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# GEOLOGICAL STUDY OF THE SEDIMENTARY SEQUENCE LITHOLOGY, DEPOSITIONAL HISTORY AND HYDROTHERMAL ALTERATION AT SOG IN TRÖLLADYNGJA AREA, SW-ICELAND

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## ABSTRACT

Findings from surface geological and geothermal investigations carried out at Sog in the Trölladyngja area in SW-Iceland are presented. Good geological information on the stratigraphy of the Holocene sedimentary sequence in Sog area has been lacking, which called for a detailed geological study to unravel the stratigraphical succession and the history of its hydrothermal activity. The findings will contribute to the ongoing geological effort to understand the entire geological/ geothermal system of the Krýsuvík-Trölladyngja-Sandfell area in SW-Iceland.

The stratigraphic succession of the Sog field dates back from the present to probably the Saalian glacial period. The bottom of the profile is clearly marked by the underlying hyaloclastite rocks whereas the top is marked by very recent sediments (brownish fine sandy soil, 0.3 m thick) overlying a thin layer of black volcanic ash from 1226 AD, the Stampar eruption at Reykjanes. The Holocene profile consists of about sixty alternating layers of sand, silt, clay and peat deposited in an ancient subglacial basin between two hyaloclastite ridges from which the sediments derive by erosion. The field is hydrothermally altered from no or very slight alteration at the top of the stratigraphic succession, to very intense alteration of the lower parts, similar to the adjacent hyaloclastite ridges. The hyaloclastites have, in places, been completely altered into bluish smectite and mixed-layer smectite / chlorite clays, in an assemblage with other hydrothermal minerals like gypsum, travertine calcite and kaolinite clay, observed in veins and extinct fumaroles. The hydrothermal activity ceased in late Saalian or Weichselian time and has in Holocene times mostly been restricted to fumarolic activity along some of the faults.


## 1. INTRODUCTION

The island of Iceland has a unique location above sea level, sitting on the oceanic Mid-Atlantic ridge which dissects the island from southwest to northeast, stretching over a distance of more than 400 km in the Iceland area. The ridge is progressively spreading and opens at the rate of 1 cm per year in both directions (west-east). Mantle-derived magma fills the gap and intermittently reaches the surface in volcanic eruptions at this divergent plate boundary between the European and American plates (Gudmundsson and Jacoby, 2007). This active plate boundary is the primary source of the volcanic activity which is accompanied by tectonic activity with frequent earthquakes. As a result of the volcanism and seismicity, the entire island, so to speak, is subject to geothermal activity. Iceland's geothermal systems are divided into high-temperature fields, confined within active volcanic systems within the spreading zone across the island, and low-temperature areas outside the active rift zone.

Sog area is mostly confined to a sedimentary basin trapped between hyaloclastite ridges. The elevation range is from 160 to about 400 m above sea level (m a.s.l.). The sedimentary sequence in the basin mostly consists of eroded material from the adjacent tuffaceous hyaloclastite ridges. The uppermost 10-12 m represent the Holocene sequence with peat and occasional tephra layers derived from some active volcanoes interspersed with clay layers. The basin was later subject to very rapid and intense erosion which drained the basin, leaving deep gullies behind. A complete sedimentary sequence was left behind in places outside the gullies, the details of which were the subject of the present study, with respect to both sedimentology and hydrothermal activity.

This study is a part of a six month training course at the United Nations University Geothermal Training Programme (UNU-GTP) in Iceland in 2008. The objective was to obtain practical experience in geological and geothermal exploration. The geological exploration offers practical training in basic geological mapping, which is usually the first step in geothermal exploration of an area. Tectonic and geothermal features become a part of the geological map, which later is used to site drill holes, be it shallow geothermal gradient wells, deeper exploration wells or production wells. The UNU-GTP field training is conducted in active geothermal fields as well as in deeply eroded volcanic fields in the roots of extinct volcanoes and their associated hydrothermal systems.

The present report deals with geological investigations of a sedimentary sequence within the Sog area. The purpose of the study was to unravel the depositional sequence, with respect to its lithology, and the subsequent hydrothermal alteration that prevailed in the area. The findings from this study will contribute to the on-going geological/geothermal exploration of the Krýsuvík-Trölladyngja-Sandfell geothermal system.

## 2. THE STUDY AREA

### 2.1 Location and accessibility

The study area is located in the southwest part of the country, by road about 38 km west of Reykjavík, the capital of Iceland. The field's longitude is about 22°05' and 22°07' W, and the latitude 63°55' and 63°58' N (Figure 1). The area is more easily accessible in dry weather than during rainy days as the steep clayish slopes of the gullies from the centre of the valley become quite slippery and sticky when wet.

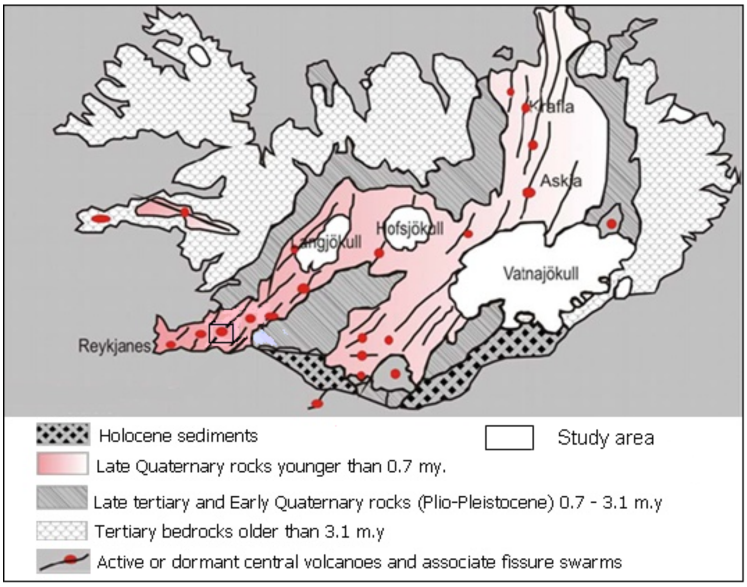


FIGURE 1: Generalized stratigraphic map of Iceland (adapted from Jóhannesson and Saemundsson, 1999)

### 2.2 Previous work

The area has previously been investigated in several research programmes, mostly at regional scale, in which geology and geothermal studies were carried out to assess the geothermal potential. Four deep geothermal wells have been drilled close to the study area, the latest two reaching to almost 3000 m depth. The highest measured bottom hole temperature is about 360°C (Fridleifsson et al., 2002; Kristjánsson et al., 2006; Mortensen et al., 2006). Both wells are relatively poor producers and further drilling activity needs be undertaken in order to find zones of higher permeability (Fridleifsson, pers. comm.).

In 2007, an extensive detailed geothermal exploration programme was launched by the Hitaveita Sudurnesja Ltd. energy company following a grant of a 10 year geothermal research licence of the Krýsuvík-Trölladyngja-Sandfell area. The exploration programme involves detailed geological and geothermal mapping, and detailed geochemical and geophysical surveys. Data from the present study may add some important knowledge to the geothermal evolution of the Trölladyngja geothermal field.

### 2.3 Methodology

The road map of Iceland was helpful for orientation and accessibility to the study area. Topographical maps, aerial photos and GPS were used for geo-references and interpretation of the topographical and tectonic features. The information presented in this report is based on geological investigations in which the following work was carried out:

- Literature review of the previous geological studies;
- Geological investigation on the rock units for identification of the major rock types and their lateral extension to delineate the lithological boundaries and the stratigraphic succession;
- Structural mapping for recent tectonic activities;
- Hydrothermal mapping to delineate the extent of hydrothermal activity within the area; and
- Sampling for absolute C-14 dating of a few Holocene peat layers.

## 3. FIELD INVESTIGATIONS

### 3.1 Geology and stratigraphy of the study area

The geology of southwest Iceland is characterised by volcanic systems ranging in age from Late-Quaternary to Holocene (younger than 0.7 million years - Ma), and consists of volcanic rocks, mainly basaltic tuffaceous hyaloclastites formed in subglacial volcanic eruptions during glacial periods, and subaerial lava flows formed in fissure eruptions during interglacial periods and the Holocene. The most prominent features are several parallel hyaloclastite ridges, 4-5 km long and NE-SW trending faults and fissures.

In the Sog – Trölladyngja area, the geology can be divided into seven units based on chronological order (see Figure 2):

*Unit VII*
This youngest unit is comprised of two lava flows formed in late Holocene time, located on the northwest and southeast sides of the hyaloclastite massive in the central part of the study area. They consist of scoraceous and massive lavas formed in two volcanic fissure eruptions. The volcanic craters themselves are scoraceous cones showing lithofacies from tephra to welded lavas.

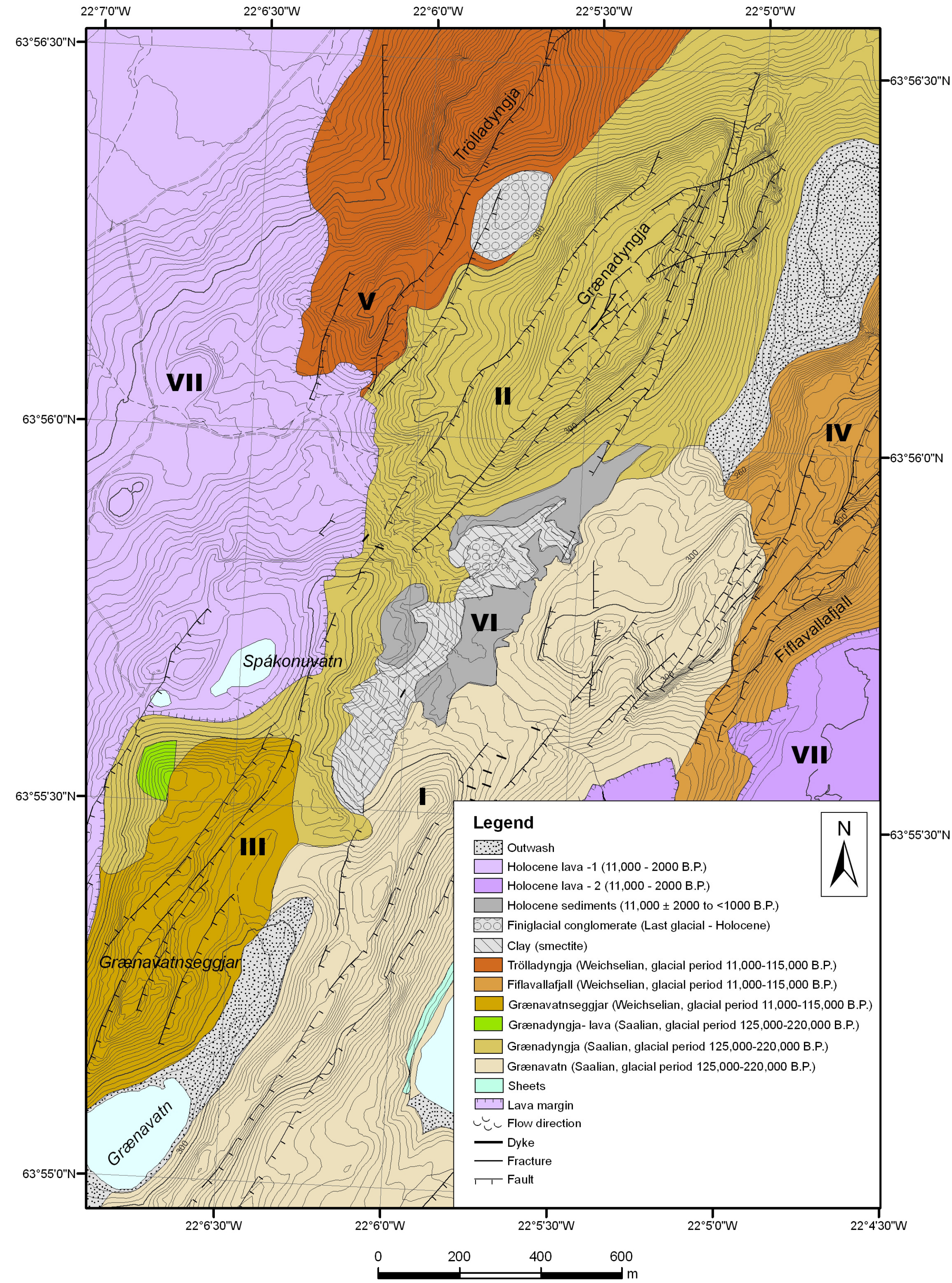


FIGURE 2: Geological map of the Sog – Trölladyngja area

*Unit VI*
This unit comprises a sedimentary formation formed by the deposition of eroded material from the enclosing hyaloclastite ridges and was deposited in a closed basin during the entire Holocene (11,500 years BP to present). The lowest part of the sediments extends way down into the Weichselian, and possibly into the Saalian.

*Unit V*
This unit comprises the Trölladyngja hyaloclastite ridge formed sometime during the Weichselian subglacial period (in the time span 115,000-11,500 years BP) located on the north-west side of the field area and consisting of dense feldspar porphyritic hyaloclastites.

*Unit IV*
This unit covers the Fíflavallafjall hyaloclastite ridge also formed sometime during the Weichselian subglacial period, located on the northeast side of the field area and composed of sparse feldspar phyric hyaloclastites.

*Unit III*
This unit comprises the Graenavatnseggjar hyaloclastite ridge formed in subglacial eruptions sometime during the Weichselian period, located on the southwest side of the field area and consisting of sparse feldspar phyric hyaloclastites. The relative age relationship between units III, IV and V is not known.

*Unit II*
The apparently second oldest formation in the field area comprises an aphyric hyaloclastite ridge, the Graenadyngja ridge, which trends parallel to Unit I, separated from it by a morphological depression (the sediment catchment basin). This unit was formed sometime during the Saalian subglacial period (often referred to as the 2$^{nd}$ last glacial, 125,000-220,000 years BP).

*Unit I*
This oldest rock unit in the field area comprises the aphyric Graenavatn hyaloclastite ridge, which trends NE-SW, formed in a subglacial eruption during the Saalian glacial period.

## 3.2 Deposition history of the sedimentary sequence

### 3.2.1 Introduction

The depositional history of the Sog sedimentary sequence dates from Holocene, and all the way back to possibly the Saalian glacial period. Weathering and erosion of the Saalian hyaloclastite ridges is the main source of the sedimentary sequence, the deposition of which in places in the lower section shows a prominent lacustrine sedimentary character. The lacustrine character is suggestive of a subglacial lake during the formation of a part of the sedimentary succession, and its hydrothermal alteration may suggest that the lake owed its existence to hydrothermal activity. Most of the sediments in the profiles are unconsolidated, and consist of slightly or non-weathered primary hyaloclastite products (including ash, cinders, lapilli, pumice, vesicular pyroclastics, blocks or volcanic bombs) that eroded from the hyaloclastite ridges into the basin. While the hydrothermally altered lower part of the succession is inorganic, the organic content in the Holocene part of the succession is quite variable. The organic soil consists of several peat layers, some of which form quite thick beds of more than a metre, and they occur all the way from the bottom to the top of the Holocene profile within the sediment unit.

The Holocene part of the sedimentary succession is parentally eroded material from the surrounding rocks and an occasional tephra layer airborne from some erupting volcanoes. The Holocene sediments consist of unaltered to weakly weathered soils while the Pleistocene part of the sequence consists of eroded material only. The sedimentary succession can be divided into three main depositional phases.

### 3.2.2 Formation of the basin

This phase represents the earliest material within the sedimentary basin which began to form immediately after the Graenavatn and Graenadyngja hyaloclastite eruptions during Saalian (Figure 3). During this period, the sedimentary deposition is bound to have been very slow as the sediments were derived mainly from rock material which melted from the bottom of the glacier by possible hydrothermal activity at that time. The maximum alteration of the earliest sediments consists of bluish smectite / mixed-layered clays, exposed on both sides at the bottom of the Sog valley (Figure 4).

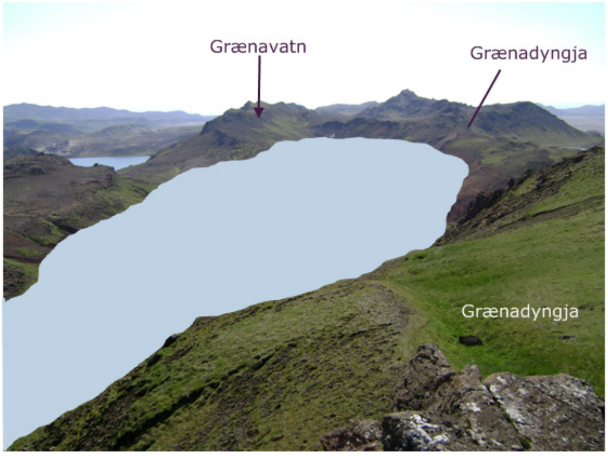

FIGURE 3: A reconstructed paleo-basin in the Sog-Trölladyngja basin area


FIGURE 4: Altered hyaloclastite at the bottom of Sog valley

### 3.2.3 Deposition of sediments

During this phase sediments were deposited under water, in a closed basin with most of the material being derived from the surrounding hyaloclastite ridges (Graenadyngja and Graenavatn). Clear evidence of this erosion is the deposition of the conglomerate in the northeastern part of the basin, where the conglomerate overlies the bed-rock unconformably. It consists of boulders (>30 cm) of tuff and fragments of basalt, pumice and scoria (Figure 5). Sedimentation continued into Holocene, including soil and some tephra layers. The Holocene sediments formed a sequence of alternating layers of sand, silt, clay and peat, intercalated with fragments and pebbles of tuff, basalt and scoria with an average vertical total thickness of about 15 m (Figure 6).


FIGURE 5: Apparent conglomerate deposit in the Sog area overlying the bedrock hyaloclastite and underlying the Holocene sequence


FIGURE 6: A section of a Holocene sediment profile in Sog

### 3.2.4 Erosion of the basin

Sometime during late Holocene (<1000±200 years BP), extensive drainage and erosion of the sedimentary basin took place when the basin opened on the northwest side, after the Graenadyngja hyaloclastite ridge had been tectonically faulted resulting in a very extensive erosion of the basin (Figure 4).

The depositional area of the Holocene erosion of Sog is extensive west of Sog, forming a fan across Höskuldarvellir plains to Sóleyjarkriki (~2 km). The outwash sediments of Trölladyngja overlie lavas of 3,000-2,000 years BP. Between them is a thin layer of black volcanic ash, probably derived from one of the Reykjanes eruptions, possibly from 1226 AD, which would imply that the erosion occurred after 1226 AD. The sediments were deposited within a very short period of time due to the large transporting force and flow-speed, rendering them unsorted and forming a thick cover. However, in the lower areas of the flood plain the transporting force decreased, the sediments settled slowly and formed a thin cover of sediments (30-100 cm) underlain by the lava.

## 3.3 Lithology

The lithology of the Sog area can be categorized into three main groups based on rock types and mineralogical assemblage.

*Hyaloclastites*
This group comprises hyaloclastite rock units which mainly consist of yellowish brown tuff, pillow breccias, and rare pillow lava. The oldest hyaloclastite rocks are aphyric, but the youngest are porphyritic basalts.

*Altered hyaloclastites*
This group comprises hydrothermally altered hyaloclastite rocks. In Sog valley they form extensive deposits of smectite bluish clays in the central part of the depression between the two hyaloclastite ridges (Units I and II above). The Sog stream with its tributaries exposes the clay and gives a clear view of the underlying altered hyaloclastite units (Figure 4).

*Sediments*
This group includes Holocene sediments, deposited in the central part of the area. The sediments consist of fine and coarse sand, gravel, silt, clay and peat derived mainly from the surrounding hyaloclastite ridges and deposited under water. Conglomerates are notable in the western part of valley close to the western edge of the central basin, probably deposited during the intense erosion when the basin had drained out.

## 3.4 Tectonic features

The main tectonic features in the Sog area are north-easterly trending structures, faults and fissures trending obliquely to the plate boundary. The sub-parallel orientation of the hyaloclastite ridges and lava crater rows with the fault and fissure trends clearly shows that they were formed in the same tectonic environment. Faults younger than the hyaloclastite ridges are quite clearly exposed alongside the hyaloclastite ridges but are often concealed by younger sediments in lower ground areas or are covered by Holocene lavas.

*Faults*
Of the three hyaloclastite systems in this area, Graenadyngja has been intersected by many major faults. One of the faults intersects this ridge on the northeast side, trending NE-SW and cutting the northern slope of south Graenavatn ridge on the edge of Lake Djúpavatn with a throw direction to the

northwest. The extension of this fault was just observed to the south where it cuts through Holocene sediments, but the relationship is not clear as the sediments are younger than the fault. From this observation, it can be assumed that this local fault affected the sedimentary sequences as well.

Another fault line lies in the western part of the Graenadyngja ridge, trending NE-SW, almost parallel to the above fault. The fault line is very clear higher on the ridge but fades out north of Graenadyngja where it intersects with Trölladyngja. However, its extension can be traced across the southwest edge of Lake Spákonuvatn; the throw direction of this fault was southeasterly.

A fault graben is another remarkable feature within Graenadyngja, affecting the crest of the ridge, forming a depression, about 5-6 m deep and about 40 m wide, trending NE-SW. Along it, several deep sink-holes can be observed, partially infilled with sediments.

On aerial photos several minor lineaments or faults were visualized, trending NE-SW parallel to the Sog valley, but follow-up ground observations did not reveal any features supporting their existence.

*Dykes*
Aphyric basaltic dykes are clearly notable in the southern part of Graenavatn, 0.3-4 m wide, trending northwest and dipping between 80° and vertical (Figure 7). Dykes are also notable in the Sog valley outcropping in the altered hyaloclastites. They are 0.3 m wide with a general trend between 30-40°NE and vertical. The dykes cluster in the median zone of the two ridges on either side of Sog. In the zone of most intense hydrothermal alteration, minerals like gypsum, zeolite, calcite and quartz occur and also aragonite as fracture fillings (Figure 8).

FIGURE 7: A basaltic dyke in the study area

FIGURE 8: Gypsum crystals found in Sog

*Landslides*
Landslides are normally caused by topographical instability. In Iceland, most are usually caused by glacial erosion. During deglaciation, unstable slopes may slide down the slopes, sometimes triggered by earthquakes. Within the field, small landslides are common in unstable grounds, especially within the central part of the Sog basin where the hyaloclastites have been altered into clays that lubricate the groundmass, making it easy for them to slide down.

*Volcanic craters*

Of interest here is the NE-SW linear orientation of craters on the south-west side of the Graenadyngja hyaloclastite ridge. This trend reflects the tectonic relationship between the craters and the fault systems. There is no doubt that those craters ejected eruptive material from an eruptive fissure that may have been connected to a magma chamber at depth.

*Veins*

Veins are common in the central part of the area, especially in the valley in the underlying altered hyaloclastite. The veins contain secondary minerals like zeolites, calcite, kaolinite and other clays (Figure 9). Currently, there is no hydrothermal activity within the field apart from a few tepid springs near the outflow gorge of the Sog stream.

FIGURE 9: Veins in hyaloclastite bedrock

## 4. DETAILED DESCRIPTION OF THE HOLOCENE SEDIMENTARY PROFILES

This study of the Holocene sediments is based on five detailed profiles from different localities: four profiles from within the Sog valley and one profile from the northwest part of the area in the fluvial fan down-stream of Sog. The profiles comprise more than sixty alternating layers, of more or less similar character but with variable lithological compositions, which probably reflect the source rock more than the nature of the sedimentation. The bluish clays and dark-brown peat are the dominant sediments as they appear in all the profiles and throughout the profile stretch. Fine black volcanic ash is another notable but unique layer (the Stampar layer) as it appears in all the profiles as a second layer from the top of the profile following brownish sandy soil. This ash was used as dating reference due to its known age, dating from 1226 AD (Saemundsson, pers. comm.).

There is no indication of hydrothermal alteration activity affecting the Holocene sediments as the peat and ash layers within them are fresh. The sediments at the bottom of the profile though are in conformable contact with the altered underlying hyaloclastites. Detailed descriptions of individual layers are given below and reference is made to the profiles shown in Figures 10-14.

*Brownish sandy soil*

This is the uppermost layer which supports vegetation common in all areas, deposited mainly by water and wind with a grain size range from fine to coarse sand and a layer thickness between 10 and 40 cm, except where erosion has taken place. This layer overlies fine black volcanic ash.

*Fine black volcanic ash*

This layer is commonly notable in basins and on the flat lowland areas, preserved from surface soil erosion. It is fine to medium-coarse grained, black in colour, sometimes brownish black when intercalated with brownish sandy soil where the two were contemporaneously deposited by free fall and wind erosion, respectively. The layer ranges between 0.5 and 2 cm in thickness. This tephra layer is believed to be from the historic Stampar eruption at Reykjanes occurring in 1226 AD. Absolute dating results have not been made but the age is based on historical documents (Jóhannesson and Einarsson, 1988).

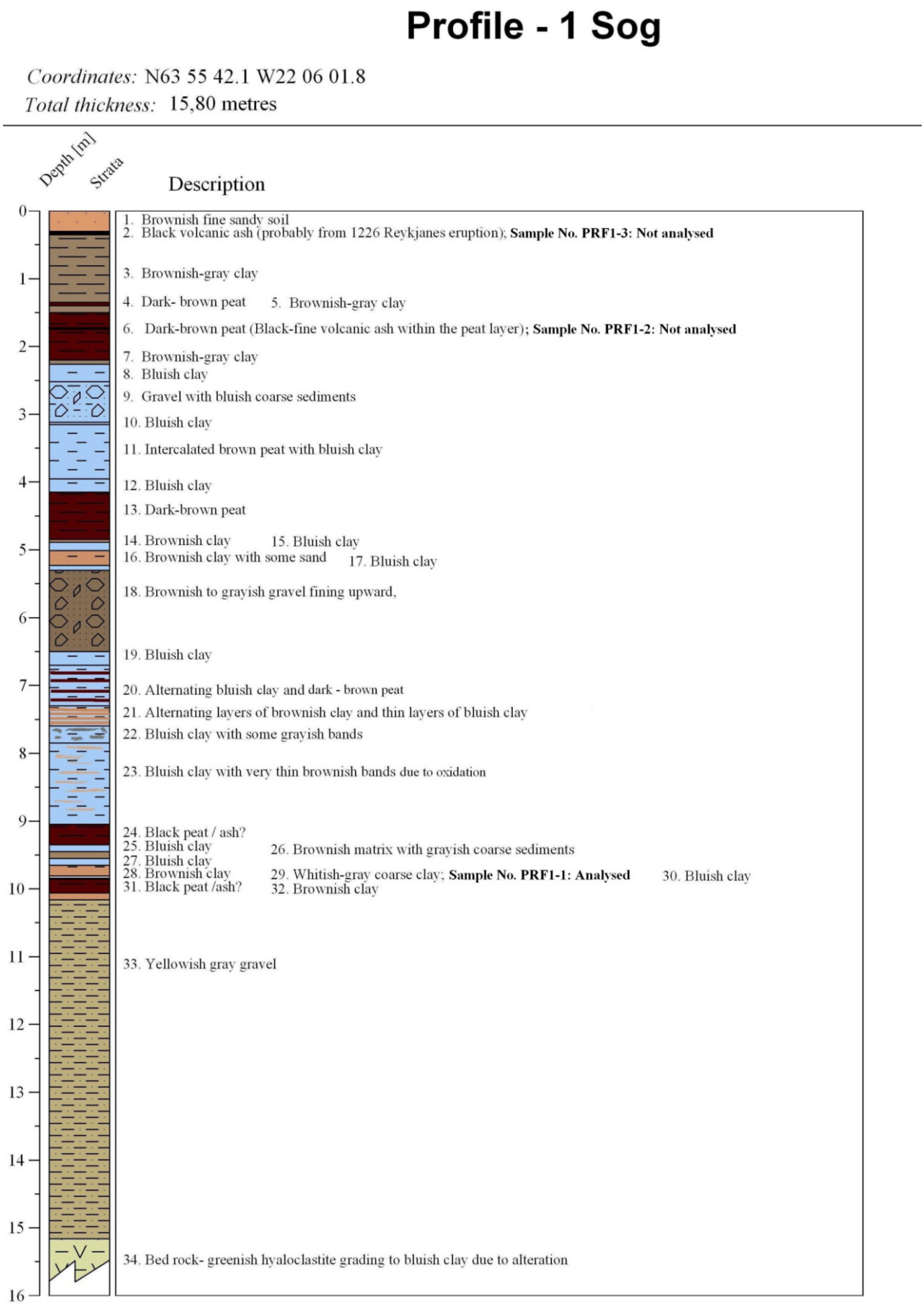


FIGURE 10: Depositional profile 1 from Sog

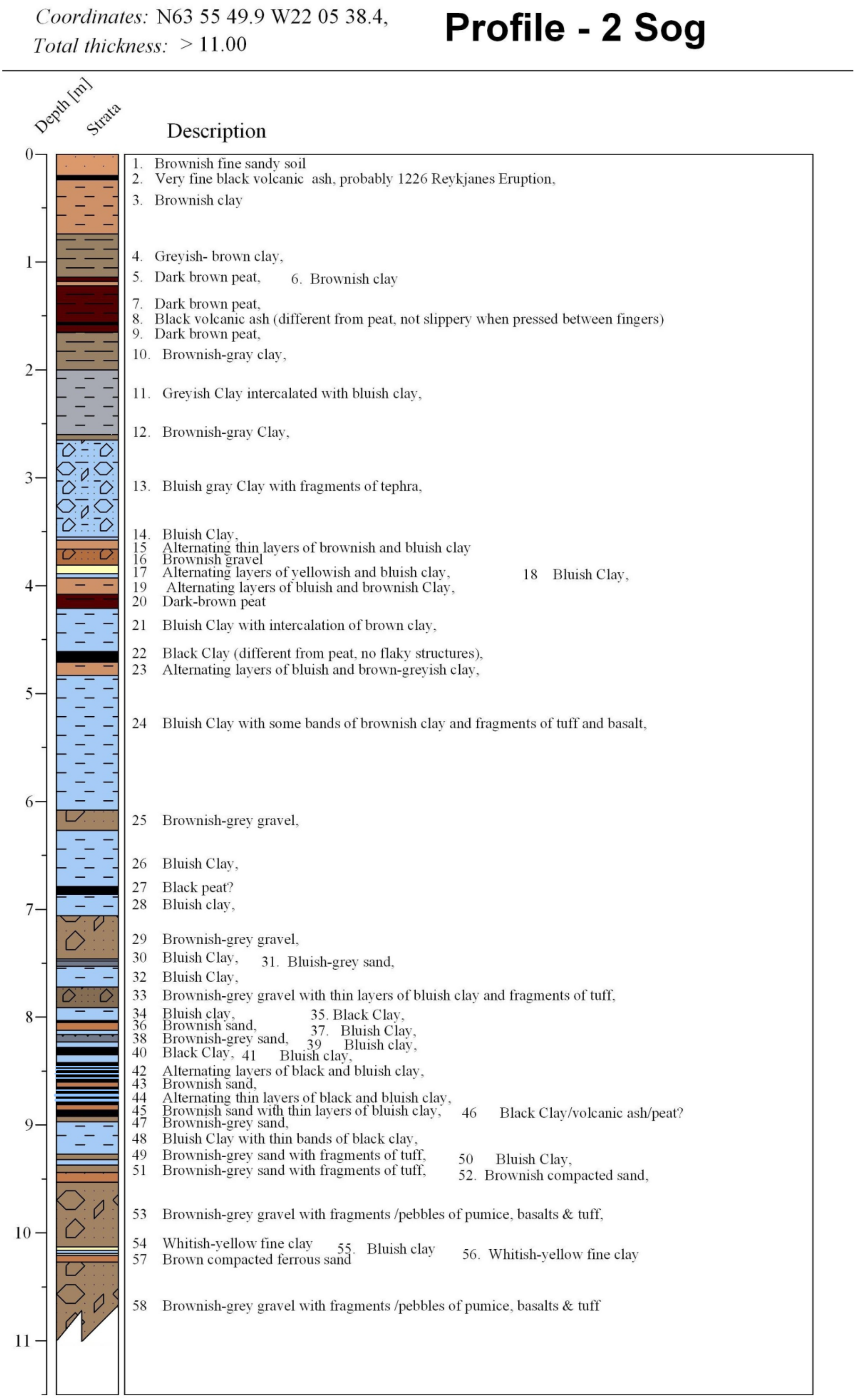


FIGURE 11: Depositional profile 2 from Sog

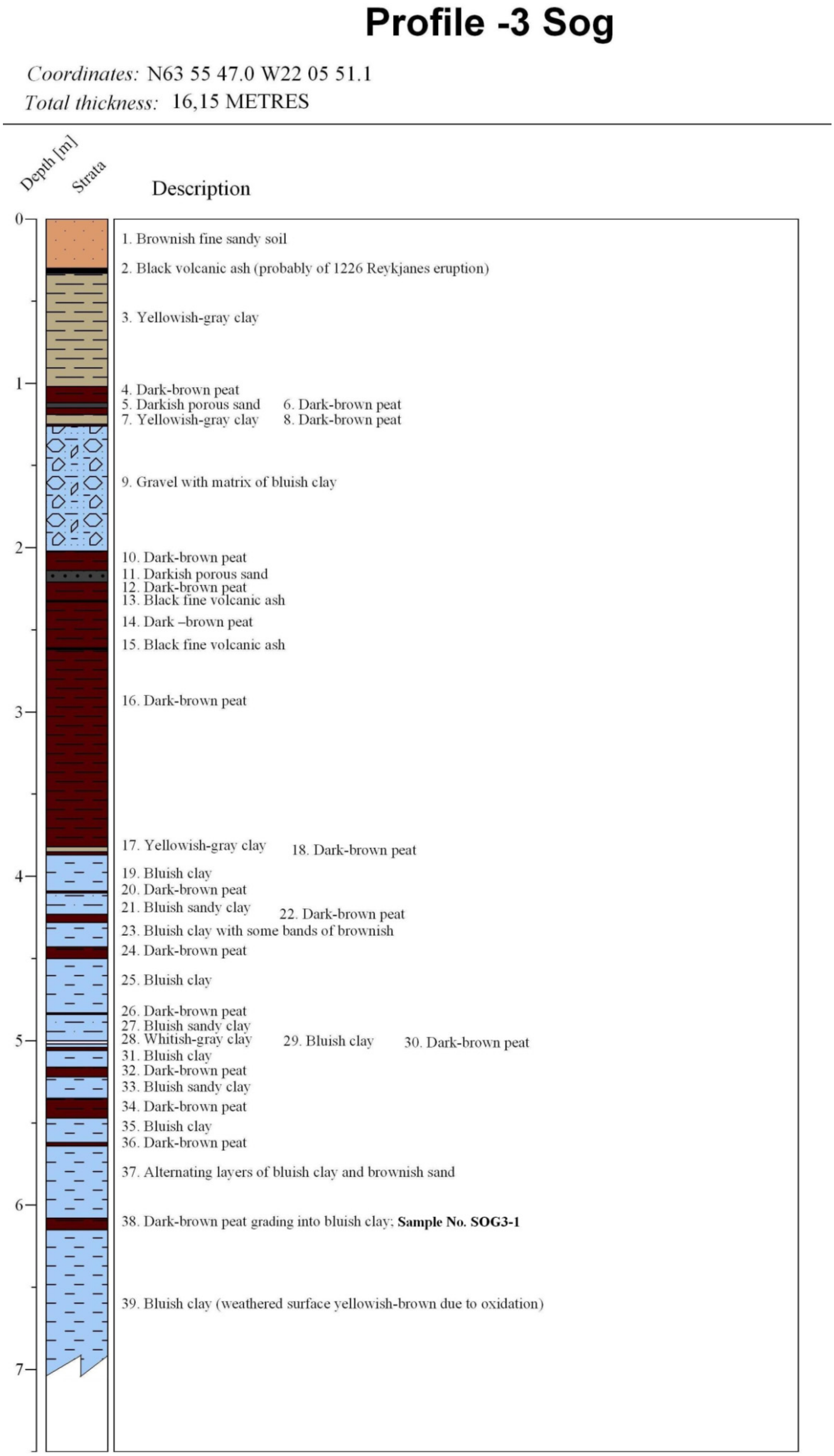


FIGURE 12: Lithological profile 3 from Sog

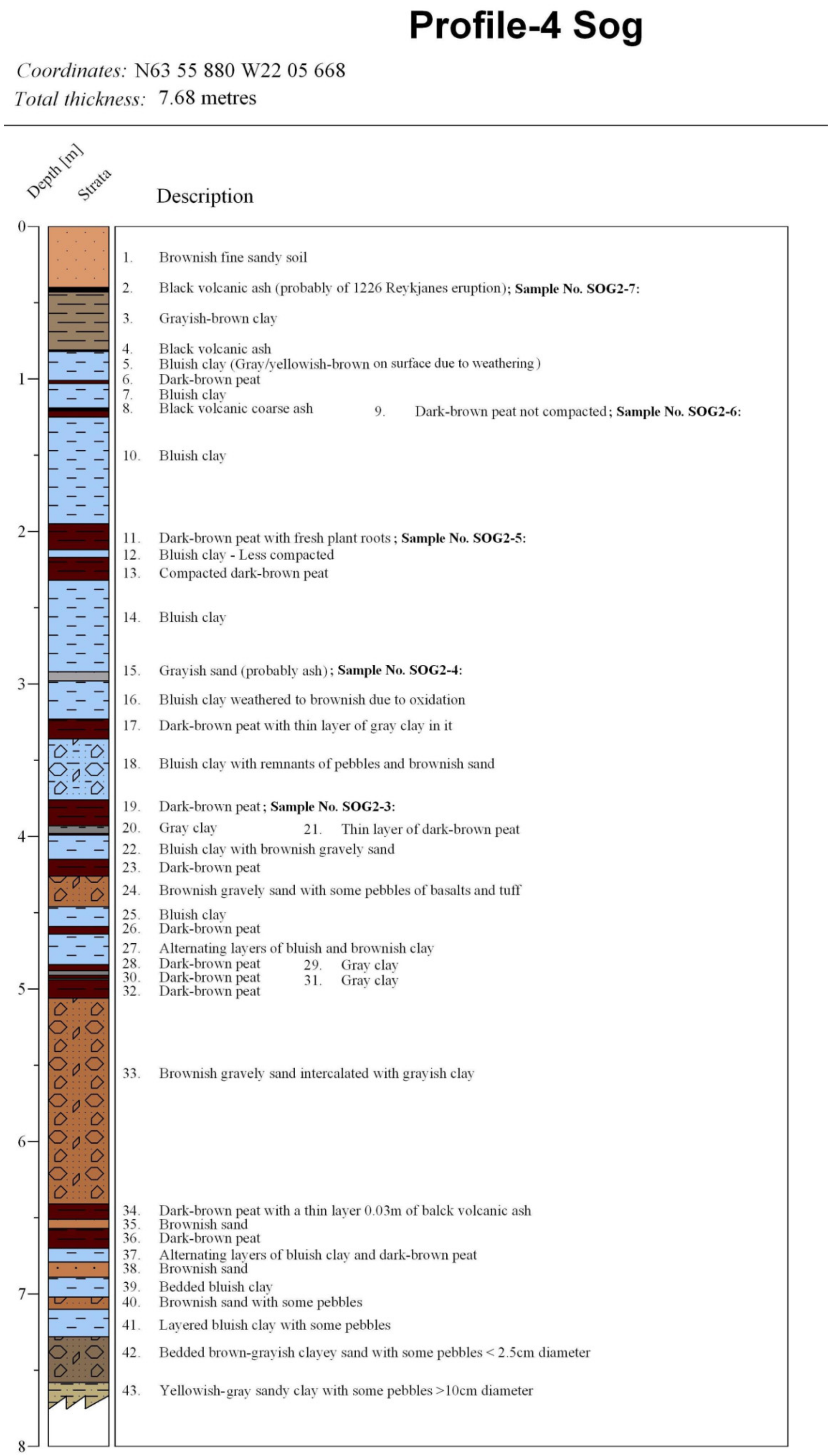


FIGURE 13: Lithological profile 4 from Sog

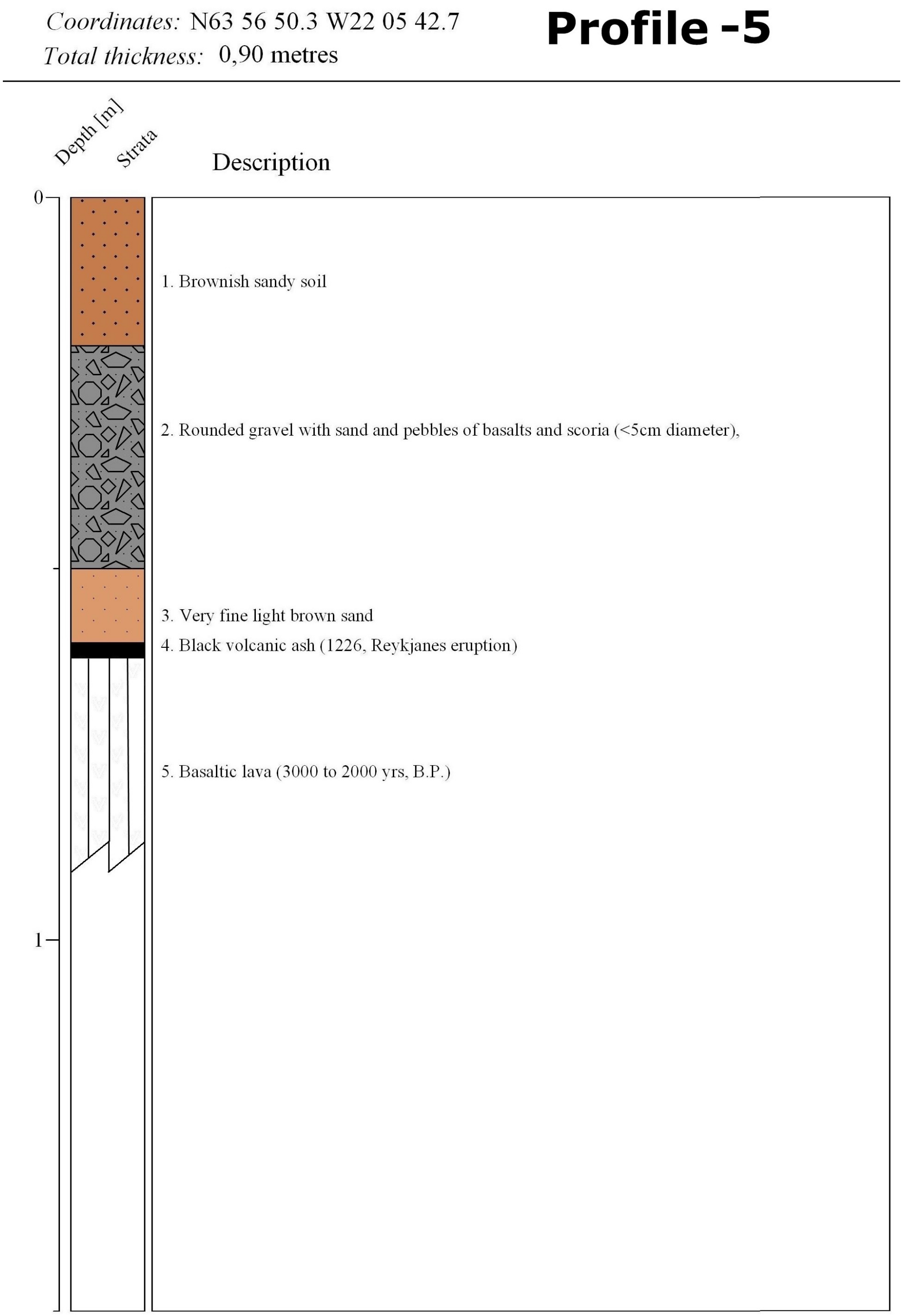


FIGURE 14: Lithological profile 5 from Höskuldarvellir

*Brownish-gray clay*
This is the third layer, existing in all three profiles with a layer thickness of about 1 m. It is brownish-grey in colour but, in some cases, the grey colour increases down the layer; the grain size ranges from coarse sand on top to very fine clay at the bottom, reflecting a decrease in the energy of deposition. It consists of sparse rounded fragments of clastic hyaloclastites, repeatedly alternating with other layers throughout the profiles.

*Dark-brown peat*
The peat, which forms several layers of variable thickness, appears in all the profiles and is very notable with individual layer thicknesses between 1 and 120 cm. It is dark-brown in colour, composed of carbonaceous material, mainly plant remains, and is generally very fine, soft and porous. Two samples collected from the top and bottom of the layer were submitted for C-14 age dating.

*Bluish clay*
Those layers consist of a very fine clay material, non-laminated with grain size < 1/256 with individual layer thicknesses between 0.5 and 125 cm. In some cases, the bluish clay is intercalated with thin layers of brownish clay and fragments of tuff, basalts and scoria, especially in profile 2 (Figure 11). This clay is bluish in colour but, when exposed, oxidizes very quickly to yellowish brown. This can be noted in exposed sections where the sections may appear yellowish-brown on the weathering surface while bluish clay is found just below the weathering surface.

*Reworked hyaloclastite (sedimentary hyaloclastite)*
The reworked hyaloclastite (sedimentary hyaloclastite) forms the lowest part of the sedimentary succession in the Sog sedimentary basin. It is mainly composed of tuffaceous hyaloclastites, clastic rock fragments of tuff, scoria, basalt and pumice. Generally, the first 4-5 m downwards consist of yellowish-grey gravel, which gradually turns into fine material and the colour becomes bluish and material properties turn to that of clay. This marks the horizontal boundary of the alteration of the hyaloclastites to smectite. An exception to this was observed at profile 3 (Figure 12) where the 4-5 m of yellowish-grey gravel were missing; this reflects that the intensity of alteration was quite high to reach this level. One fact which can support this observation is the presence of highly altered ground just to the south of this location. The deposition of hydrothermally altered minerals, related to a dyke intrusion, which trends northeast through this area, may have influenced this intense alteration.

## 6. HYDROTHERMAL ALTERATION

Mapping of the hydrothermal features, both extinct and active (hot and warm springs, hot-grounds, fumaroles, mud-pots and altered ground) was carried out, as well as some soil temperature measurements to delineate the boundaries of the hydrothermally altered fields. By studying the types of the hydrothermally altered minerals, such as smectite, mixed-layer clays (MLC), kaolinite, zeolites, quartz, calcite, aragonite, pyrite and gypsum, the pressure and temperature conditions leading to their formation could be deduced.

The most prominent features regarding active manifestation are fumaroles and several altered whitish yellow grounds, easily recognized in the field by their distinctive colour. Two active fumaroles were found with temperatures of about 100°C; two springs seeping warm water with temperatures between 14 and 16°C were also observed. Observation also revealed that most of the altered whitish-yellow grounds were linked to extinct fumaroles from which aragonite, travertine calcite, gypsum and kaolinite were deposited, and quartz, calcite and zeolites deposited in veins.

*Kaolinite*
Kaolinite is commonly deposited within acidic surface environment, deposited as a residual product of leached ground. Within active mud pots, the kaolinitic clay forms gray slurry that, during boiling, sounds like the boiling of a thick porridge. Kaolinite was recovered in extinct fumaroles and in gray mud-pots in the active fumaroles, boiling at ~ 100°C (Figures 8 and 15).

*Calcite and aragonite*
Calcite and aragonite are common within the central part of the Sog valley, especially in the altered hyaloclastite bedrocks, filling fractures (veins) of up to 20 cm thick (Figure 9).

*Gypsum*
Gypsum crystals were recovered from dyke-associated hydrothermal activity in the altered hyaloclastites in the south central part of Sog valley (Figures 8 and 16).

FIGURE 15: Mud pots in the Sog area

*Travertine*

Travertine was deposited from fumarolic activities at two localities in the southern part of the valley (TRV-1 & TRV-2 in Figure 16). Both locations are now extinct fumaroles aligning in a general NE-SW trend but without clear evidence of connection to a fault. The travertine was deposited and superimposed on top of hyaloclastites which had been completely graded into bluish gray clay (Figure

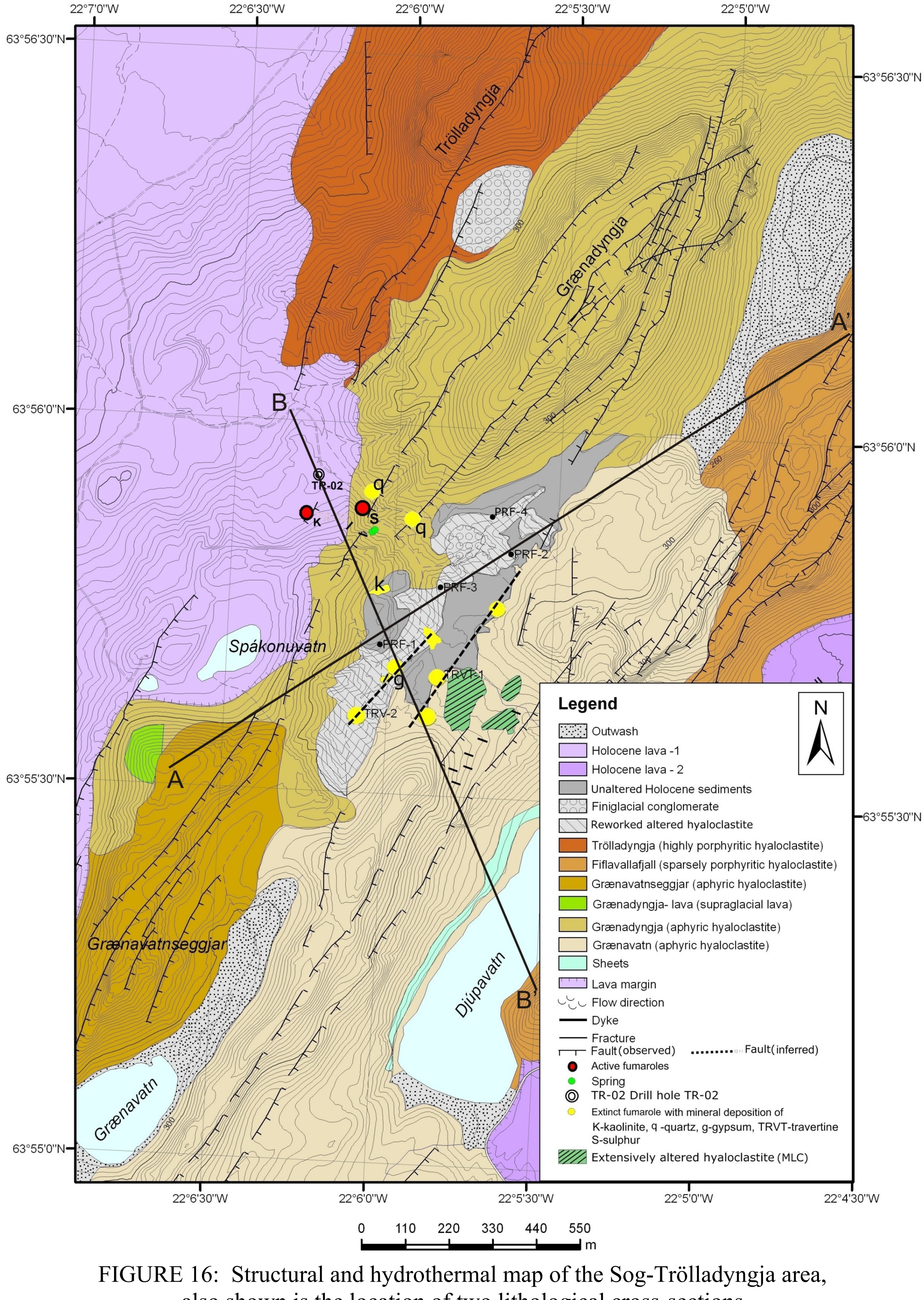


FIGURE 16: Structural and hydrothermal map of the Sog-Trölladyngja area, also shown is the location of two lithological cross-sections

17). Smectites are hydrous aluminium silicates with magnesium and calcium as additional chemical constituents, along with a small quantity of iron. A typical chemical composition of smectite clay is $SiO_2$ 51%; $Al_2O_3$ 12%; $Fe_2O_3$ 2%; FeO -; MgO 5%; and CaO 2%. Smectite is formed from the alteration of volcanic ash and hyaloclastite rocks, at temperatures below 200°C. The hyaloclastite bedrock of the Graenavatn and Graenadyngja hyaloclastite in the Sog area has, in places, been completely hydrothermally altered to smectite bluish gray clay. This unit is clearly exposed on both sides of the valley and covers a large part of the area within the Sog basin (Figure 4).

FIGURE 17: Travertine minerals

*Mixed-layer clay*
A smectite-chlorite mixed-layer clay alteration is notable at the central part of Graenavatn hyaloclastite ridge where three hyaloclastite heaps outcrop; they are greenish and dense hyaloclastite rocks. It can be assumed that with the active hydrothermal activities at that time, that there was a thick ice cover of more than 300-400 m, in addition to the overlying rock mass of maximally 200-300 m. Hence, it was possible to have temperatures above 230°C, which may have rendered the alteration of the hyaloclastite. These mixed layer clays form the bedrock of the Graenavatn and Graenadyngja hyaloclastite ridges (Figure 18).


FIGURE 18: Mixed-layer clay hyaloclastite hummocks

*Sulphur and efflorescence minerals*
Sulphur is found within one of the two active fumaroles but mostly the crust of efflorescence minerals is sulphates of bitter taste. Those fumaroles have a temperature of ~100°C and emit moist steam which oxidizes and gives the smell of rotten eggs.

*Quartz*
Hydrothermally formed quartz minerals are indicative of high-temperature conditions, above ~200°C (Fridleifsson, 1983). In the study area, quartz was found to have formed in mineral veins within an extinct hydrothermal field exposed in the northwest part of the area (Figure 9). Measuring homogenization temperature in fluid inclusions from within quartz crystals can be used to estimate the formation temperature of the geothermal field at the time of quartz formation. However, a fluid inclusions study was not undertaken in this project.

## 7. CONCLUSIONS AND RECOMMENDATIONS

Figures 19-20 show two lithological cross-sections through the Sog area; their location is shown in Figure 16. They show well the assumed erosion and the different lithological units.

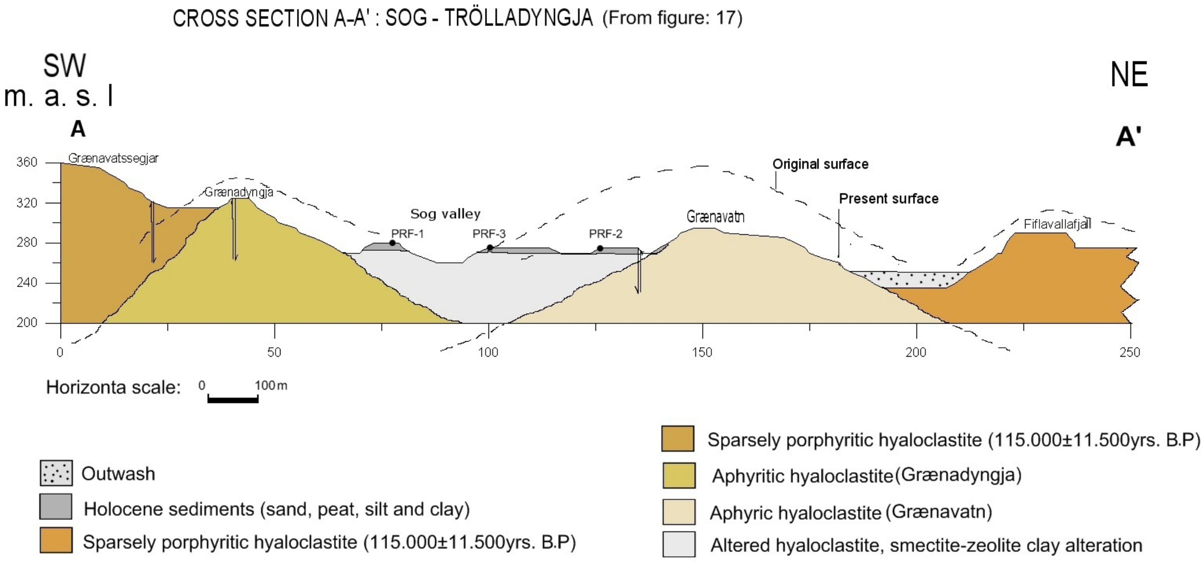


FIGURE 19: Lithological cross-section A-A'

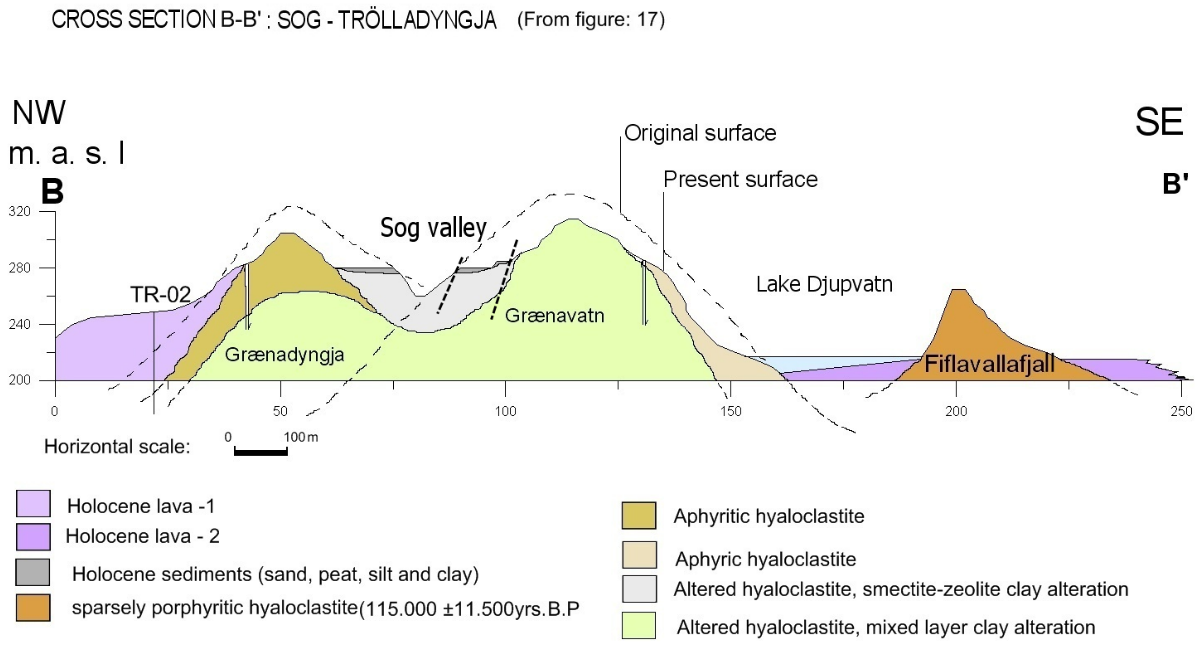


FIGURE 20: Lithological cross-section B-B'

The stratigraphic succession of the Sog-Trölladyngja area probably dates back from the Saalian glacial period, (125,000-220,000 BP) and extends to less than 1000 years BP. The Holocene sediments were deposited during the entire Holocene period (~11,500 years) and the stratigraphic record has been well preserved in the Sog valley where different alternating layers of sediments are clearly notable. In this study, age determination is tentatively based on correlations to other known similar formations while absolute dating of peat samples is still awaited from a laboratory.

The area appears to have been very active hydrothermally since Saalian times well into the Weischelian period (115,000- ~11,500), while hydrothermal activity seems to have ceased dramatically in late Weichselian or very early Holocene time. There are few indications of hydrothermal activity during the Holocene period apart from a few sites along active faults and, presently, there are only two active fumaroles with temperatures close to boiling, and a few warm springs. A more detailed study needs to be carried out to reach a conclusion as to when the geothermal system began cooling down close to the surface.

The location of this area within the active tectonic zone, and the results of the two deep drill holes in the neighbourhood, indicate that this area still has a potential for a harnessable geothermal resource which warrants more detailed geological investigation to identify the best locations from which to exploit the heat source.


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