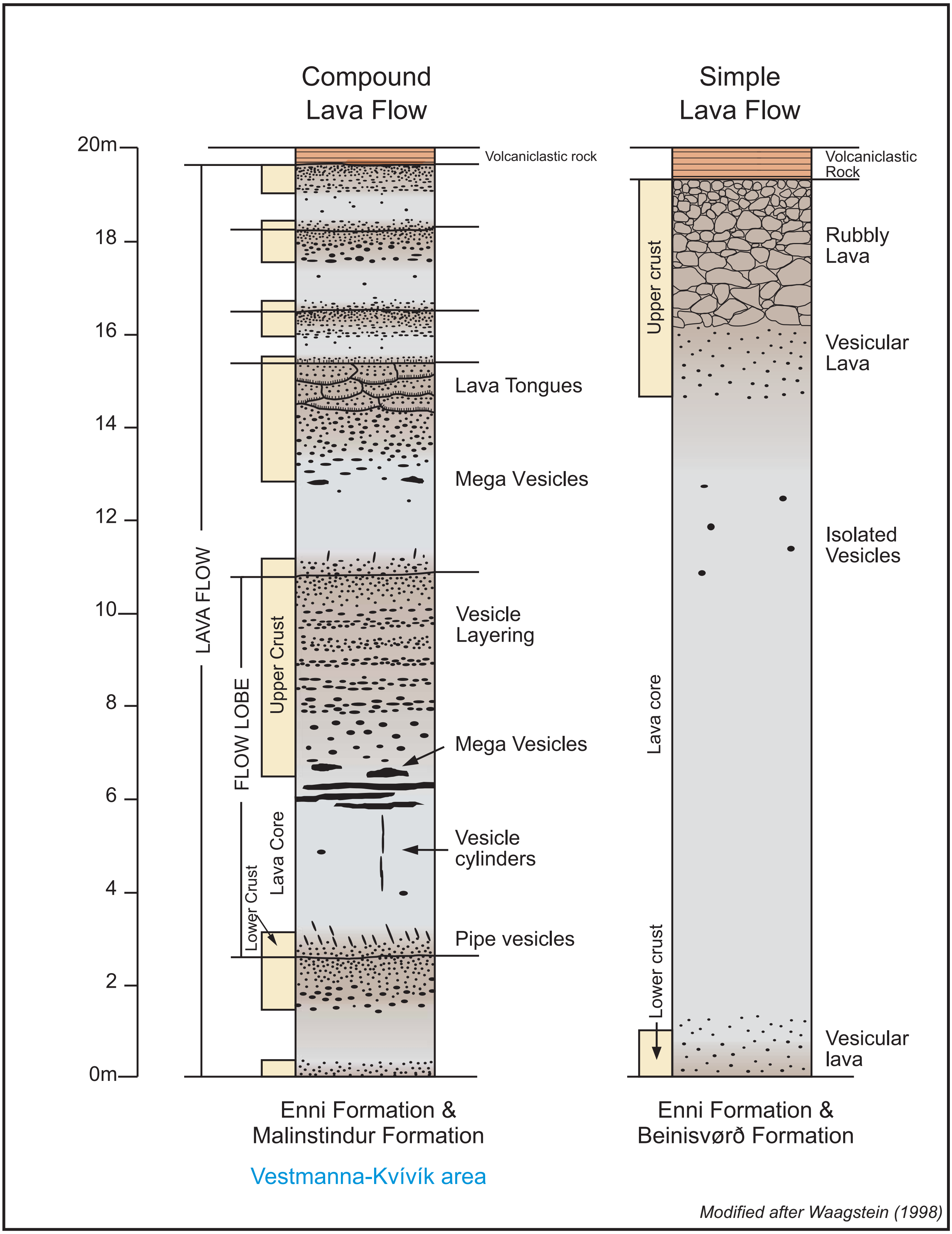

Figure 3 Lava flow morphology. Idealised vertical sections through a lava flow showing characteristic differences between a compound flow and a simple lava flow. Vesicular intervals are indicated with yellow boxes. Small features like vesicles, rubble and veins are not drawn to scale. The Vestmanna-Kvívík area is characterised by compound lava flows.

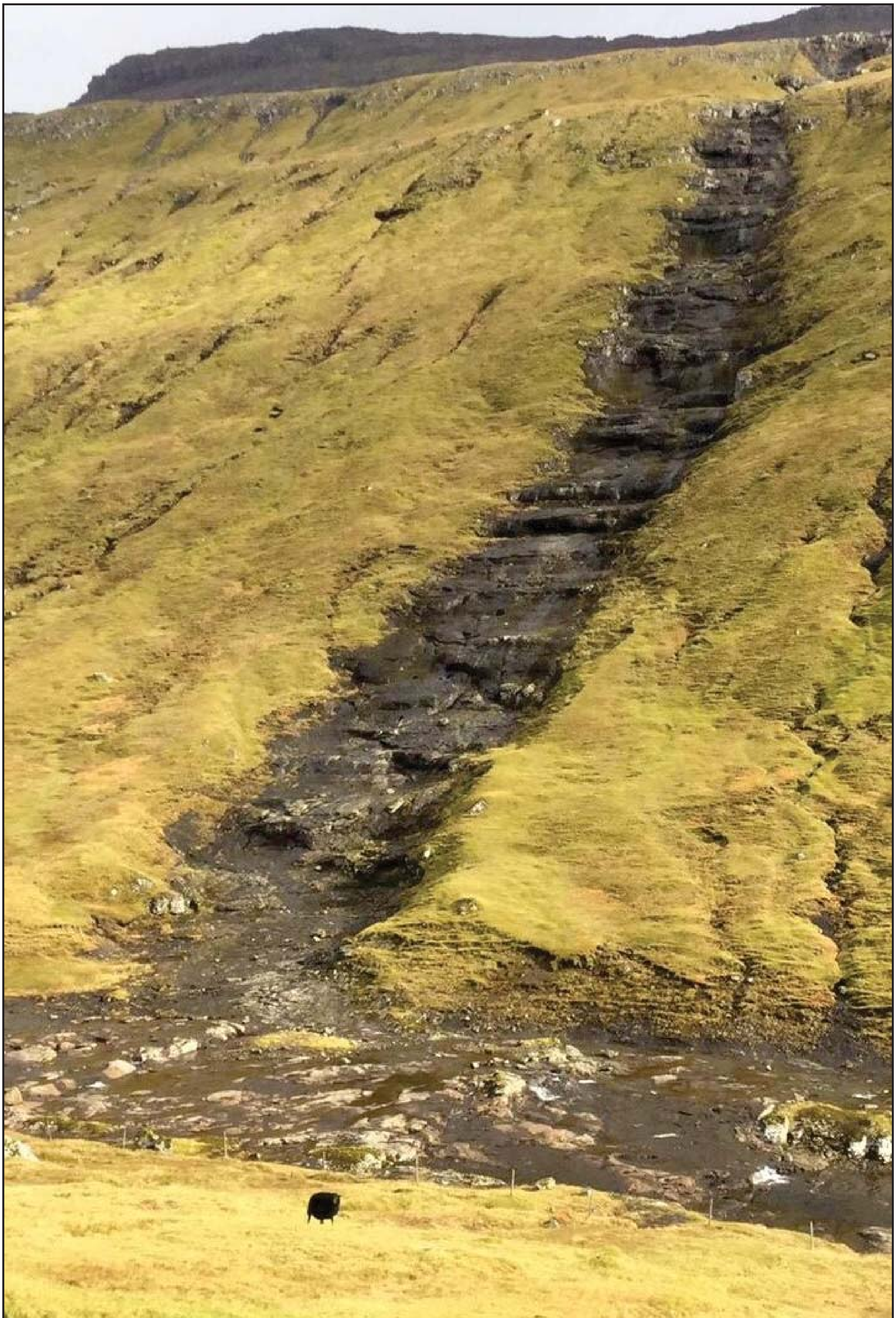

Figure 4 Compound lava flows that consist of numerous thin (generally <1m to a few metres thick flow units. Each “step” in the stream corresponds to a flow unit.

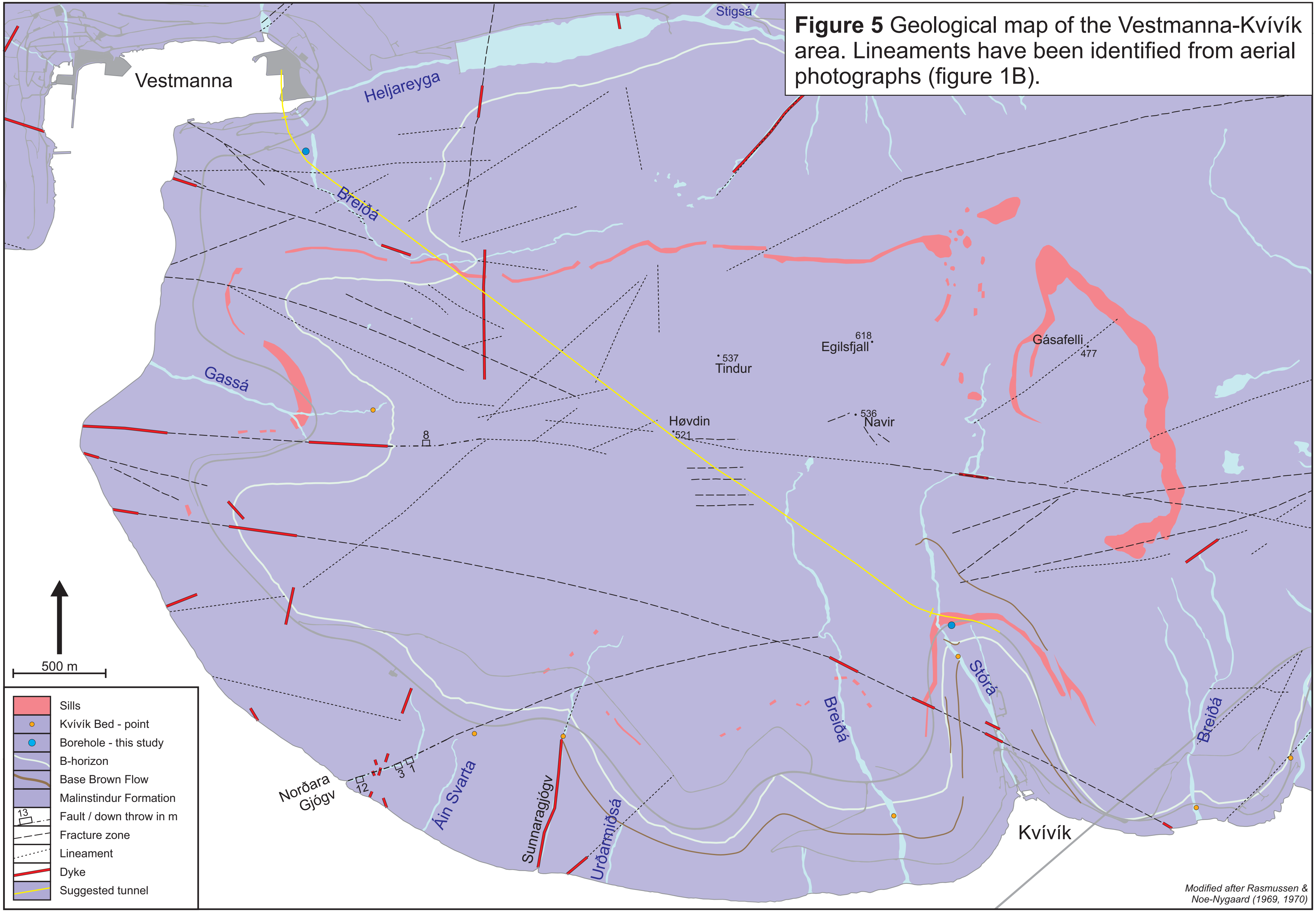

Figure 5 Geological map of the Vestmanna-Kvívík area. Lineaments have been identified from aerial photographs (figure 1B).

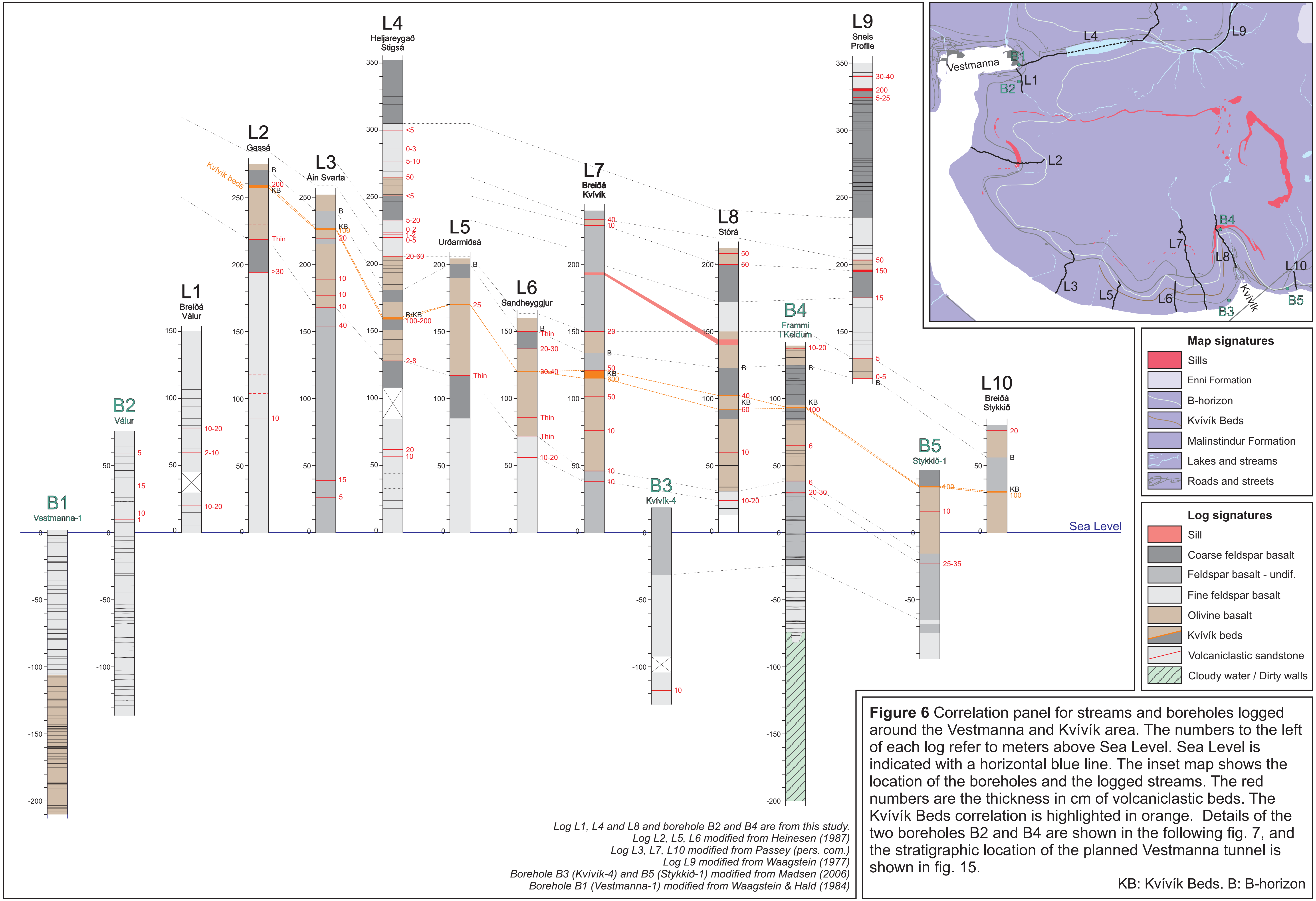

Figure 6 Correlation panel for streams and boreholes logged around the Vestmanna and Kvívík area. The numbers to the left of each log refer to meters above Sea Level. Sea Level is indicated with a horizontal blue line. The inset map shows the location of the boreholes and the logged streams. The red numbers are the thickness in cm of volcaniclastic beds. The Kvívík Beds correlation is highlighted in orange. Details of the two boreholes B2 and B4 are shown in the following fig. 7, and the stratigraphic location of the planned Vestmanna tunnel is shown in fig. 15.

KB: Kvívík Beds. B: B-horizon

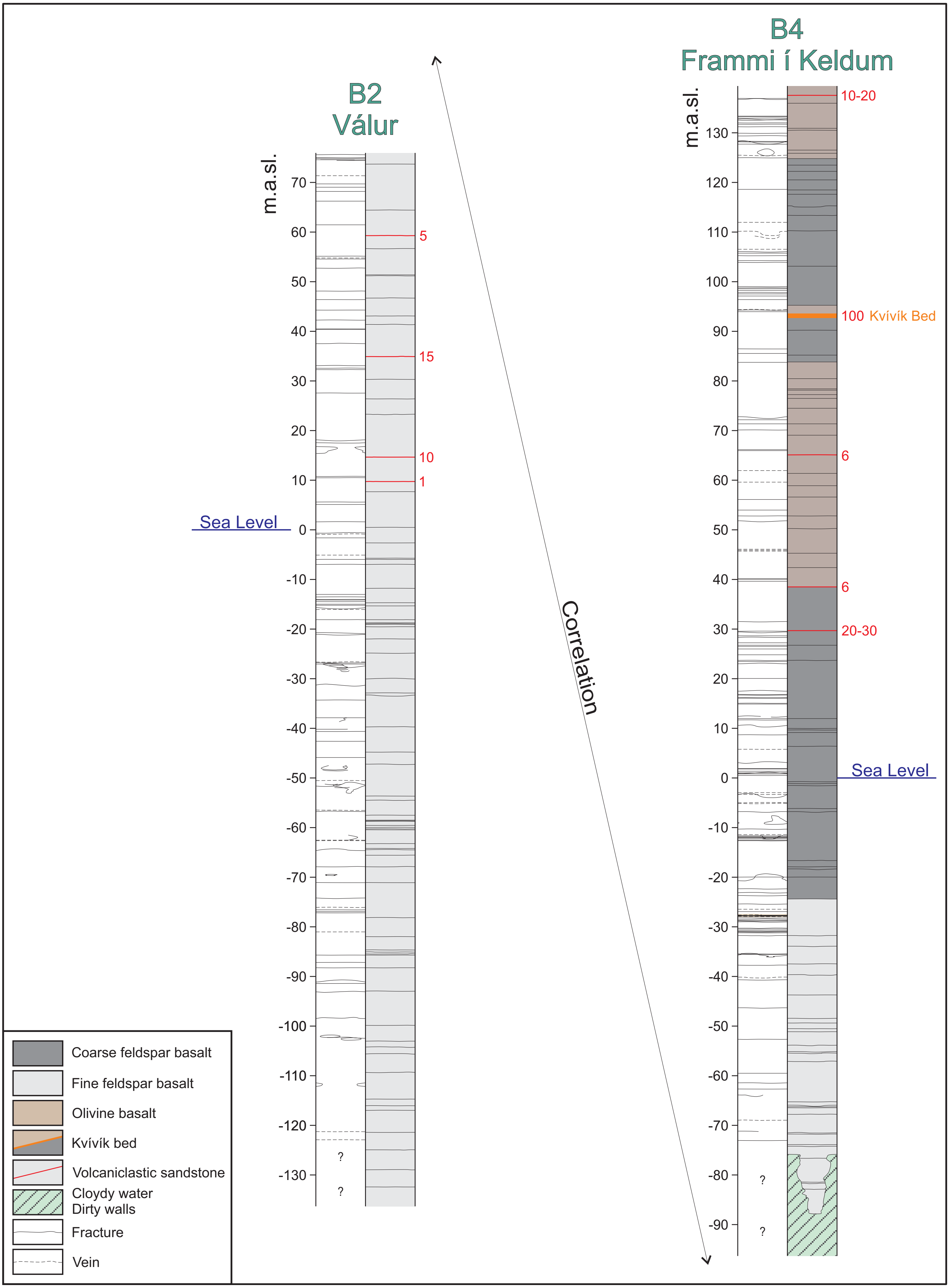

Figure 7 Overview of the logged boreholes in Válur (B2) and Frammi í Keldum, Kvívík (B4). The left column of each log shows observed fractures and veins and the right column shows the lithology. The numbers in red refer to thickness in cm of volcaniclastic sediments.

Figure 8 Brown weathering compound flows.
A Overview of the stratigraphy in the area of the Stigsá Stream - see also fig. 6, L4. The entire section consists mainly of compound lava flows with 1-4 m thick flow units. Brown, gray and orange lines indicate the base of different stratigraphic units as indicated in the tentative log to the left of the picture.
The lower crag consists mostly of numerous brown flow units, whereas the upper crag mostly consists of pale flow units with fine plagioclase phenocrysts. Note the fracture zone, that might displace the flows a little.
B Close up of the brown flows. Each metre thick lava flow unit has a lower massive core and an upper vesicular crust. The hammer is 35 cm long. Stórá Stream in Kvívík.

Figure 9 Pale weathering (grey) compound flows. **A** Close up of large feldspar phenocrysts (1-2 cm). **B** Fossá. The massive appearance of three of the grey flow units with flow boundaries indicated by the yellow lines . Note the up to 0,75 m wide caves to the right in the picture.

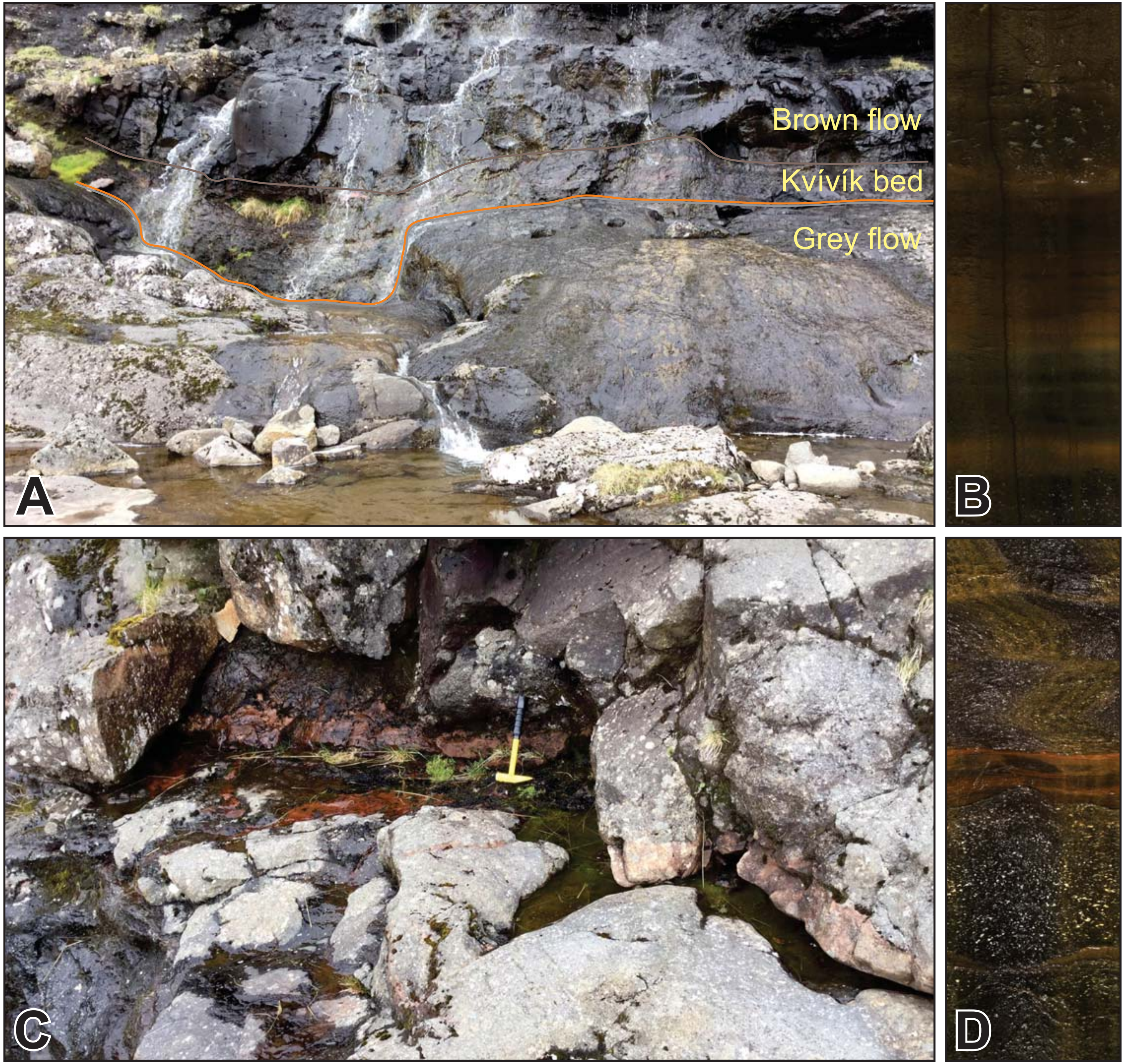

Figure 10 Volcaniclastic sandstones.

A Kvívík beds. Massive, banded. 1-2 m thick infilling a depression in the underlying grey flow (feldspar basalt). Above the Kvívík beds is a brown flow (olivine basalt). Stigsá in Vestmanna (L4 in figure 6).

B Kvívík Beds in the B4 borehole at Kvívík at 93 metres above sea level. 1 m thick. Clearly banded with red, brown and green bands.

C Volcaniclastic sandstone in Breiðá, Válur (L1 in figure 6). Ca 15 cm thick.

D Volcaniclastic sandstone in the B4 borehole at Kvívík at 137 metres above sea level. ca 15 cm thick.

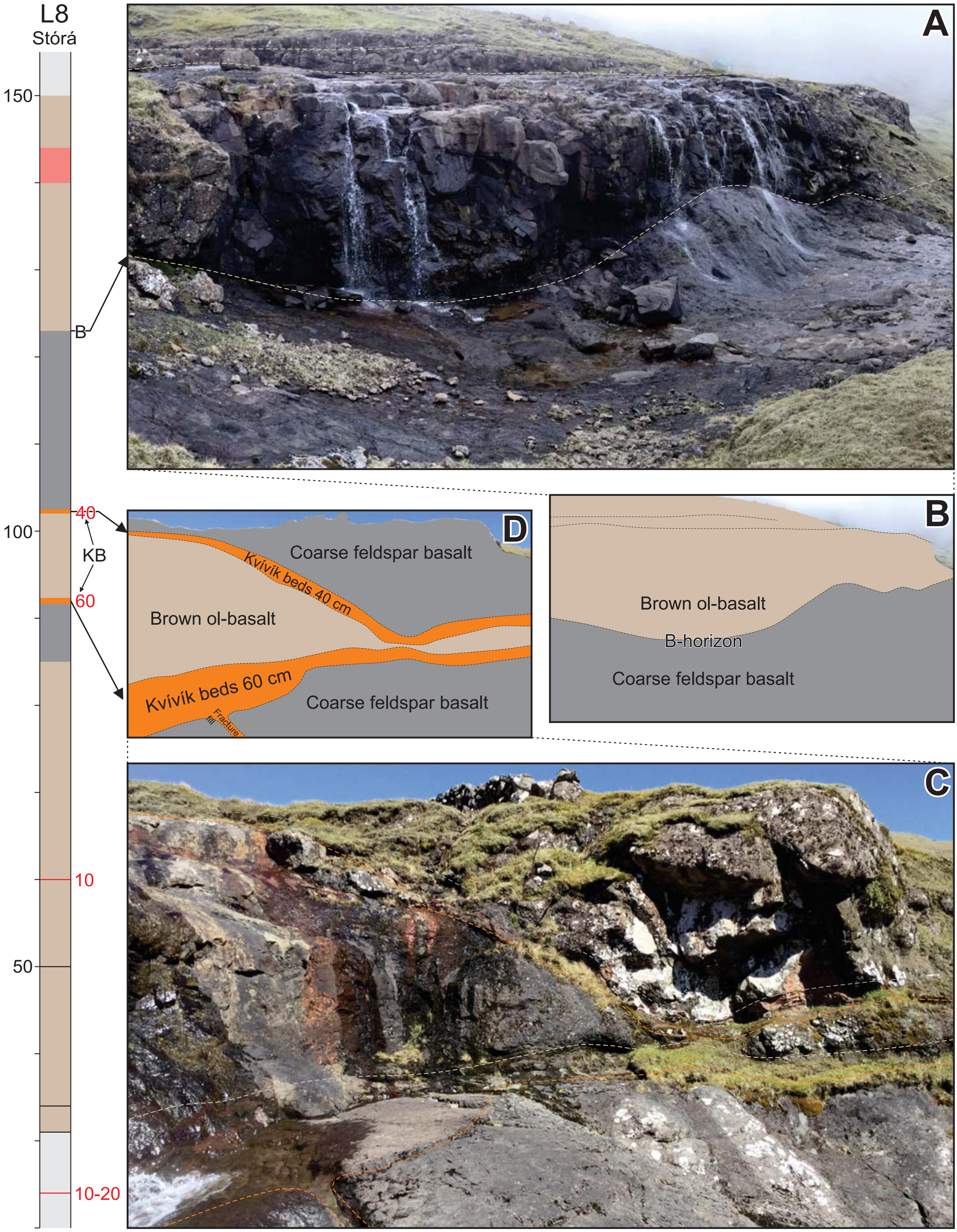

Figure 11 The B-horizon and the Kvívík Beds at Stórá, Kvívík. See log L8 to the left and in figure 6 for stratigraphic position. **A** B Horizon. **B** Drawing of fig 11A. **C** Kvívík Beds are split in two separated by a brown flow unit that is thinning to the right. **D** Drawing of fig. 11C

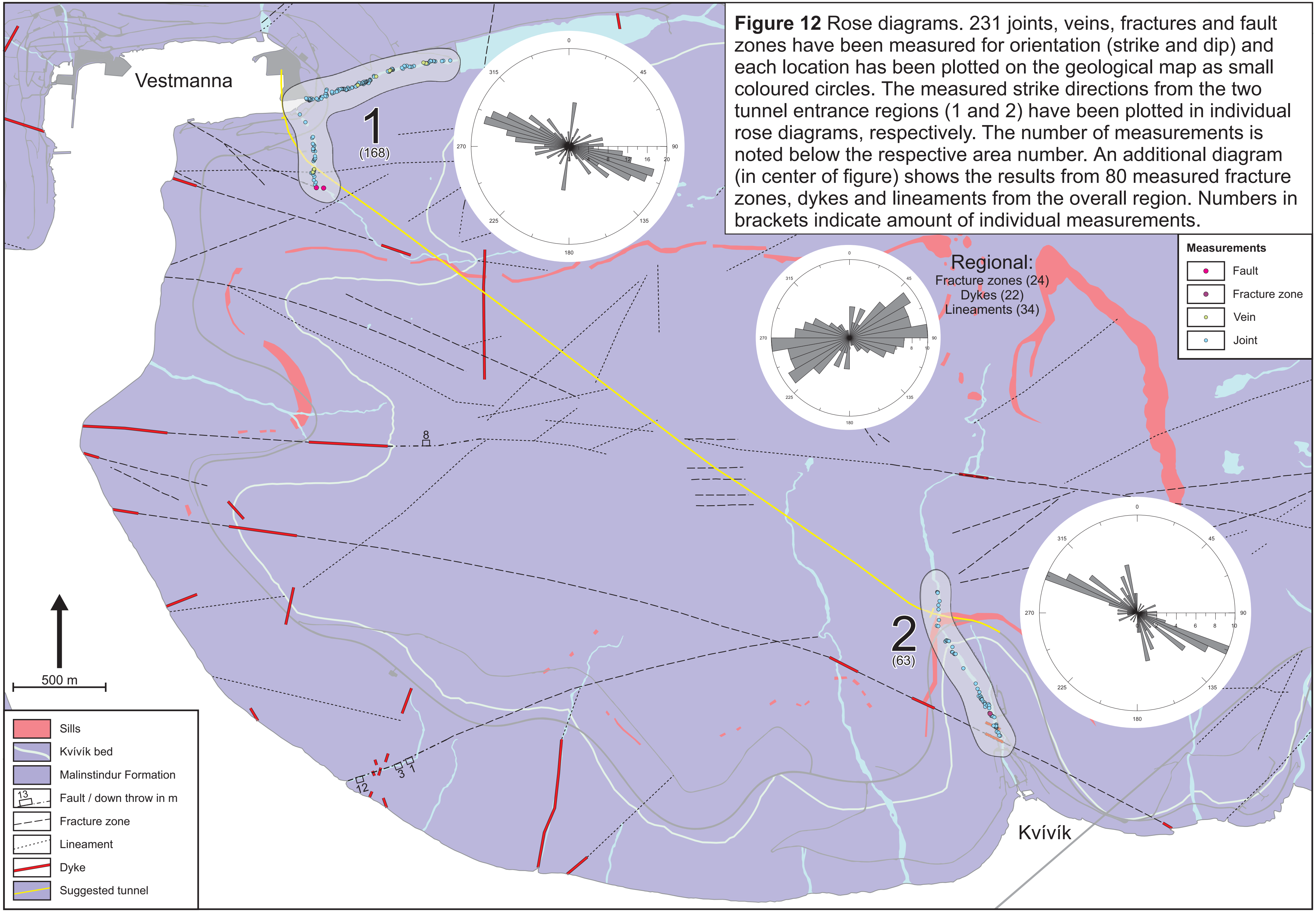

Figure 12 Rose diagrams. 231 joints, veins, fractures and fault zones have been measured for orientation (strike and dip) and each location has been plotted on the geological map as small coloured circles. The measured strike directions from the two tunnel entrance regions (1 and 2) have been plotted in individual rose diagrams, respectively. The number of measurements is noted below the respective area number. An additional diagram (in center of figure) shows the results from 80 measured fracture zones, dykes and lineaments from the overall region. Numbers in brackets indicate amount of individual measurements.

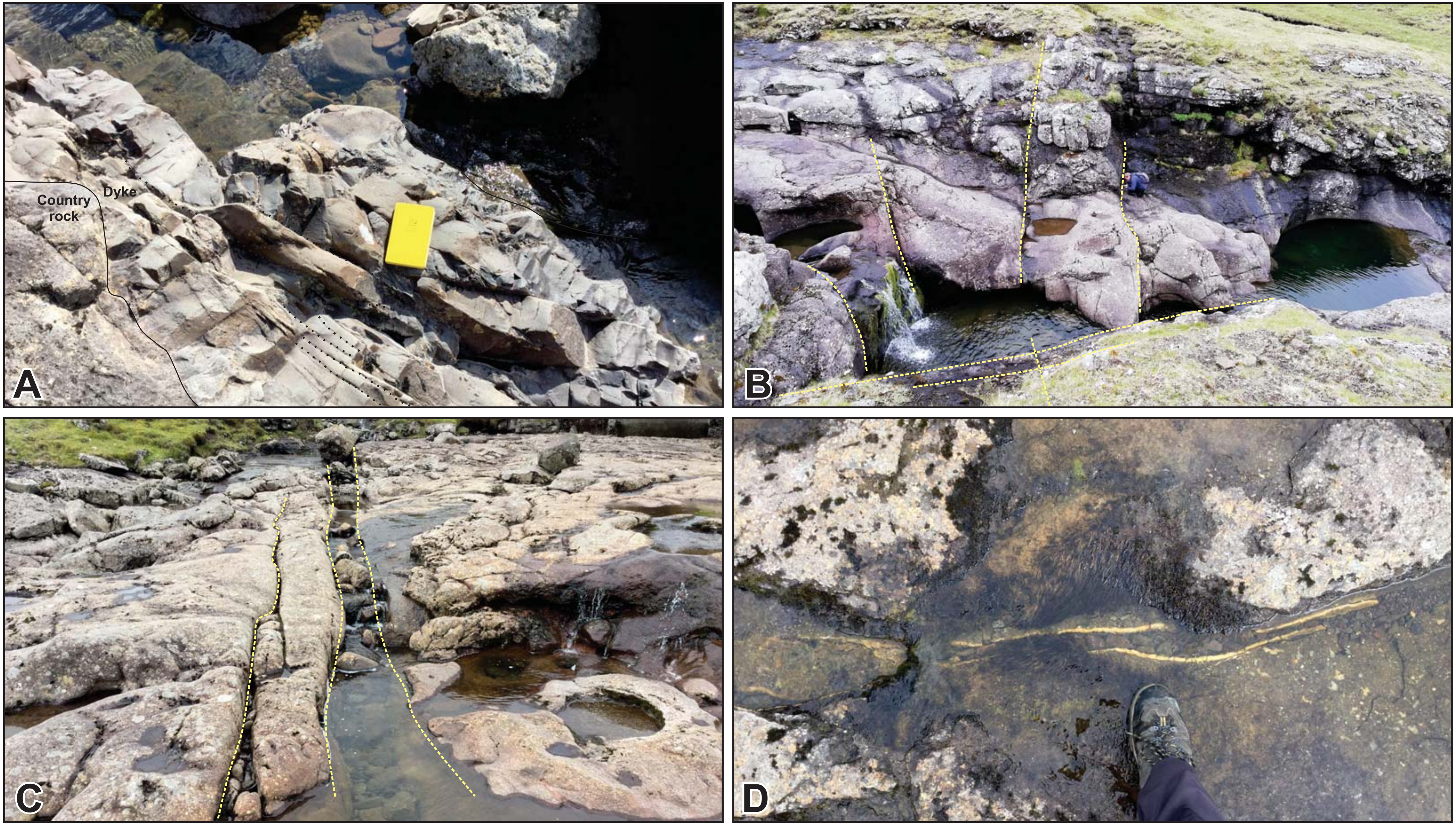

Figure 13 Dykes, joints and veins. **A** Ca 1 m thick dyke that has columnar joints (broken lines) orthogonal to the contact and a set of fractures (dotted lines) parallel to the contact. **B** Joints with a distance of a few meters marked with yellow. See person for scale. **C** Three joints marked with yellow are a few dm apart. **D** Yellowish white veins, that are 2-10 mm thick.

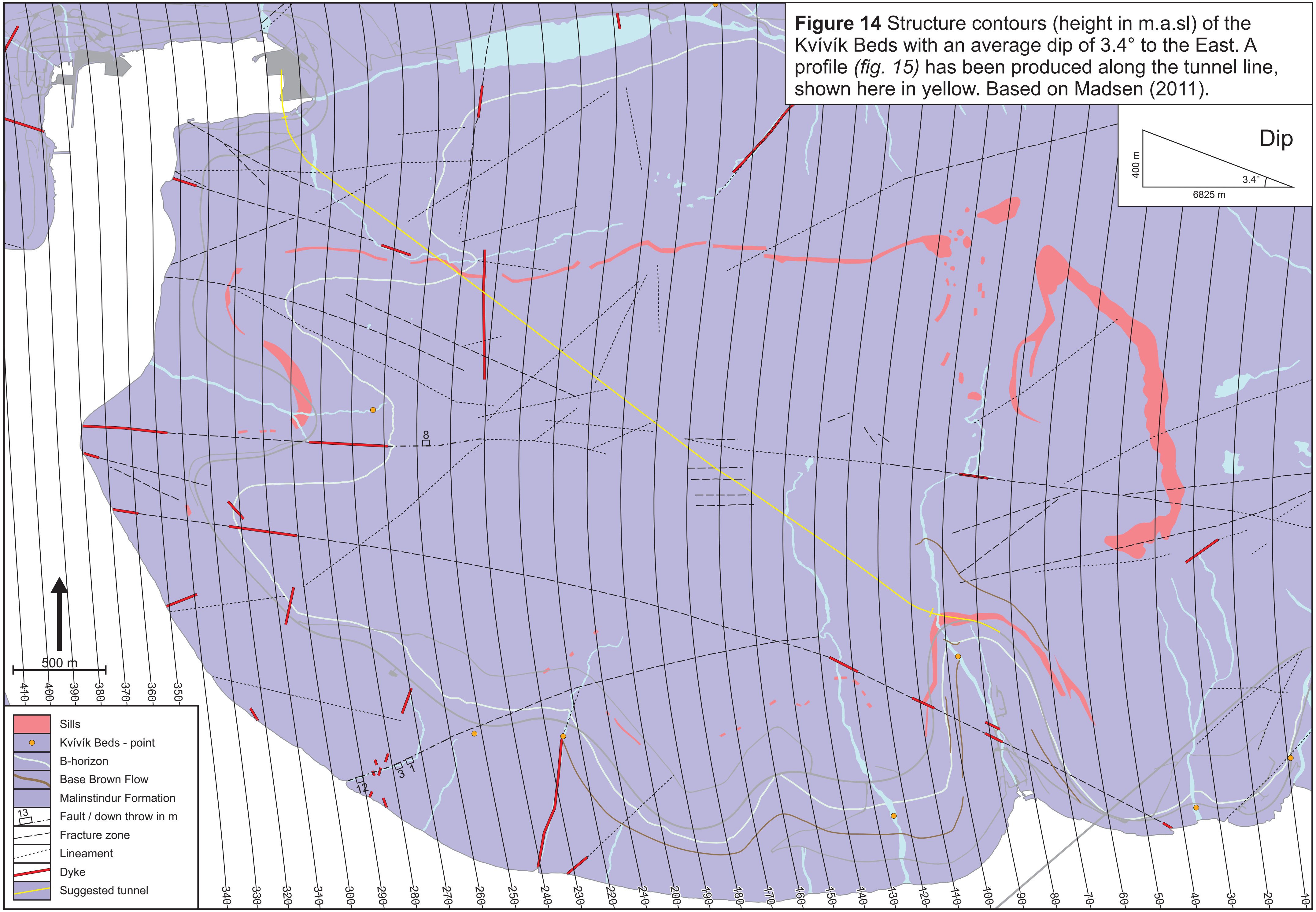

Figure 14 Structure contours (height in m.a.sl) of the Kvívík Beds with an average dip of 3.4° to the East. A profile *(fig. 15)* has been produced along the tunnel line, shown here in yellow. Based on Madsen (2011).

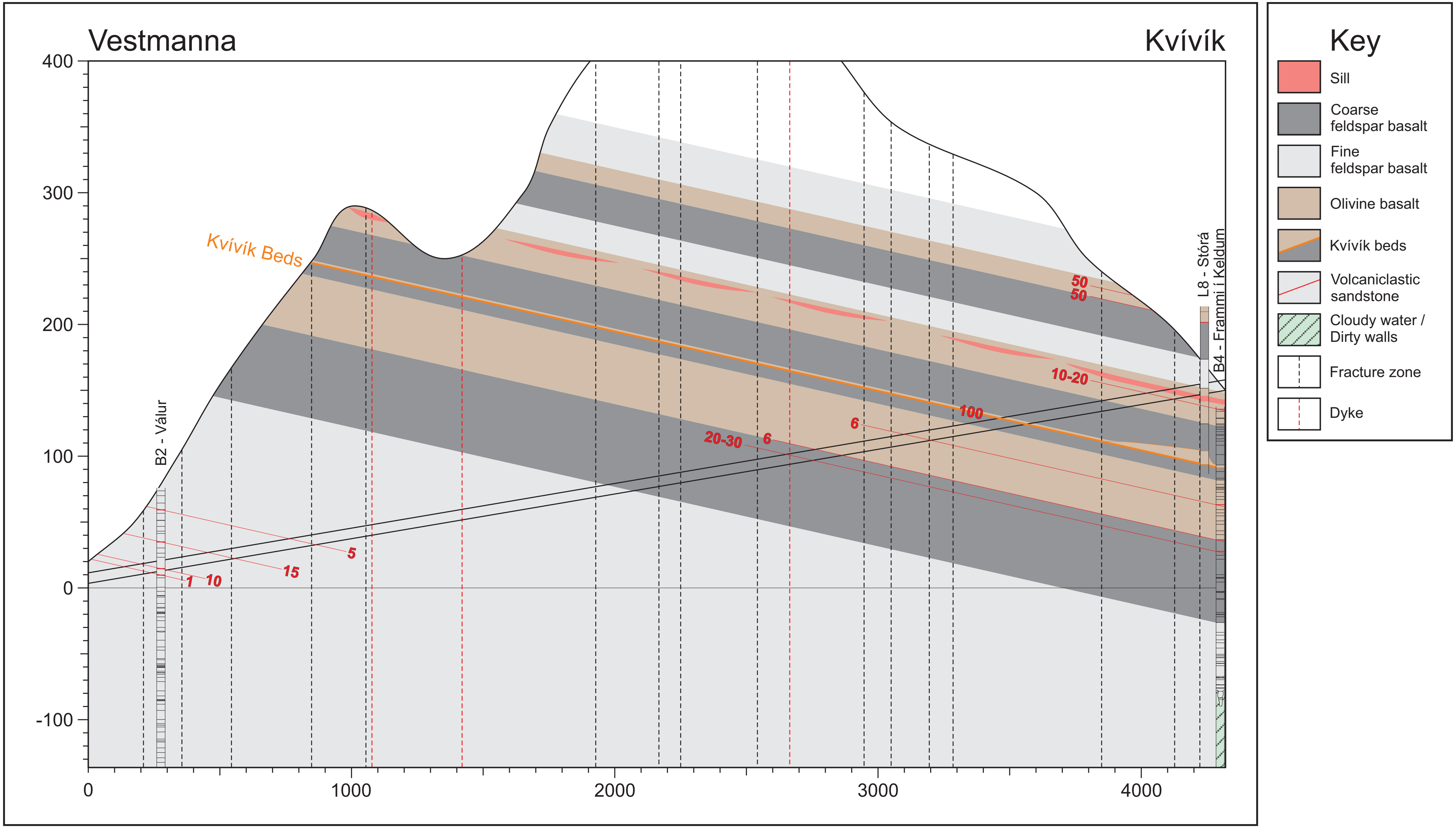

Figure 15 Geological profile along the tunnel line based on the structural contours of the Kvívík Beds (*figure 14*). Details are basedon the logged stream L8-Stórá and boreholes B2-Válur and B4-Frammi í Keldum (figure 6 & 7). The thickness in cm of the volcaniclastic units are written with red numbers. The vertical broken lines indicate fracture zones (black) and dykes (red) along the tunnel route.