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BOREHOLE GEOLOGY OF SG-9, SVARTSENGI GEOTHERMAL FIELD, SW-ICELAND

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ABSTRACT

This report describes the stratigraphic sequence and the alteration in drillhole SG-9 in the Svartsengi high temperature field, SW-Iceland. The stratigraphic column consists of three series, a 442 m thick olivine tholeiite lava series, a 216 m thick hyaloclastite unit, and a 242 m thick tholeiite lava series. Correlation of the stratigraphy of SG-9 with other drillholes in Svartsengi suggests the existence of a buried fault in the area. The upper aquifer (441 m) conicides with a basalt/ hyaloclastite boundary, whereas the lower one (907 m) conicides either with a basalt/hyaloclastite boundary or a vertical fracture. The alteration minerals are arranged in three zones: 1) smectite-zeolites, 2) mixed-layer clay minerals, and 3) chlorite-epidote. The alteration mineral of dolomite, which has not been reported before in an active thermal area in Iceland, occurs between the depths of 250 and 420 m. The correlation of the hydrothermal alteration between SG-9 and SG-8 implies that the alteration zones occur at deeper levels towards the west.

LIST OF CONTENTS

Page

ABSTRACT 3
1 INTRODUCTION 7
  1.1 Purpose and scope of study 7
  1.2 Analytical techniques 7
  1.3 Geological and geothermal setting 8
2 BOREHOLE GEOLOGY OF SG-9 13
  2.1 Drilling history 13
  2.2 Stratigraphy 14
  2.3 Aquifers 16
  2.4 Alteration 16
3 CORRELATION OF SG-9 WITH OTHER DRILLHOLES 19
  3.1 Stratigraphy 19
  3.2 Alteration 19
4 CONCLUSIONS 21
ACKNOWLEDGEMENTS 22
REFERENCES 23
FIGURES 25-39

LIST OF FIGURES

Fig. 1 Structural map of the neovolcanic zones in Iceland
Fig. 2 Geological map of the western Reykjanes peninsula
Fig. 3 The location of drillholes and the surface geology of the Svartsengi geothermal field
Fig. 4 A resistivity cross section along line A-A′ in Fig. 3
Fig. 5 The stratigraphic column of SG-9
Fig. 6 Secondary mineral distribution of SG-9
Fig. 7 Tentative E-W geological cross section through the Svartsengi field
Fig. 8 Secondary mineral distribution of SG-8

TABLE

Table 1 The concentrations (in m moles/kg) of chemical species in the water feeding wet-stream wells in four high temperature fields in Iceland along with the calculated quartz equilibrium temperature (t_{qtz} °C) 11

1 INTRODUCTION

1.1 Purpose and scope of study

The author of this report was the recipient of an UNU Fellowship to attend the 1980 UNU Geothermal Training Programme held at the National Energy Authority in Iceland. The author's specialized training was in the field of borehole geology. The training programme included an introductory lecture course (4 weeks) dealing with the various fields of geothermal science, training on a drill rig in the various aspects of drillhole geology and drilling technology (5 weeks). The author also received some practical training in X-ray mineral analysis (1 week) and a total of 3 weeks of field excursions to areas in Iceland of geothermal and geological interest. This report is the result of about 10 weeks research on the geology of the drillhole SG-9 in the Svartsengi high temperature field in SW-Iceland using the various techniques learnt during the training. Concomitantly with this research, J.L. Zuniga is realizing a geophysical logging interpretation of SG-9 (Zuniga, 1980). One of the reasons for the selection of a drillhole in Iceland for this research is that no drillhole has as yet been drilled in the geothermal areas of the author's home country, Honduras.

1.2 Analytical techniques

Samples of drill cuttings were collected at 2 meters intervals by the drillers and put into 100 ml plastic jars. The samples were washed to remove drilling mud and other foreign material and then examined with a conventional binocular stero-microscope at 10-50x magnification. During this examination, 47 samples were chosen for thin sectioning at different intervals, for petrographic analysis of the primary and secondary constituents of the rocks. Similarly, secondary mineral grains were picked from the samples for X-ray diffraction (XRD) analysis. The penetration rate was worked out from the geolograph of the drill rig and plotted alongside the stratigraphic column. The depths of the samples, which are marked according to the geolograph, were corrected with respect to the time it takes for the cuttings to reach surface (this is dependent upon the type of circulation fluid used as well as its flow rate and the drillhole diameter) and the penetration rate. Changes in penetration rate which often are due to changes in the lithology of the rocks were in many cases used to find the more exact location of the samples.

1.3 Geological and geothermal setting

a. Geology of Iceland

Iceland lies astride the Mid-Atlantic Ridge which represents the constructive boundary of the European and the American plates. The main geological formations of Iceland are shown in Fig. 1. The oldest formation is Tertiary (3-16 m.y.) and consists of a lava succession in general dipping gently towards the volcanic zones. The second formation is of Quaternary, Plio-Pleistocene age (0.7-3 m.y.). The succession consists of alternating sequences of lavas and hyaloclastites. The former is formed during the interglacial periods whereas the hyaloclastites are formed as a result of subglacial eruptions of the ice ages. The third and youngest formation is contained within the Neovolcanic Zone and is composed of Upper-Pleistocene and Postglacial formations (< 0.7 m.y.). As seen in Fig. 1 this zone delineates the zones of rifting. The rifting within the Neovolcanic zone is mainly confined to distinct fissure swarms. A central volcano in general forms at the central part of each fissure swarm. These volcanoes are the foci of magmatic activity within the fissure swarms and it has been shown from studies in the deeply eroded regions (i.e. in the Tertiary and Quaternary regions) that high percentage of intrusions are occuring in the core of these volcanoes (Säemundsson, 1979). The high temperature areas, which are defined as those where temperatures surpass 200°C at depths less than 1 km, are confined largely to the central volcanoes of the active zones of rifting and volcanism, and are thought to draw heat both from the regional heat flow and from local accumulations of igneous intrusions emplaced at a shallow level in the crust (Fridleifsson, 1979).

b. The geology of the Reykjanes peninsula

Five active fissure swarms, arranged en echelon, are found within the volcanic zone of the Reykjanes peninsula as shown in Fig. 1. These fissure swarms are primarily recognized, as the name implies, by the dense faulting and fissuring (eruptive and non-eruptive), and also by the location of high temperature areas and magnetic anomalies within the central part of each swarm (Sigurgeirsson,1970). The postglacial eruptives (less than 12,000 years old) from these fissure swarms have been divided on morphological and petrographical characteristics into lava shields and fissure lavas as are illustrated in Fig. 2 (Jakobsson, et al., 1978). The strata underlying the postglacial eruptives are alternating sequences of lavas and hyaloclastites of Late Pleistocene age. The hyaloclastite formations break in several places up through the postglacial lava cover, especially within the central axis of the peninsula. So far, no acid or intermediate rocks have been found on the Reykjanes peninsula (Jakobsson, et al., 1978). The surface thermal manifestations of the high temperature areas are believed to represent indications of hydrothermal convective systems which may reach to a depth of about 2-3 km (Jakobsson, et al., 1978).

c. The geology of the Svartsengi area

The Grindavík swarm is the second westernmost fissure swarm in the Reykjanes peninsula. About 30 eruptions are believed to have occurred within the swarm during Holocene age (Postglacial) and are mostly fissure lavas (Jakobsson, et al., 1978). The Svartsengi high temperature field, about 45 km southwest from Reykjavík, lies within the Grindavík fissure swarm. The production area forms a flat land, located to the north of Thorbjörn mountain and west of Svartsengisfell mountain. The surface geological formations are illustrated in Fig. 3. The oldest rock formations outcrop at Thorbjörn and Svartsengisfell mountains, consisting to large extent of pillow lava and some hyaloclastite. The second main geological surface formation is postglacial lava flows which cover entirely the production area. These lavas are both of aa and pahoehoe types. Two small lava craters are found at the northern foot of Thorbjörn mountain. The lava issued from these craters is likely to be found underlying the topmost lava to the north and east. As seen in Fig. 3 another relatively old surface lava occurs to the east of drillhole SG-5. It is probably derived from the adjacent craters to the east. The two youngest lavas cover largely the Svartsengi area, the northern one is derived from approximately 10 km long fissure to the east of Svartsengisfell, and the lava flow to the south is derived from a short fissure west of Thorbjörn (see Fig. 2). These lavas are mostly of aa type.

d. The Svartsengi high temperature field

Active surface geothermal features are lacking and the hydrothermal alteration is insignificant, mostly represented by patches of clay alteration in the hyaloclastite formations in the northern slopes of Thorbjörn mountain and eastern part of Svartsengisfell (Jónsson, 1978). The area of hydrothermal alteration has been roughly estimated as 1-2 km^2 (Arnórsson, et al., 1975). Only in certain weather conditions can steam be seen rising from fractures in the lava east of Svartsengisfell (Jónsson, 1978).

In the Reykjanes peninsula the cold groundwater movement is greatly affected by the tectonics and is in fact characterized by a very high permeability of the bedrock causing a low groundwater level in spite of infiltration. The groundwater in the region is confined to a 50-55 m thick lens in the main exploitaion area floating on seawater (Sigurdsson, et al., 1978).

Resistivity in the ground is lowered by increasing temperature. A similar lowering in resistivity results from increasing salinity of groundwater. The discrimination between the effects of temperature and salinity is sometimes difficult. The outer boundary of the Svartsengi high temperature field is therefore rather loosely defined from resisitivity measurements, and is estimated to be about 5 km^2 at 200 m depth and increasing downwards (Georgsson, 1979). A resisitivity profile of the field is presented in Fig. 4.

Table 1 shows the dissolved solids in water from wells from different high temperature areas in Iceland (from Arnórsson, et al., 1978). The Reykjanes and Svartsengi fields contain much higher concentrations of Na^+, K^+, Ca^{++}, and Cl^- in comparison with Namafjall, Nesjavellir, and Hveragerdi.

The temperature profiles are rather similar in the Svartsengi drillholes. Due to the incomplete temperature profile in SG-9, the drillhole of this report, the temperature profile of SG-4 is tentatively used for comparison (see Fig. 6). Between about 40 m and 230 m the temperature ranges from 40°-70°C, but increases sharply from 230 m to about 180°C at 320 m. From there the temperature increases greatly to about 235°C at about 500 m below which it remains nearly constant.

Presently the geothermal wells at Svartsengi yield a 240°C brine, with a salinity roughly two-thirds of that of sea water. The brine is utilized

TABLE 1

The concentrations (in m moles/kg) of chemical species in the water feeding wet-stream wells in four high temperature fields in Iceland along with the calculated quartz equilibrium temperature (t_{qtz} °C). From Arnórsson et al., 1978.

Dissolved Species	Reykjanes well 8	Svartsengi well 4	Namafjall well 4	Nesjavellir well 5	Hveragerdi well 4
pH	5.86	5.47	7.48	7.43	6.99
Na^+	355.6	251.8	5.46	5.64	6.38
K^+	34.9	23.6	0.564	0.608	0.298
Ca^{++}	37.8	24.5	0.011	0.017	0.024
Mg^{++}	0.013	0.185	$5.42\cdot10^{-5}$	$7.24\cdot10^{-5}$	$5.81\cdot10^{-4}$
H_4SiO_4	10.00	7.41	8.69	8.97	4.42
$H_3SiO_4^-$	0.011	0.005	0.270	0.238	0.072
H_2CO_3	35.6	9.71	1.43	4.06	1.90
HCO_3^-	0.479	0.187	0.946	2.24	1.92
CO_3^{--}	$2.49\cdot10^{-6}$	$2.27\cdot10^{-6}$	0.0001	0.0002	0.0007
H_2S	0.875	0.044	1.99	2.17	0.337
HS^-	0.037	0.002	2.79	2.60	0.441
S^{--}	$6.15\cdot10^{-8}$	$5.00\cdot10^{-10}$	$3.48\cdot10^{-5}$	$2.88\cdot10^{-5}$	$1.06\cdot10^{-6}$
HSO_4^-	0.002	0.003	0.003	0.001	0.001
SO_4^{--}	0.027	0.047	0.603	0.180	0.474
HF^o	0.003	0.002	0.001	0.002	0.0008
F^-	0.003	0.004	0.078	0.090	0.094
Cl^-	446.7	327.3	0.443	0.376	3.14
$NaCl^o$	87.1	27.9	0.0035	0.0032	0.011
KCl^o	4.15	1.31	0.0002	0.0002	0.0003
$NaSO_4^-$	0.141	0.172	0.392	0.124	0.156
KSO_4^-	0.012	0.015	0.040	0.013	0.007
$CaSO_4^o$	0.057	0.090	0.022	0.011	0.014
$MgSO_4^o$	0.001	0.028	0.004	0.002	0.006
$CaCO_3^o$	0.0003	0.0002	0.0003	0.0008	0.0008
$MgCO_3^o$	$1.83\cdot10^{-7}$	$2.48\cdot10^{-6}$	$1.36\cdot10^{-6}$	$3.66\cdot10^{-6}$	$2.19\cdot10^{-5}$
t_{qtz} °C	271.6	237.0	253.3	254.7	198.8

for space heating by means of heat exchangers (Thorhallsson, 1979). The geothermal plant produces 50 MW_t (thermal) for district space heating for the neighbouring towns which have about 20,000 inhabitants, and 2 MW_e (electric). An increase to 75 MW_t and 6 MW_e will be completed shortly.

2 BOREHOLE GEOLOGY OF SG-9

2.1 Drilling history

The SG-9 is the 8th geothermal hole to be drilled in the Svartsengi geothermal field (SG-1 was drilled for cold water), and is located in the west part of the field at a distance of approximately 215 m from the nearest holes, SG-7 and SG-11 (Fig. 3). The hole was completed in 41 working days or between February 7th-25th and April 28th-June 9th of 1980. The cable tool was initially used down to 55 m with 22"bit, but succeeded by rotary drilling down to 597 m with 17 1/2" bit, and later with 12 1/4" bit to the bottom of the hole at 994 m. Prior to the rotary drilling the hole had been cased down to 58 m with 18 3/8" casing. A 13 3/8" casing was cemented and reached to 591 m depth. A slotted liner extends from the casing down to the bottom. Two types of circulation fluids were used, mainly mud to 597 m and water to 994 m.

The cuttings recovery in the hole is about 70%, basalt and hyaloclastite nearly 60% and 10% respectively. The absence of cuttings are mainly from two depth intervals: A partial lack of cuttings occurred in the depth interval between 436-594 m. This was due to a complete circulation loss (> 56 l/s) at 441 m. In spite of repeated attempts to close this aquifer it remained partially open during drilling down to 597 m when it was cased off. No cuttings were retrieved below 900 m as a result of complete circulation loss at 907 m.

Between approximately 200 m to 597 m the cuttings retrieved at the surface showed increasing rounding. Furthermore, at this depth interval there were persistent occurrances of very fresh crystallized basalt and glass fragments. Both these observations induced the view that large caves were being formed in the upper part of the hole. This view was confirmed when the caliper log was run prior to the 13 3/8" casing operation (Fig. 5). The formation of caves in a drillhole may cause some difficulties as the flow rate at these locations is markedly lowered. In the case where the flow rate decreases beyond the settling rate of the cuttings, this can lead to the no recovery of cuttings at the surface and, in addition, to a concentration of the cuttings at depth in the drillhole which may result in the drill stem becoming stuck. Although the problem did not become so acute it was evident that the cuttings showed considerable mixing on their way to the surface. However, in spite of these problems it is believed that the constructed stratigraphic column within the aforementioned depth interval, represents a fairly accurate picture of the stratigraphy.

2.2 Stratigraphy

The stratigraphic profile constructed from the petrographic analyses of the cuttings is shown in Fig. 5. The stratigraphic sequence can be divided into 3 main sections, i.e. a series of olivine tholeiite lavas, a unit of hyaloclastite, and a tholeiite lava series.

a. Olivine tholeiite lava series

Due to the absence of cuttings in the uppermost 56 m (cable tool drilling), the upper boundary of this series is tentatively put at surface level. Similarly, due to the absence of cuttings between 436 m and 497 m, the lower boundary of this series was tentatively selected at 442 m where there is a relatively abrupt increase in the average penetration rate (basalt-hyaloclastite transition). This series can be divided into several lava flows. The distinction of individual flows is based primarily on the character of the lava where the upper part is predominantly glassy to very fine grained as well as being highly vesicular, whereas the central and lower part is chiefly medium to coarse grained and has lower vesicularity. Petrographically the lavas show a similar grading in crystallinity where the upper part is represented by the crystallization of principally plagioclase laths, but also some clinopyroxene, olivine and magnetite, emplaced in a glassy groundmass. The central and lower part of the lavas show a dominant sub-ophitic texture with largely interstitial crystallization of magnetite. Most of the flows are sparsely prophyritic (plagioclase, clinopyroxene and olivine). Individual lava flows may often be inferred from the penetration rate where the upper vesicular part shows high penetration rate, which diminishes towards the denser and more crystallized part of the flow. A certain correlation exists between high penetration rate and caves formed in the series (see Fig. 5, caliper log), as the erosion caused by circulation fluids is highest in the softer and more fractured part of the lava flow. The minimum number of flows in the depth interval of 56 m to 436 m is 40, ranging in thickness from 2-27 m giving an average thickness just under 10 m.

b. Hyaloclastite unit

As mentioned earlier, the upper boundary of this unit was inferred at 422 m whereas the boundary of the underlying tholeiite series occurs at 658 m. The hyaloclastite was formed under the ice sheet as a result of the quencing of magma in water. It consists consequently of a mixture of vitroclastic glass and partially crystalline basalt. As seen in Fig. 5 the hyalocalstite unit is divided into three lithological types. The first type, the hyaloclastite tuff, is dominantly composed of perlitic glass. The second type is the hyaloclastite breccia made up of similar amounts of perlitic glass and partially crystallized basalt. The third type is the basaltic breccia which consists of a majority of partially crystallized basalt and minor perlitic glass. Petrographically the hyaloclastite unit shows a similar grading in crystallinity from pure vitroclastic near opaque glass to holocrystalline basalt, the latter of mostly granular texture and only rarely showing sub-ophitic texture. The presence of crystallized basalt between 535-545 m is rather uncertain, mainly due to severe mixing in the samples of fragments from upper levels in the hole.

c. Tholeiite series

The upper boundary of this series is found at 658 m whereas the lower boundary is arbitrarily put at 900 m, below which no cuttings are available. This series can be divided into several lava flows. Individual flows are recognized by the glassy to very fine grained and highly vesicular upper part and the fine to medium grained and less vesicular central and lower part. Generally the penetration rate reflects this lava structure by being high in the upper part of the flow and decreasing towards the base. The main distinction between this series and the olivine tholeiite series above is the dominant granular texture of the former with euhedral relatively early crystallization of the iron ore, as opposed to the latter where the sub-ophitic texture dominates with interstitial iron ore. A few of the flows are porphyritic (plagioclase, pyroxene and minor olivine). A minimum of 25 tholeiite lava flows were encountered in this series ranging in thickness from 2 to 18 m and having an average thickness of about 8 m. In addition the series includes a 29 m thick olivine tholeiite lava flow (755-784 m) and a 14 m thick horizon of basaltic breccia (870-884 m).

2.3 Aquifers

The drillhole intersects two major aquifers (Fig. 5). The upper one, which occurs at 441 m depth, resulted in a total circulation loss (> 56 l/s) during drilling, which in turn led to the no recovery of the cuttings. However, below this depth there was a notable increase in the penetration rate which corresponds fairly well with that experienced in the hyaloclastite unit below. It is therefore proposed that this aquifer occurs at the boundary of the olivine tholeiite series and the hyaloclastite unit. A total circulation loss was also experienced in the lower aquifer at 907 m depth. No cuttings are available below 900 m depth making it difficult to assess the nature of this aquifer. It is noteworthy, however, that at this level the penetration rate shows a sharp increase from about 15 m/hr to over 30 m/hr. It is therefore thought likely that this aquifer is either at a lithological boundary of a lava flow and a hyaloclastite or that the drillhole intersected a subvertical fracture.

2.4 Alteration

As mentioned in 2.2 the primary mineral constituents of the rocks penetrated in SG-9 are plagioclase, olivine, pyroxene, iron ore and glass. These show differential resistance to alteration as a consequence of temperature permeability and geothermal fluid circulation in the rock.

The volcanic glass shows the least resistance and starts to break down below about 280 m depth. The breakdown of olivine starts at approximately 300 m and it is completely altered below 430 m depth. The plagioclase and the pyroxene start to alter at about 430 m depth, but in general remain partially altered to the bottom of the stratigraphic section. This alteration stage was also noted in the binocular stereo microscope by the mottled appearance of the olivine tholeiite lavas (see Fig. 5).

The alteration mineral assemblages encountered in SG-9 are illustrated in Fig. 6 and include carbonates (calcite, arogonite, (dolomite), quartz, opal, chalcedony, mordenite, wairakite, anhydrite, pyrite, epidote and clay minerals. The secondary minerals are found filling open spaces (vesicles, fractures) as well as replacing the primary constituents of of the rock.

Three types of carbonates were found in SG-9, i.e. calcite, aragonite and dolomite. The latter two were distinguished from calcite on grounds of the XRD-patterns, as well as the aragonite being tentatively distinguished petrographically by its radial features.

Calcite is far the most common carbonate mineral and is found throughout the hole. Its abundance is low in the uppermost 300 m and high below that depth. Above about 430 m the calcite is mainly found as vesicle and vein fillings, but below that depth it is in addition found as an alteration product of olivine, plagioclase, pyroxene, and glass. The most likely explanation of the greater abundance in the lower parts is the change in pH caused by boiling (Arnórsson et al., 1978).

Aragonite is only found in the uppermost 435 m. Dolomite, which is a calcium magnesium carbonate is found between 250-420 m. It has not been identified previously in active geothermal areas in Iceland. Dolomite is associated with saline geothermal fields in other areas in the world such as Imperial Valley and Mexicali (Browne, 1978).

Quartz, opal and chalcedony occur together, but opal and chalcedony are less frequent than quarz. Opal appears intermittently in the uppermost 600 m depth. Chalcedony is erratic from 350-900 m depth. Quartz occurs from 225-900 m depth. The occurrance of opal, chalcedony and quartz together may be explained by local disequilibrium presumably due to supersaturation of silica in the hydrothermal system (Arnórsson, et al., 1978). Quartz is found as an alteration of plagioclase and volcanic glass and occurs also in veinlets and vesicles.

The zeolites are represented by mordenite and wairakite. Mordenite occurs erratically within 250-420 m depth interval. Wairakite has been observed petrographically only at 628 m depth. It was distinguished petrographically from analcime by its distinct biaxial feature (Deer, Howie and Zussman, 1963; Steiner, 1977). In high temperature areas in Iceland wairakite occurs between 180°C-300°C (Kristmannsdóttir, 1978).

Anhydrite occurs erratically throughout the hole and its deposition is common in saline geothermal systems in Iceland, but its temperature of occurrance is unknown (Tómasson and Kristmannsdóttir, 1972).

A few samples of clay have been analysed by the XRD method (Franzson, 1980). The smectite occurs in the uppermost 375 m depth succeded by a mixed layered smectite/chlorite and a swelling chlorite. Chlorite is found from about 550 m down to the bottom of the hole. The clay minerals are both found as vesicle and vein fillings as well as alteration product of the primary constituents of the rocks.

Epidote appears at 670 m depth and is pervasive to the bottom of the section. Epidote is found in vesicles and veinlets as well as an alteration product of some of the primary constituents.

Pyrite occurs first at 425 m depth and shows a nearly continuous occurrance to 900 m. Pyrite is predominantly found in veins and vesicles but is also found as altering the groundmass.

A probable albitization of plagioclase is observed below 430 m depth. Its existence will though have to be confirmed by microscope analysis.

Kristmannsdóttir (1979) has divided the geothermal alteration pattern of the presently active high temperature areas of Iceland into four zones, based mainly on changes in clay mineralogy i.e. smectite-zeolites zone (100 - 200°C), mixed-layer clay minerals zone (200-230°C) chlorite-epidote zone (230-280°C), and chlorite-actinolite zone (> 280°C). As seen in Fig. 6 the alteration mineralogy of SG-9 has accordingly been subdivided into three zones; smectite-zeolite zone (0-400 m), a zone of mixed-layer clay minerals (400-550 m), and chlorite-epidote zone (> 550 m).

3 CORRELATION OF SG-9 WITH OTHER DRILLHOLES

3.1 Stratigraphy

The E-W stratigraphic cross section of the Svartsengi area, shown in Fig. 7, is the authors attempt to correlate the lithological units of the drillholes using data from Arnórsson et al. (1975) and unpublished data from Jens Tómasson and Hjalti Franzson.

The lava succession corresponding to the olivine tholeiite series of SG-9 is found in all the drillholes and ranges in thickness from about 300 m (SG-6) to about 460 m (SG-9). This thickness variation reflects to some extent the topography of the underlying hyaloclastite unit as well as the probable existence of faults (see below). In other drillholes three hyaloclastite horizons interfinger the series at about 100 m (SG-2, 3,5,6,10), 200 m (SG-2,3,4,5,6,7,8,10) and about 300 m (SG-7,11). None of these were encountered in SG-9.

The hyaloclastite unit in SG-9 is present in all the deeper drillholes. Its thickness varies from 120 m (SG-11) to 270 m (SG-6). Low viscosity lavas, such as those erupted on the Reykjanes peninsula, tend to form a surface of low relief. This is demonstrated by the top of the lava series on which the hyaloclastite unit rests on, which lies, with two exceptions, at 550-590 m depth. In SG-9 the base of the hyaloclastite occurs at about 660 m depth. As indicated in Fig. 7 this suppression of the base of the unit is believed to be due to a fault displacement amounting to about 70 m with a throw to the west. With a similar line of reasoning two faults with deplacements of 30 and 70 m are proposed on either side of SG-8. These faults have not been active in recent times as no indication of these are seen on the surface.

The tholeiite series of SG-9 correlates with the lava series underlying the hyaloclastie unit in the other drillholes.

3.2 Alteration

A preliminary study indicates that the alteration pattern of the Svartsengi high temperature field is relatively uniform (Franzson, 1980).

The following text is an attempt to correlate the alteration pattern of SG-9 with that of SG-8 (Fig. 8), which is situated about 330 m from SG-9 to the ESE.

The first appearance of an alteration mineral gives often an indication of the past or present temperature condition at a given depth level. Differences in depths of the first occurrences of some of the alteration minerals in SG-9 and SG-8 may therefore indicate differences (past or present) in the temperature profiles of these holes. In SG-8 quartz and anhydrite are found throughout the hole, whereas in SG-9 they occur only below 330 m. Pyrite being present throughout SG-8 appears only below 420 m in SG-9. Epidote was first noted at about 550 m in SG-8 but not until at 675 m depth in SG-9. Although the clay mineral analyses are limited in mumber in SG-9, it is evident that the boundaries of the smectite zone / zone of mixed-layered clays, and the zone of mixed-layered clays /chlorite zone, is 50-100 m lower than in SG-8. This comparison with SG-8 thus shows that these alteration minerals consistently appear at lower levels in SG-9.

As mentioned earlier, a reliable profile of the rock temperature in SG-9 is not available at present, which makes it difficult to assess whether it complies with the alteration assemblages. However, as the preliminary results from the alteration study of the other deep Svartsengi drillholes suggest an affinity with the measured rock temperatures (Franzson, 1980), it is tempting to propose that the alteration pattern in SG-9 is an indication of lower temperatures prevailing in the upper part of the drillhole. It is, however, also possible that the 70 m fault, proposed to lie east of SG-9 (c.f. Fig. 7), may have lowered the alteration zones relative to the other holes.

4 CONCLUSIONS

The main conclusions of this report are the following:

a. The stratigraphic column of SG-9 consists essentially of three stratigraphic formations i.e. a 440 m thick series of olivine tholeiite lavas underlain by an approximately 240 m thick hyaloclastite formation, which in turn is resting on a tholeiite lava flow series with a minimum thickness of 250 m.

b. According to circulation losses druing drilling, two major aquifers were intersected. The upper aquifer occurred at 441 m depth and was later cased off. This aquifer occurs near the inferred boundary of the olivine tholeiite lava series and the hyaloclastite formation. The lower aquifer, which is the main production aquifer in the hole, was intersected at 907 m. This aquifer may either be along a basalt/hyaloclastite boundary or a vertical fracture.

c. A good correlation exists between the stratigraphic units of SG-9 and those in other drillholes in the Svartsengi field. However, judging by the displacement of the base of the hyaloclastite formation, a buried fault with a throw of about 70 m to the west is proposed to lie to the east of SG-9 and separate it from the other holes in the geothermal field.

d. The geothermal alteration shows a progressive intensity with depth. The smectite-zeolite zone reaches to about 400 m followed by a zone of mixed-layer clay minerals to about 550 m. The chlorite-epidote zone occurs below 550 m depth.

e. Dolomite occurs as an alteration mineral at 250-420 m. It has not been reported before in an active geothermal area in Iceland but is known to occur in geothermal brine fields (Imperial Valley and Mexicali).

f. A comparison with the alteration pattern of SG-8 reveals a discrepancy where many of the alteration mineral present in SG-9 appear at lower levels and where the clay mineral zonation lies about 50 to 100 m deeper than that of SG-8. This suppression of the alteration zones may imply a deepening to the west of the geothermal reservoir, but may also largely be caused by the displacement on the fault separating the two wells.

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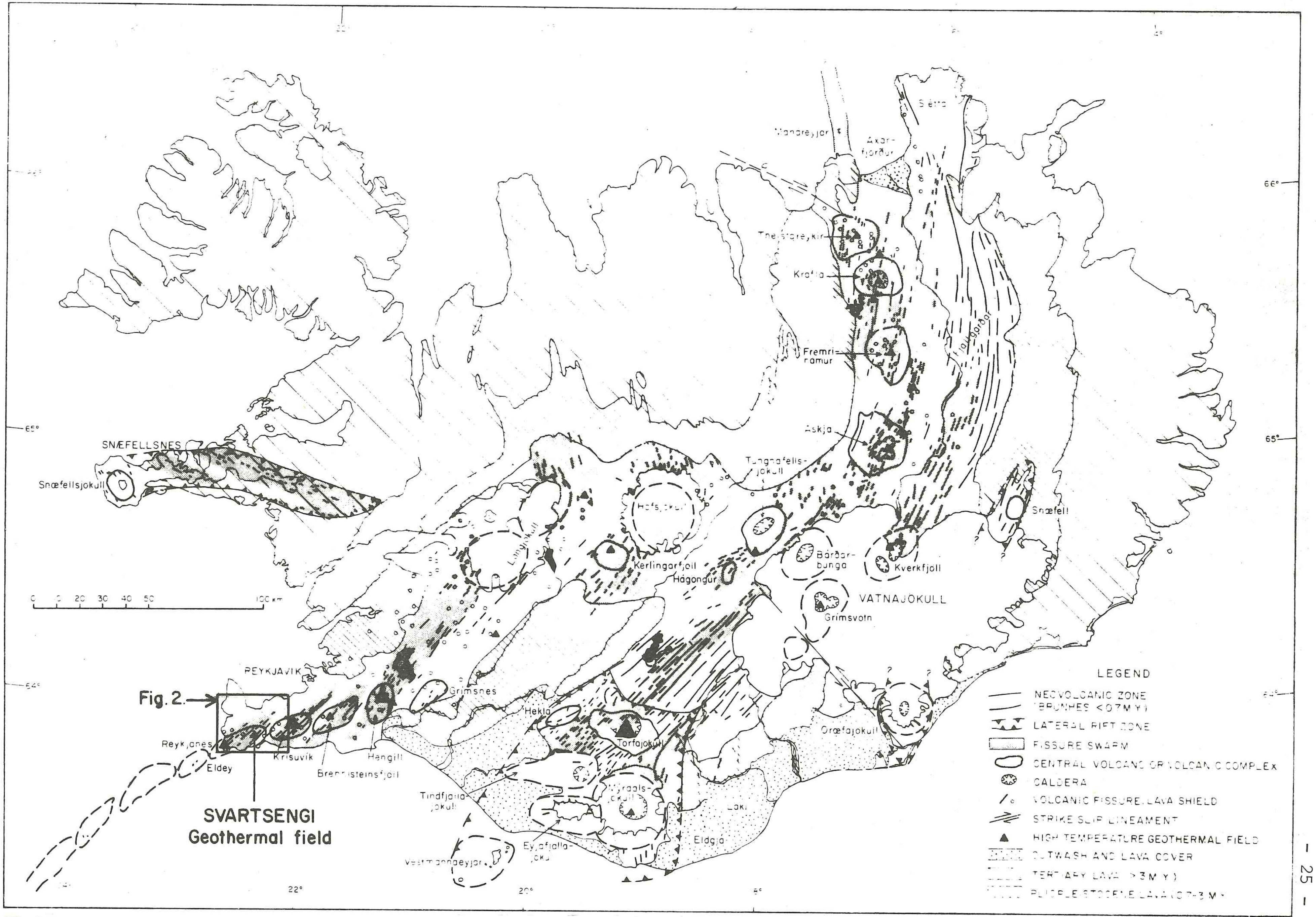


Fig.1. Structural map of the neovolcanic zones in Iceland (from Sæmundsson, 1978).

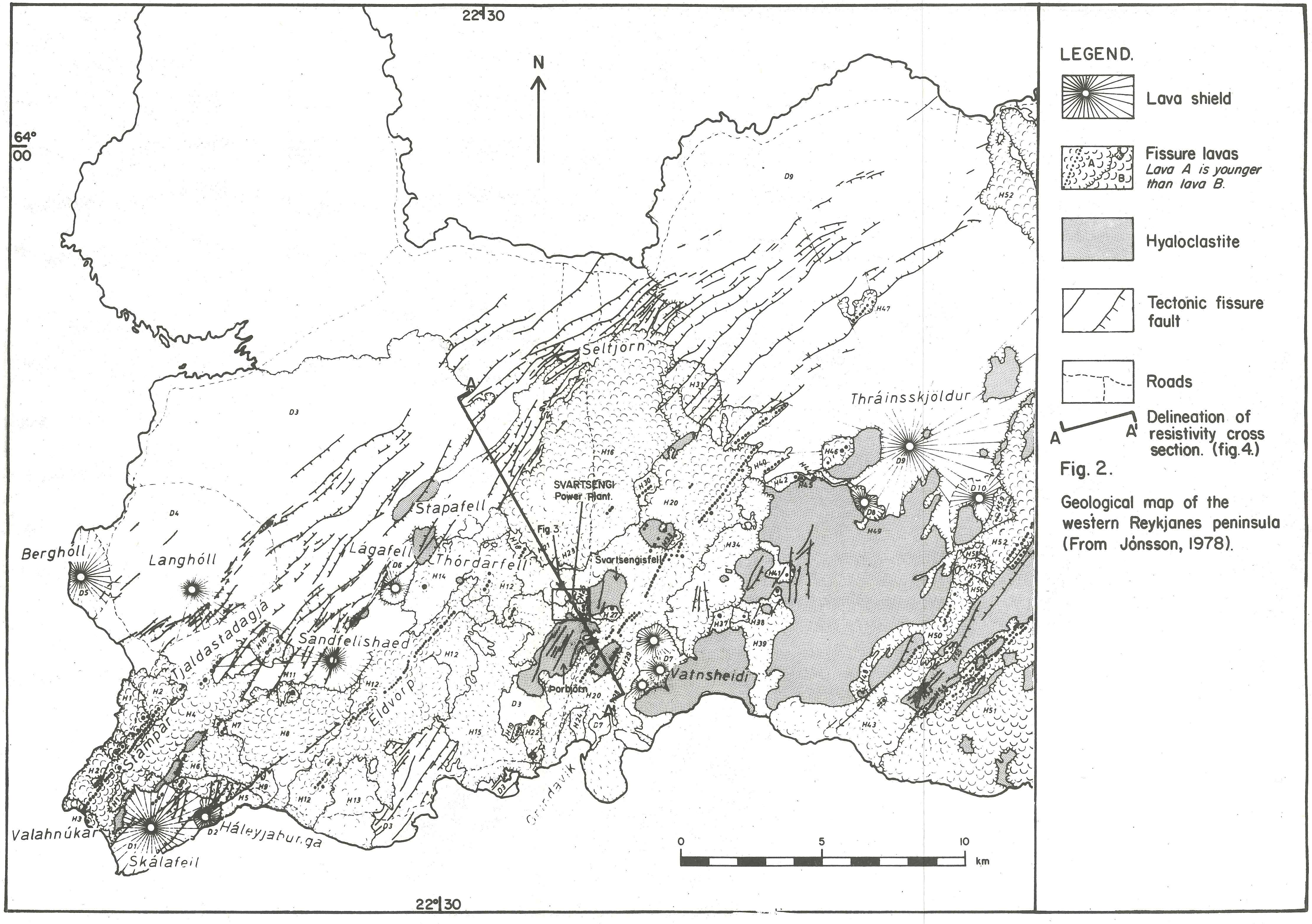


Fig. 2.

Geological map of the western Reykjanes peninsula (From Jónsson, 1978).

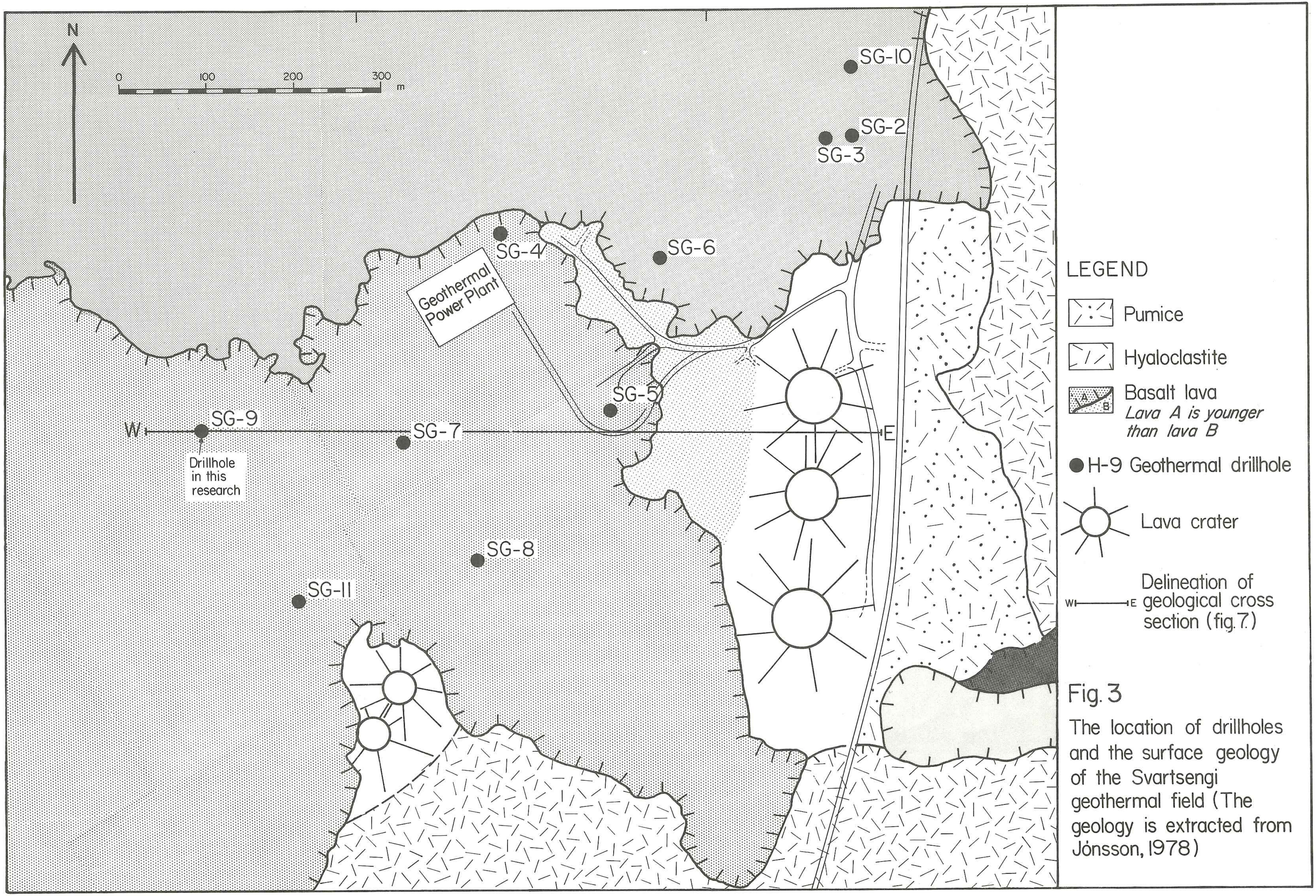


Fig. 3

The location of drillholes and the surface geology of the Svartsengi geothermal field (The geology is extracted from Jónsson, 1978)

'80.09.11. JF/EBF HSÞ. Svartsengi F-20017.

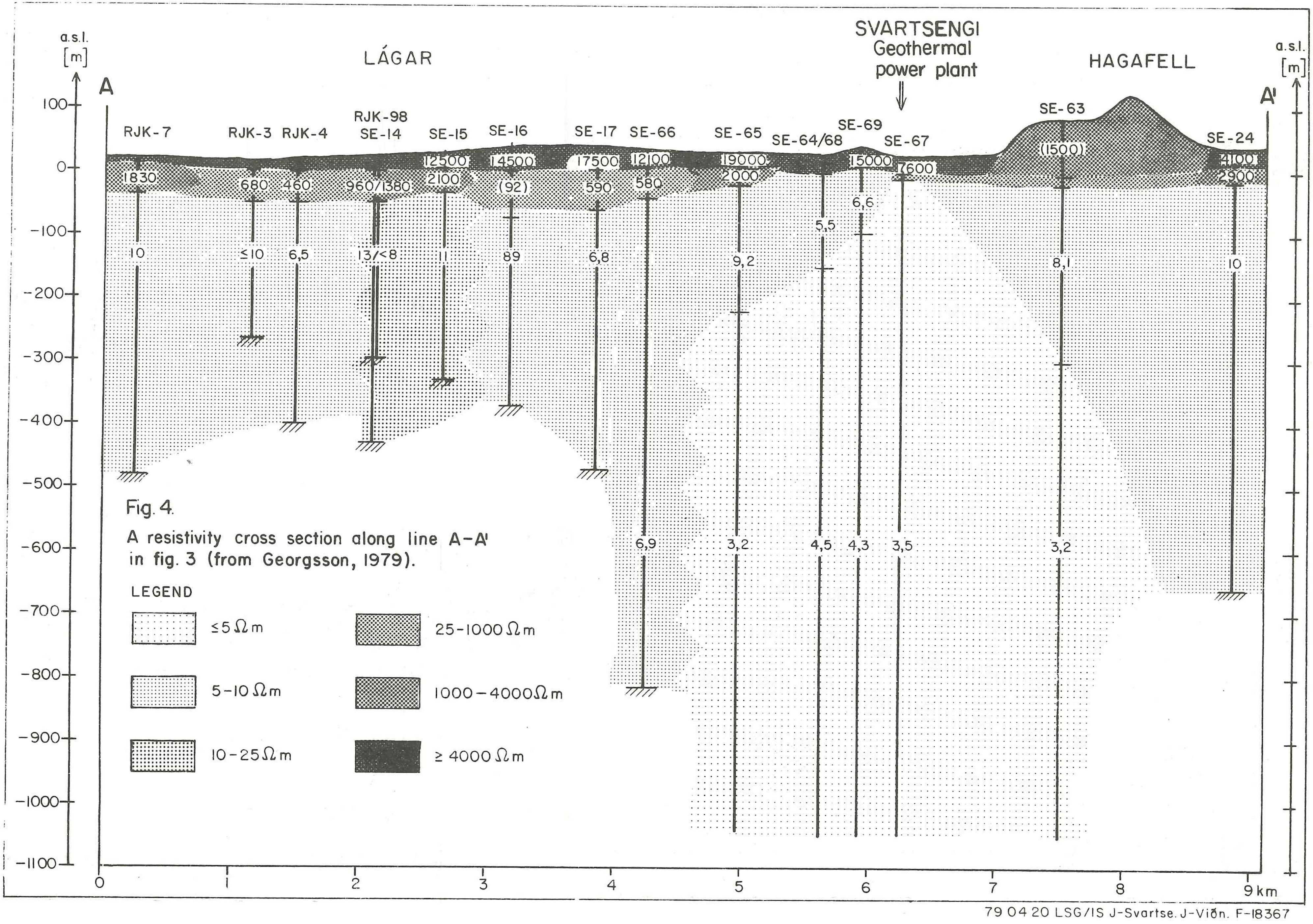


Fig. 4.

A resistivity cross section along line A-A' in fig. 3 (from Georgsson, 1979).

79 04 20 LSG/IS J-Svartse. J-Viðn. F-18367

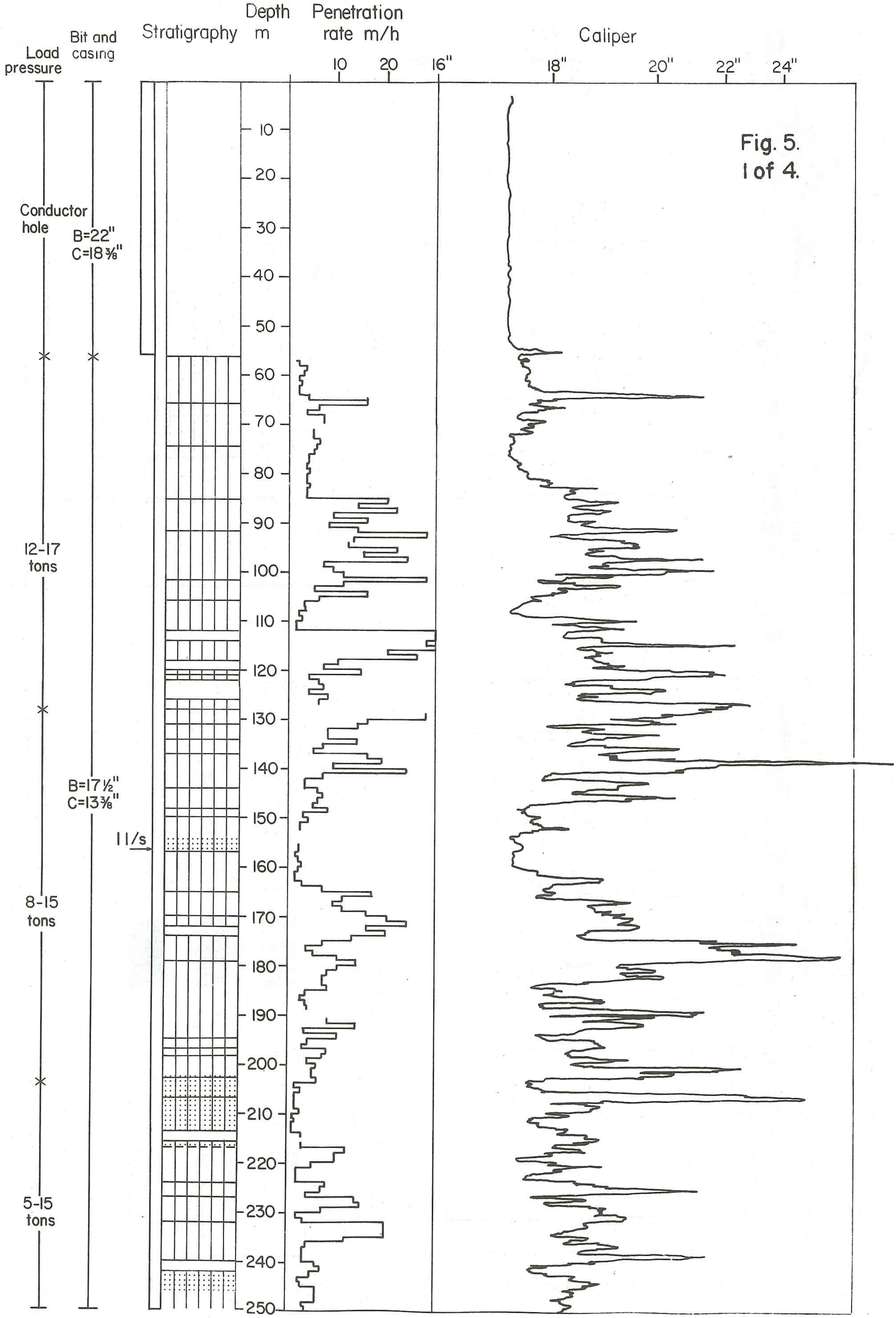


Fig. 5.
1 of 4.

'80.10.08 JF/EBF. HSP Svartsengi F-20088.

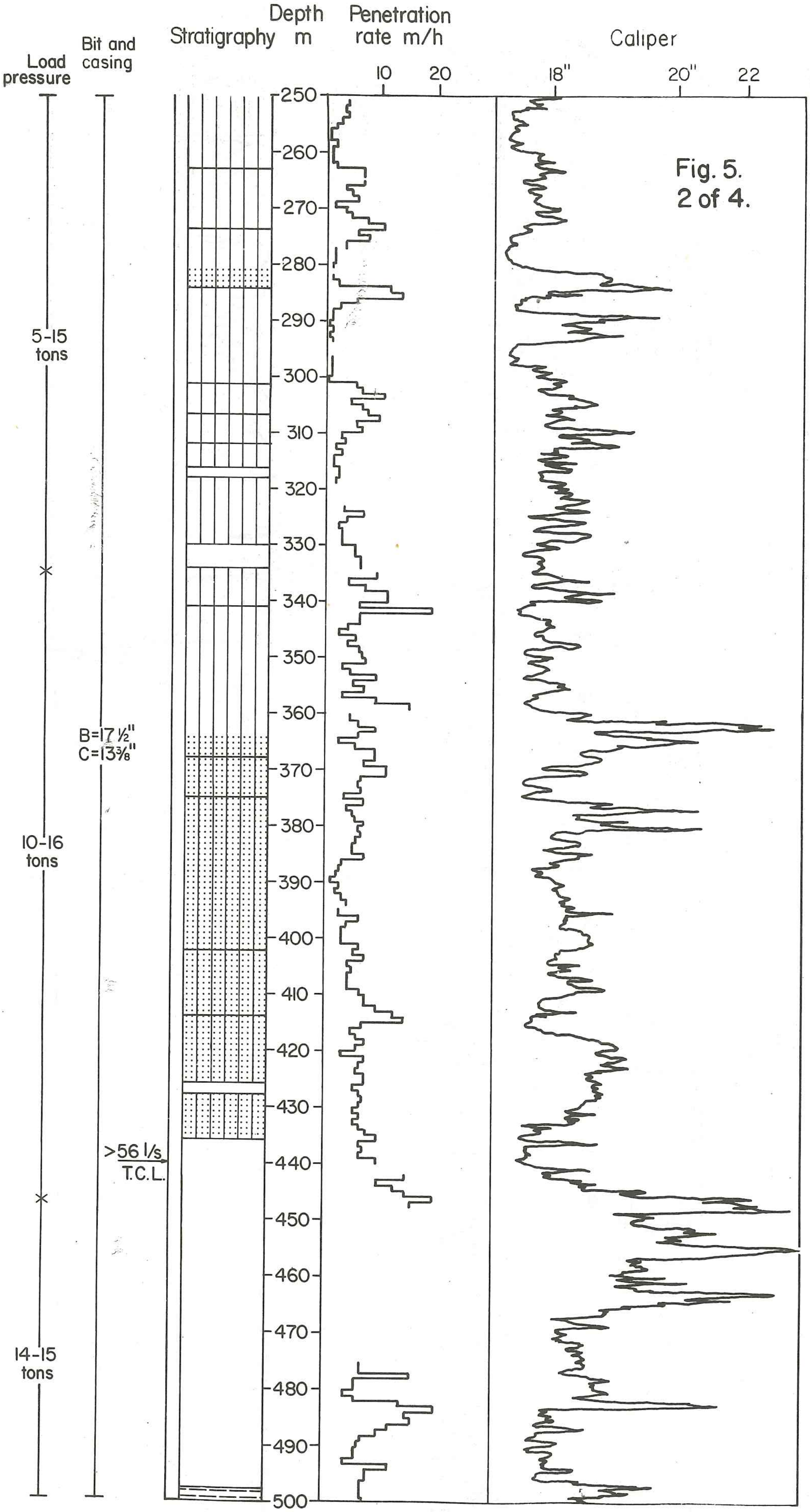


Fig. 5.
2 of 4.

'80.10.08 JF/EBF. HSP Svartseng F-20088

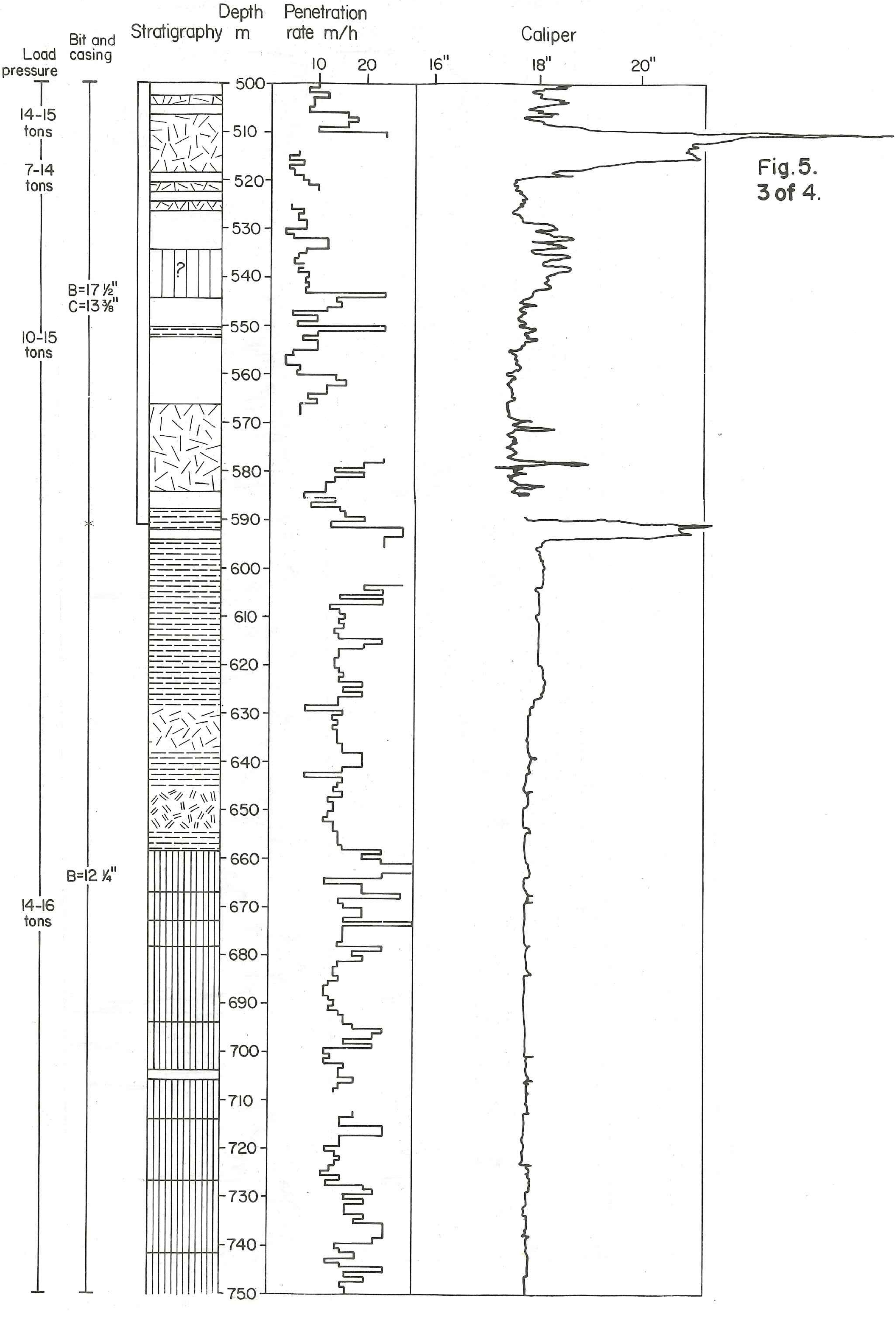


Fig. 5.
3 of 4.

'80.10.08. JF/EBF. HSP Svartsengi F-20088

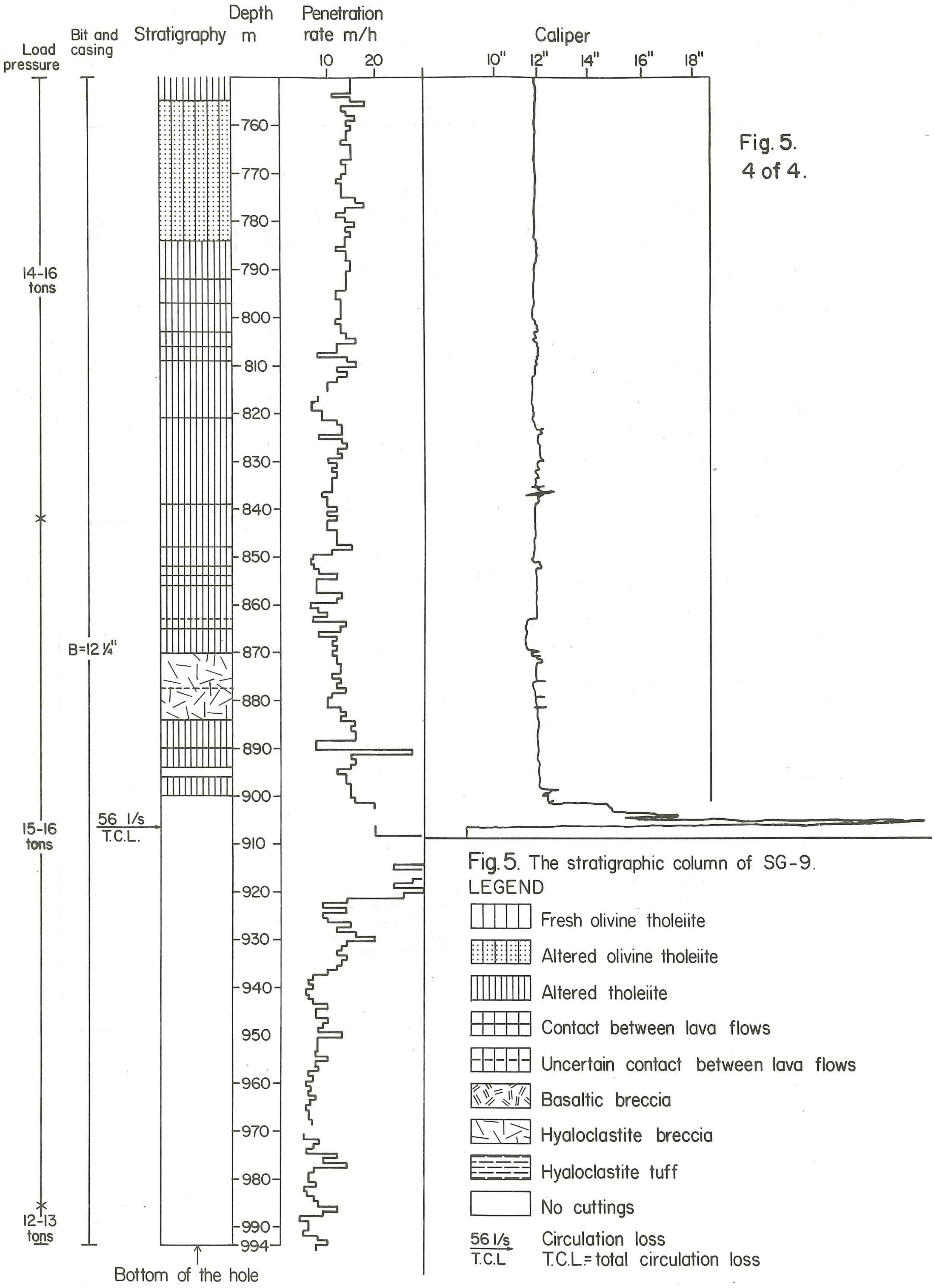


Fig. 5. The stratigraphic column of SG-9.

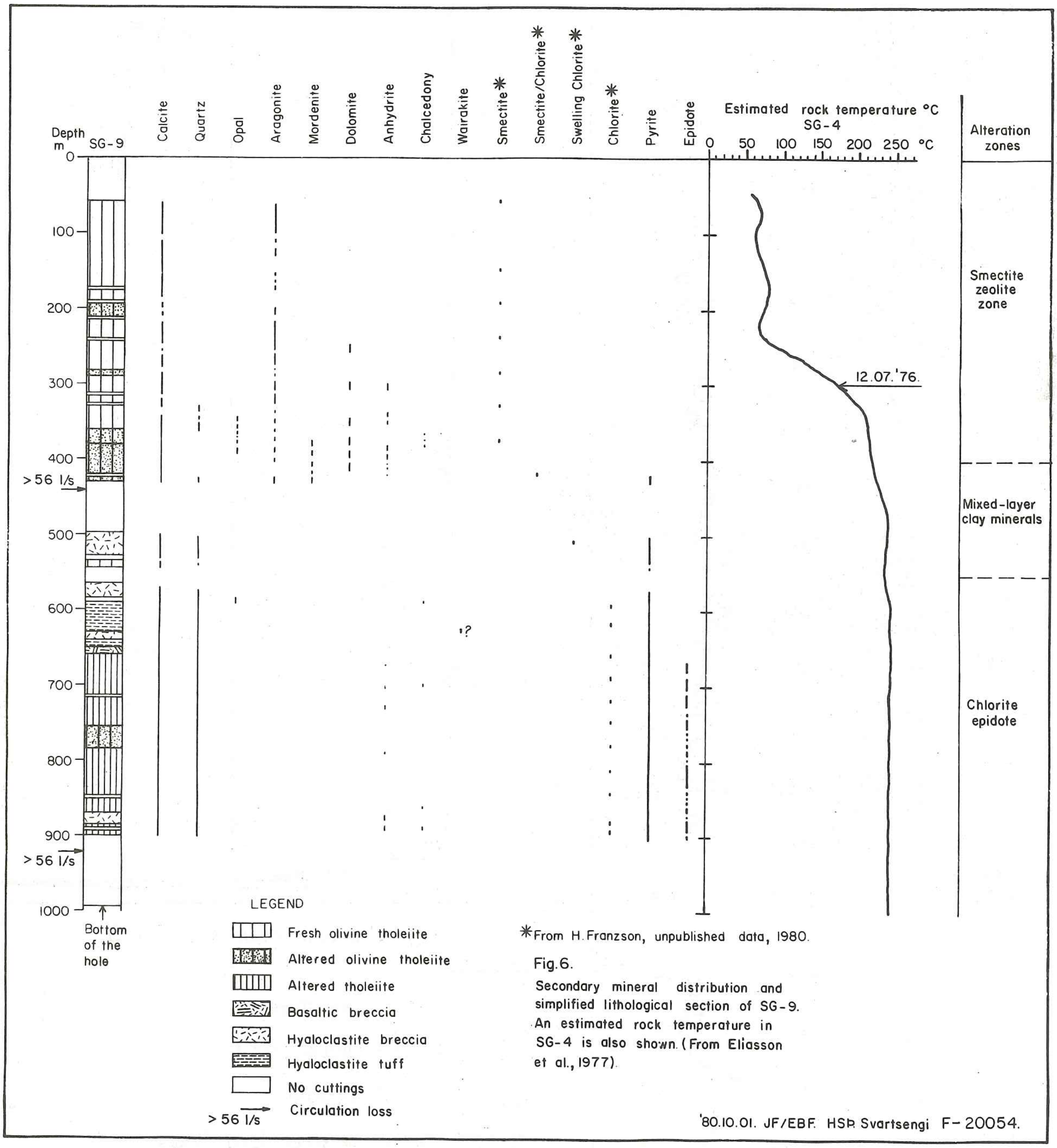
LEGEND

- Fresh olivine tholeiite
- Altered olivine tholeiite
- Altered tholeiite
- Contact between lava flows
- Uncertain contact between lava flows
- Basaltic breccia
- Hyaloclastite breccia
- Hyaloclastite tuff
- No cuttings

56 l/s → T.C.L. Circulation loss

T.C.L.= total circulation loss

'80.10.08. JF/EBF. HSP. Svartsengi. F-20088



*From H. Franzson, unpublished data, 1980.

Fig. 6.

Secondary mineral distribution and simplified lithological section of SG-9. An estimated rock temperature in SG-4 is also shown. (From Eliasson et al., 1977).

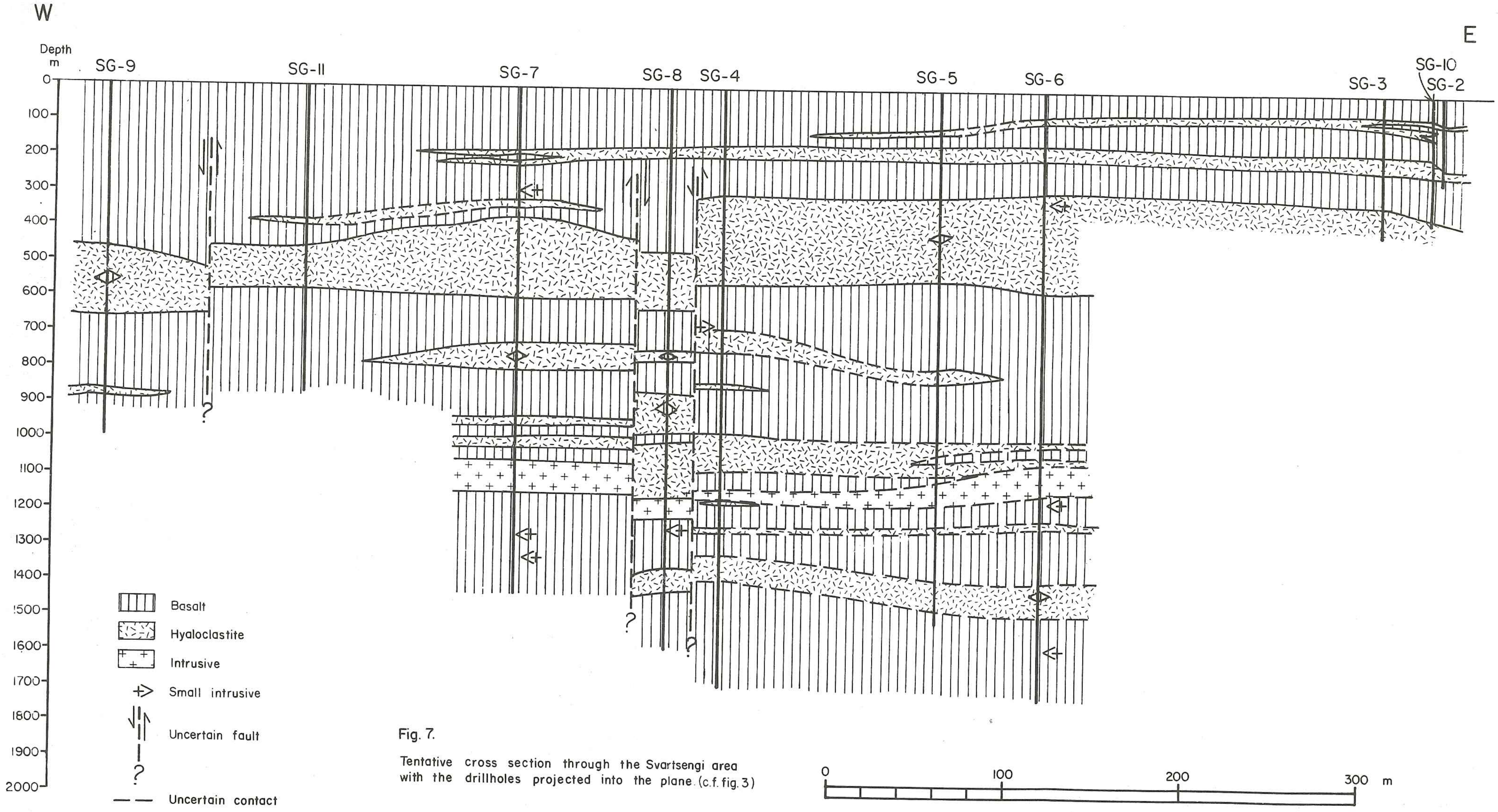


Fig. 7.

Tentative cross section through the Svartsengi area with the drillholes projected into the plane. (c.f. fig. 3)

'80.10.01. JF/EBF. HSÞ. Svartsengi. F-20055.

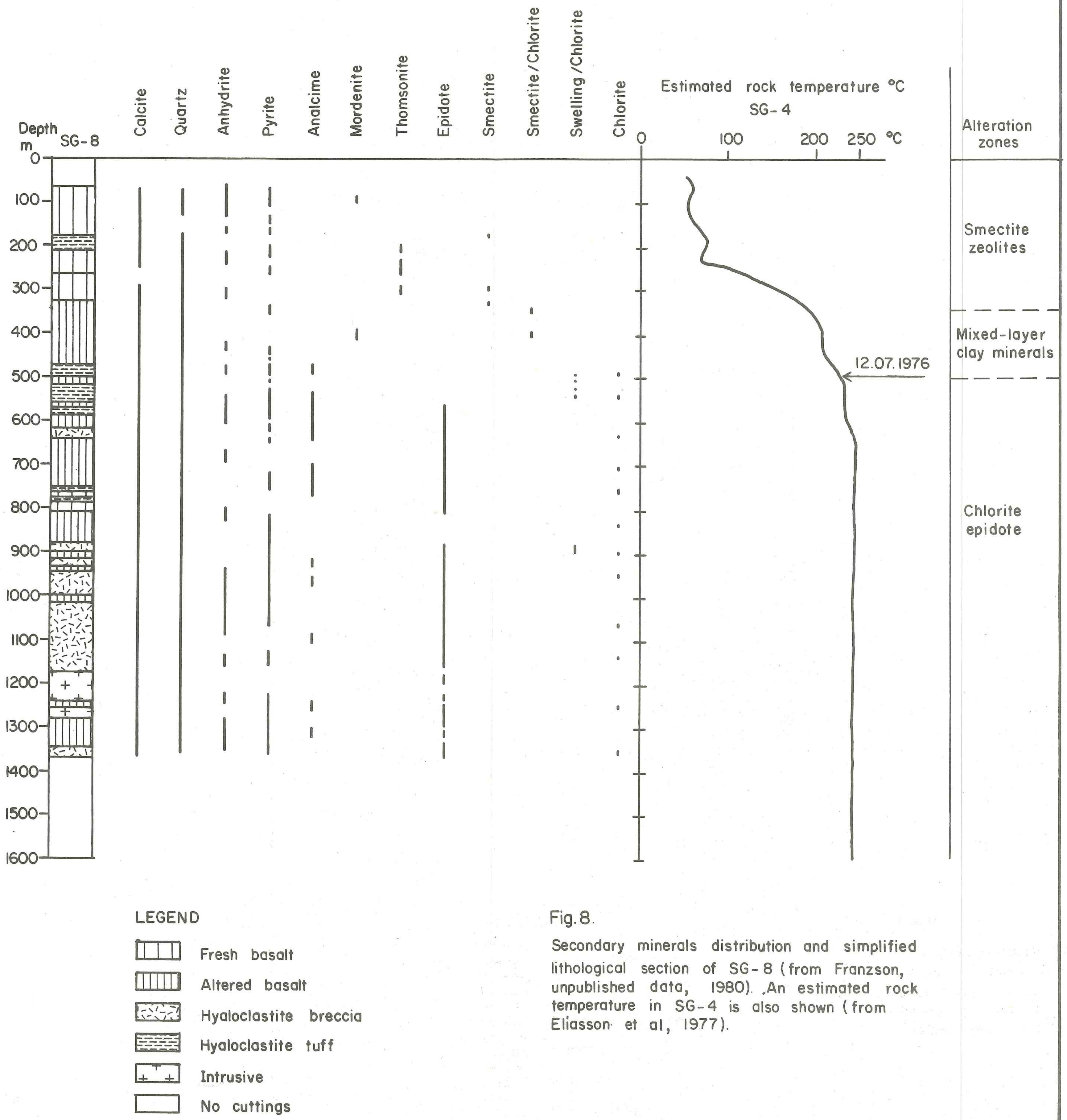


Fig. 8.

Secondary minerals distribution and simplified lithological section of SG-8 (from Franzson, unpublished data, 1980). An estimated rock temperature in SG-4 is also shown (from Elíasson et al, 1977).

'80.10.07. JF/EBF. HSÞ Svartsengi. F-20078.