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GeoScience Division

Borhole LL-03
Laugalandi í Holtum
Geological report

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Prepared for Norsk Hydro

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Borehole LL-03 Laugalandi í Holtum

Geological report

Modified English translation based on Orkustofnun Report (OS JHD 7802):
Laugaland í Holtum. Geothermal exploration and drilling of well 3
by
Lúdvík S. Georgsson, Haukur Jóhannesson, Margrét Kjartansdóttir and
Einar Gunnlaugsson

Prepared for Norsk Hydro

OS-99008 **February 1999**

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Abstract:
The report is a shortened geological account on borehole data from well LN-10 in Laugaland í Holtum. It is prepared as part of a VSP-experiment carried out by Norsk Hydro in three Icelandic wells in 1998. Well LN-10 was drilled in 1977 to 1308 m depth to provide hot water to a district heating system. The borehole was selected for the experiment mainly because it provides easy access to a typical, regularly developed pile of basaltic lavaflows. The Laugaland area is located on the western flank of the active Eastern rift zone in South Iceland. The bedrock belongs to the oldest part of the Hreppar formation and is considered to be 2.5-3.0 m.y. old. Based on correlation between boreholes, the dip at Laugaland is estimated to be 1-4° to the NW. Two nearly vertical dykes striking NE-SW have been detected in the vicinity of well LL-03 by surface magnetic measurements. Two fracture zones, one striking N15°E and the other N75°E, have also been detected by surface resistivity measurements. The rocks penetrated by the borehole are mostly basaltic lavaflows with thin red, sedimentary interbeds Hyaloclastites are quite rare in the well and mostly composed of reworked tuffs and breccias. The secondary minerals place the field in the mesolite/scolesite alteration zone.

Lykilorð:	ISBN-no:
Laugaland í Holtum, geology, borehole, logging, temperature, chemistry	
	Project manager's signature:
	Reviewed by: Authors

LIST OF CONTENT

TABLES

FIGURES

1. INTRODUCTION

In 1998 Norsk Hydro carried out VSP-measurements in cooperation with Schlumberger in three Icelandic wells, HH-01 Haukholt, LN-10 Thorlákshöfn and LL-03 Laugaland. Orkustofnun provided assistance in the selection of appropriate wells and logistics support during the operation itself. As part of the project, Orkustofnun was also to provide a summary of the information available from each of the boreholes in the form of a report in English. The present report constitutes this summary for well LL-03. Well LN-10 in Thorlákshöfn was described in an earlier report (Guðmundur Ó. Friðleifsson and Steinar Thór Gudlaugsson, 1998).

Well LL-03 is located in a low-temperature geothermal field at Laugaland in the Holt district of South Iceland (Figs. 1 and 2; Table 1). The field provides hot water to the villages of Hvolsvöllur and Hella and to many farms in the vicinity. Five wells have been drilled at Laugaland, wells L-1, L-2, LL-03 and LWN-4 and GN-1. The geology and geophysics of the geothermal field has been described in several reports in Icelandic (Lúðvík S. Georgsson et al., 1978; Lúðvík S. Georgsson and Steinar Thór Gudlaugsson, 1984; Lúðvík S. Georgsson et al., 1987; Grímur Björnsson et al., 1993).

Well LL-03 was selected as a suitable target for the VSP-experiment mainly because it is a stable, unused well with a short casing and provides easy acess to a typical, regularly developed pile of basaltic lavaflows. Furthermore, the lithology is fairly well constrained by cuttings sampled at a 2 m interval and an unusually extensive suite of logs is available.

The present report is mainly a shortened and updated version of Lúðvík S. Georgsson et al. (1978), the only report that deals specifically with well LL-03. Being 20 years old, the original report is deficient in some respects. The lithostratigraphic log (geological section) is less detailed than is currently the practice. Also, an integrated interpretation of cuttings and resistivity logs (the only geophysical logs available at the time) in terms of lithostratigraphy seems not to have been attempted.

It is clear that a more detailed and accurate lithostratigraphic log could have been obtained by reexamining the cuttings using more modern methods of cuttings analysis and by integrating this information with the suite of geophysical logs that have become available. This falls outside the scope of the present report but could be part of a final report on the logs obtained during 1998. Instead we have chosen to present the original lithostratigraphical analysis unchanged and redraw, in the form of a new composite log, the lithostratigraphical column together with a suite of the best geophysical logs obtained by Orkustofnun since the publication of the original report (Fig. 3).

Note that discrepancies in the placing of stratigraphical boundaries exist between a) the lithostratigraphical description on pages x-y, b) the lithostratigraphical column in Figure 3 and c) and the geophysical logs in Figure 3. The reason between the discrepancy between a) and b) is that attempts were made to correct for the travel time of cuttings to the surface in the lithological column in the original report, wheras the boundaries were left uncorrected in the text. As can be seen from the juxtaposed geophysical logs, this correction has not been completely successful and there is considerable room for improvement.

We have made no use of the geophysical logs obtained by Geoforschungszentrum Potsdam (GFZ). Orkustofnun does not have copies of the logs and permission to use them in a final report would have to be negotiated with the GFZ. In this connection, the borehole televiewer log is especially interesting. It could provide important constraints on the dips of the lavapile and any intersecting dikes.

It should also be mentioned that lithostratigraphical colums and geophysical logs are available from wells LWN-4 and GN-1 (Fig. 2A). These data could be used to obtain better constrains on the dips in the area, in case this is needed for the interpretation of the VSP-data.

Table 1. *Well LL-03, overview.*

Year drilled	1977
Total depth	1308 m
Drillbits used	15" to 16 m, 7 7/8" to 1308 m
Casing	14" to 16.2 m
Cemented interval	884.2 m to 932.6 m
Borehole geology	Regular pile of subaerial lavaflows containing less than 5% sedimentary interbeds, hyaloclastite, breccia and dikes
Cuttings	Every 2 m
OS logs	Temperature, caliper, natural gamma ray, neutron-neutron and normal resistivity (16" and 64")
Logs by Geoforschungszentrum Potsdam	Borehole compensated sonic (BCS), dual induction log (DIL), natural gamma ray and borehole televiewer (BHTV)

2. GEOLOGICAL SETTING OF LAUGALAND

The Laugaland area is located on the western flank of the active Eastern rift zone in South Iceland (Fig. 1). The nearest active volcano is mount Hekla 40, km to the NE. The bedrock belongs to the oldest part of the so-called Hreppar formation dating back from Early Pleistocene - Late Pliocene time (0,8-3,2 m.y. BP). The bedrock in the Laugaland area is considered to be 2.5-3.0 m.y. old.

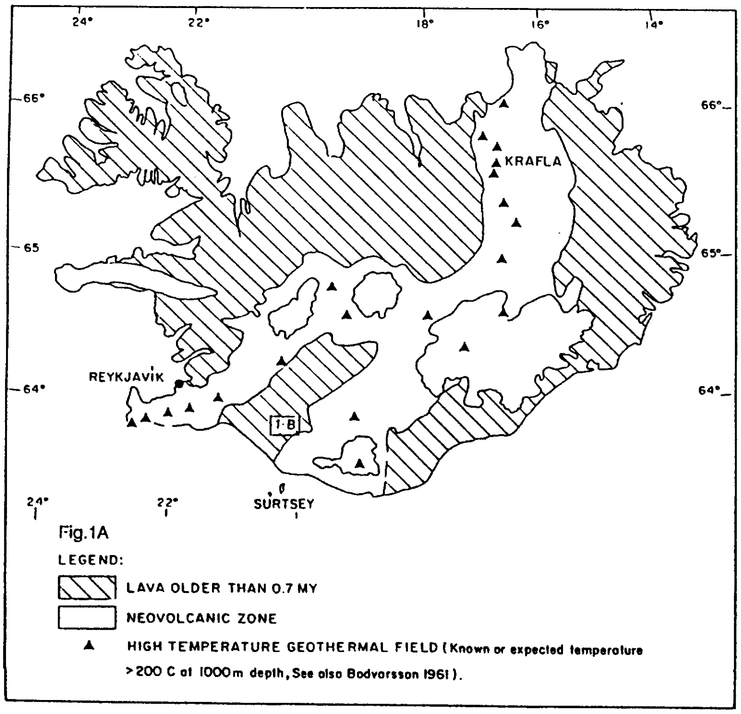
The Hreppar formation is composed of lava flows with interbeds of hyaloclastites from glaciation periods and also contains some sedimentary beds. In the older part of the formation, interglacial lava flows dominate over hyaloclastites as can be seen in the geological section of the hole where only thin (<30 m) beds of hyaloclastite are present (Fig 3).

The regional dip in the Laugaland area varies from place to place. To the west of Laugaland it is 4-8° NW. The dip at Laugaland has been estimated to be 1-4° to the NW from the correlation between boreholes (Lúðvík Georgsson and Steinar Thór Gudlaugsson, 1984), but about 6 km further north it is 10-12° NW.

Laugaland is located within the South Iceland Seismic Zone (SISZ) which extends from the Western rift zone across the South Iceland lowlands towards mount Hekla in the Eastern rift zone. The SISZ is characterized by short open fissures, which strike perpendicular to the SISZ zone in numerous short fissure systems arranged en echelon. The zone is also characterized by a left-lateral fault movement at depth, linking the Western and Eastern Iceland rift zones, and the Kolbeinsey midoceanic ridge further north. Confined within the SISZ zone are numerous low-temperature geothermal fields, like the Bakki field, near the Thorlákshöfn village, and the Laugaland field in Holt.

Dykes are not common the vicinity of Laugaland, but two dykes striking NE-SW were detected in the vicinity of well LL-03 by magnetic measurements (Fig. 2a). According to Lúðvík S. Georgsson and Steinar Þór Guðlaugsson (1983) the dykes in the Laugaland area found by magnetic survey have nearly vertical dip. Two low-resistivity fracture zones, one striking N15°A and the other N75°A are found in the Laugaland area.

Three fault and fissure directions can be distinguished in the Holt area: N0-10°E, N60°E and N20-40°E (Fig 1b) The first two fissure groups are most likely related to the lateral fault movements connected to the the SISZ zone, but the N20-40°E oriented fissure are probably older than the first two and less active.



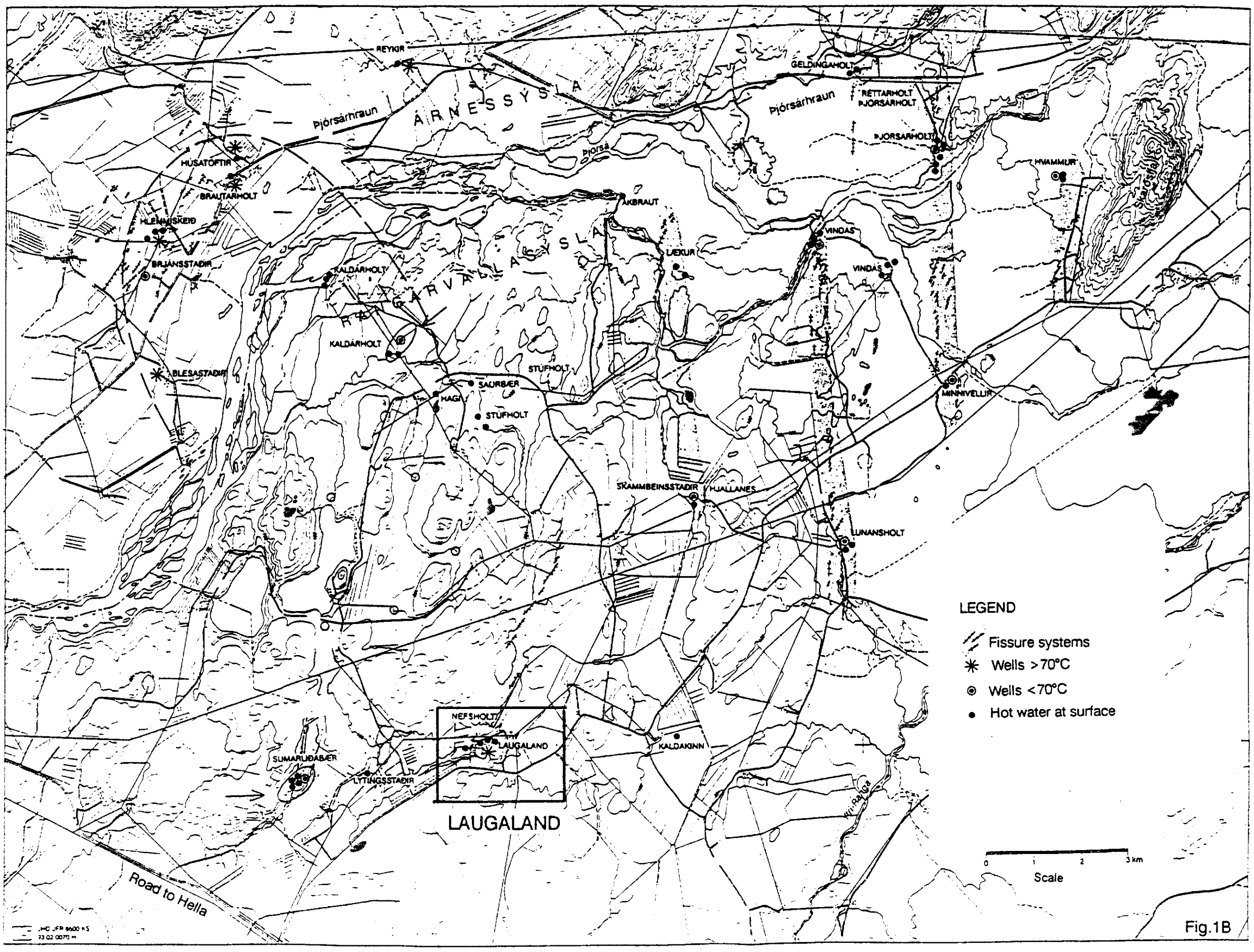
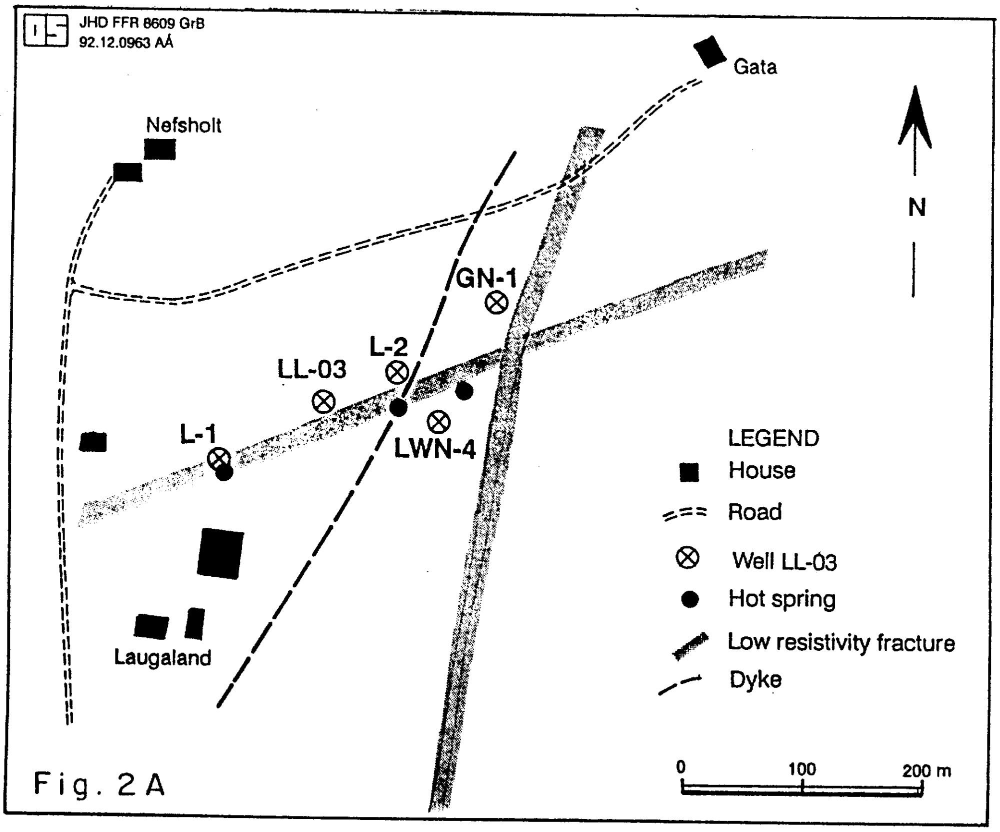


Figure 1. a) Location map, b) Geological setting.



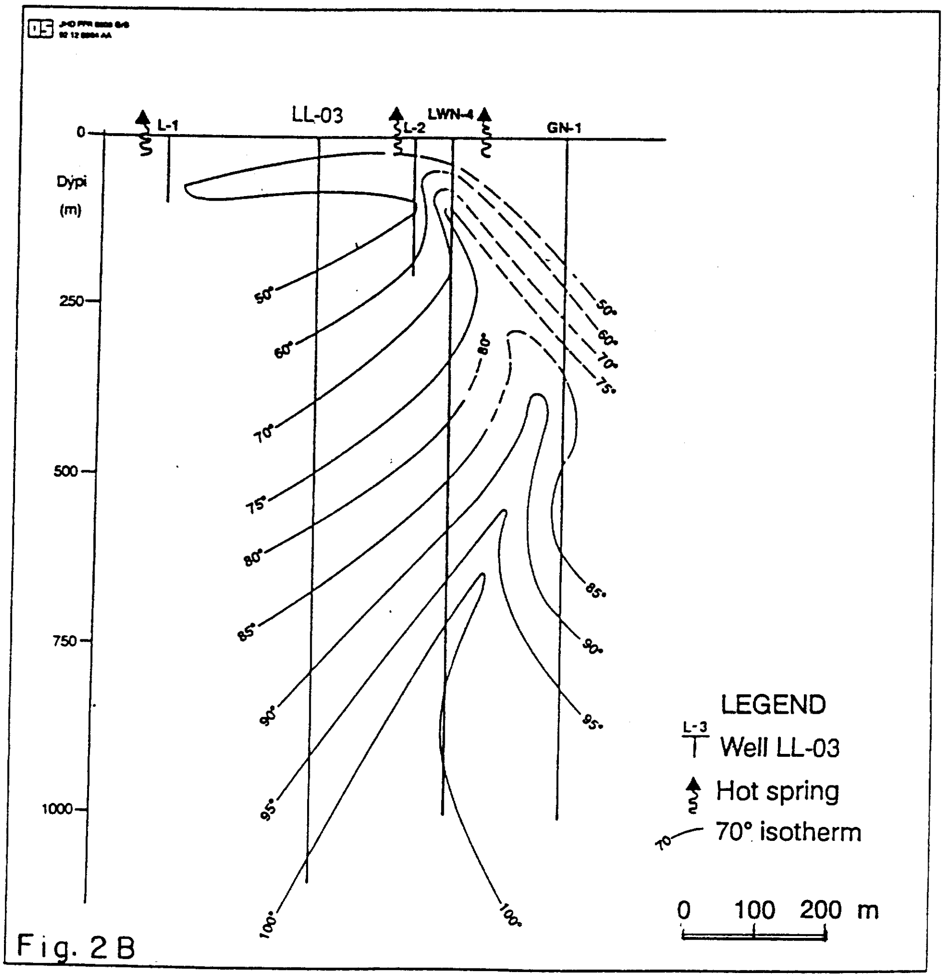


Figure 2. a) Map of Laugaland geothermal field.
b) Thermal cross section through the Laugaland geothermal field.

3. BOREHOLE LL-03

3.1 Drilling and design

The drilling of well LL-03 began on June 21st, 1977 and ended on July 19th, 1977. A 15" drillbit was used to 16.2 m depth and and a 14" casing was then set to 16.2 m depth. Drilling was continued with a7 7/8" drillbit to 1308 m depth. The drilling proceeded smoothly down to 980 m depth. After that a collapse of the well between 920-975 m was noticed. The hole needed to be cemented between 884.2-932.6 m to allow further drilling. One feed point was lost there.

3.2 Lithology

Samples of the drill cuttings were collected from the circulation fluid at 2 m intervals. They were examined under a microscope and a few thin sections were also made.

The rock is mostly made of basaltic lava flows and thin, red sedimentary beds are fairly regularly distributed throughout the section (Fig. 3). Hyaloclastites are quite rare in the well. The sparse occurrences found are composed of somewhat reworked tuffs and breccias. The depth intervals are: 100-130 m, 590-600 m and 664-684 m.

Secondary minerals are relatively rare; the secondary types placing the field in the mesolite/scolesite alteration zone.

3.2.1 Lithology

0-16 m. Cuttings lacking

16-34 m. Finegrained basalt mixed with rock cuttings of sedimentary origin.

34-100 m. At top are cuttings from a fine-grained oxidized sedimentary rock followed by hydrothermally altered glassy basalt and cuttings of clay minerals. Fillings in fractures are calcite, analcime, heulandite and several other alteration minerals that were not identified.

100-130 m. Reworked hyaloclastitic sediment.

130-222 m. Basaltic lava flows with thin interbeds. Two thin sections were made:
No. 7466, from 134 m shows homogeneous cuttings of fresh-looking tholeiite basalt.
No. 7467 from 176 m shows fresh looking tholeiite basalt with pyroxene phenocrysts. Flow banding in the lavas appears prominent.

222-226 m. Light red fine-grained sedimentary interbed.

226-240 m. Tholeiite lavas mixed with oxidized cuttings around 235 m, otherwise homogeneous.

240-280 m. Porphyritic tholeiite lava mixed at top and bottom with scattered oxidized sedimentary cuttings.

Thin section No. 7468 from 270 m depth shows homogeneous cuttings of tholeiite basalt with phenocrysts of plagioclase and pyroxene.

280-288 m. Most likely tholeiite lava. Scolecite, analcime and gyrolite are identified zeolites.

288-300 m. The uppermost part is made of yellowish red and gray, clay-rich interbed followed by scoriaceous cuttings with white mineral fillings. In the middle part are cuttings of dense, fresh-looking tholeiite basalt.

300-312 m. Dark, very fine-grained and dense basalt, same kind as found inside the sedimentary interbed above, possibly an intrusion?

312-315 m. Red oxidized sedimentary interbed.

315-334 m. Rather dark basalt, more likely olivine tholeiite than tholeiite lava, with hydrothermal clay fillings. A fine-grained basalt, relatively fresh, occurs between 322-328 m.
Thin section (No. 7469) from 330 m depth shows two types of cuttings. One is very fine-grained basalt resembling andesite but lacking flow-banding. The other type is a very coarse grained tholeiite basalt with secondary minerals in vesicles and fractures. In spite of large pyroxene phenocrysts, ophitic and subofitic texture is almost completely lacking.

334-344 m. Most of the cuttings show red oxidized basalt, rather fine-grained.

344-376 m. Fine-medium grained basalt and oxidized scoria.

376-394 m. The upper- and lowermost samples show cuttings of sedimentary rock and oxidized basalt but otherwise the section is made up of tholeiite lavas.

394-444 m. This part of the borehole cuts tholeiite basalt lava flows separated by thin interbeds which are difficult to locate exactly because large red cuttings of sedimentary rock are evenly distributed in the samples.

444-508 m. Rather coarse cuttings of tholeiite basalt similar to the basalt above. Scolecite and heulandite are prominent. Red cuttings of sedimentary rock are scarse.

508-554 m. Large, cuttings of sedimentary rock are abundant between 518-524 m. At 524-534 m white secondary mineral fillings like scolecite, heulandite and analcime are abundant. Red scoria is found at 520 and 538 m.
Thin section (No. 7471) of cuttings from 516 m shows heterogeneous material. One half of the cuttings is scoriaceous basalt with zeolite fillings, and the other half is fine-grained tholeiite basalt.

554-560 m. Rather coarse basalt, slightly altered.
Thin section (No. 7472) of cuttings from 558 m shows rather coarse tholeiite basalt with intergranular texture.

560-590 m. Tholeiite basalt lavas. At 574 m the rock is more coarse-grained and could be olivine tholeiite.

590-600 m. Hyaloclastic rock with greenish hue. Thin section (No. 7473) of cuttings from 592 m shows oxidized, almost black, basalt and also fine-grained tholeiite basalt with evenly distributed crystals of black ore.
Cuttings from hyaloclastite breccia and a few zeolite cuttings are also seen.

600-632 m. Tholeiite basalt lava together with scattered cuttings from more coarse-grained basalt also.

632-636 m. Light red, rather coarse-grained sedimentary bed.

636-664 m. The uppermost part comprises greyish tholeiite lava which becomes darker downwards. Around 650 m there is a coarser-grained basalt, probably a tholeiitic dyke.
Thin section (No. 7474) of cuttings from 646 m shows fine-grained tholeiite basalt with sparse pyroxene phenocrysts and flow texture. Cuttings of acid igneous rock are also present.

664-682 m. Tuffbreccia, often with rather fresh-looking glass, and basalt grains.
Thin section (No. 7475) from 674 m shows porous and glassy cuttings filled with zeolites and clay minerals. Inside the glassy cuttings fragments, both fine-grained and coarse-grained basalt fragments with ophitic texture are seen.

682-708 m. Rather coarse-grained basalt.

708-728 m. Very coarse cuttings, mostly from breccia, but also cuttings from basalt and sedimentary rock.

728-734 m. Greyish, dense tholeiite basalt.

734-746 m. Rather coarse-grained tholeiite lavas.
Thin section (No. 7476) of cuttings from 742 m shows fresh-looking tholeiite basalt often showing brown-coloured alteration.

746-794 m. Most likely coarse-grained tholeiite basalt. It is difficult to establish contacts between different lava beds due to contamination from overlying beds. Between 764-790 m, dense, greyish tholeiitic basalt is found.

794-840 m. The uppermost part is made of dark sedimentary rock. Coarse grained tholeiite and olivine basalt is found below.
Thin section (No. 7477) of cuttings from 810 m shows tholeiite basalt. Thin plagioclase lists are conspicuous in some of the cuttings.

840-872 m. Most of the cuttings come from tholeiite basalt. At 860 m fillings of scolecite and heulandite are common in vesicles and cavities.

872-932 m. Rather coarse tholeiite basalt and olivine tholeiite. At 900-910 m the sample is contaminated by red sedimentary cuttings.

Thin section (No. 7478) from 880 m shows highly altered olivine tholeiite with subophitic texture and fine-grained, moderately altered tholeiite basalt.

932-944 m. Dolerite. At the upper contact, light-coloured fillings of scolecite, calcite and quarz are seen in vesicles.
Thin section (No. 7479) of cuttings from 940 m does not manifest dolerite, but fresh olivine pehnocrysts indicate that this is very likely the case.

944-988 m. Fine-grained tholeiite lava at top but possibly olivine tholeiite lava deeper down. Cuttings of concrete are common in the 975-980 m interval.
Thin section (No. 7480) from 970 m shows several cuttings of olivine tholeiite but the majority of the cuttings come from hydrothermally altered tholeiite basalt.

988-1022 m. A red sedimentary bed dominates in the upper part but is underlain by coarse-grained basalt, most likely olivine tholeiite lava.

1022-1066 m. Relatively dense, fine-grained tholeiite lavas.

1066-1080 m. Coarse-grained basalt probably olivine tholeiite lava.

1080-1182 m. A mixture of basalt of varying grain sizes. Coarse-grained basalt is especially found at 1130 m. Oxidized scoria is found at 1180 m depth. At 1150 m depth the rock appears fractured.

1182-1214 m. Rather fine grained-tholeiite basalt.

1214-1308 m. Rather fine-grained tholeiite basalt. Fractures with secondary minerals are found in the basalt at 1220 m depth. Cuttings of red scoria are common in the samples.

3.3 Chemistry, temperature and aquifers (feed points)

There are two main water-conducting systems found in well LL-03 (Fig. 4). The upper system is at 50-220 m depth and the lower is at 635-920 m.

Table 2 shows chemical analysis of thermal water from three wells in the Laugaland area during 1968-1978. The samples from wells L-1 and L-2 yield similar results. In well L-2 no difference is detected in samples of water from 76 m and 106 m. Water samples from well LL-03 have about 50% higher salinity than water samples from wells L-1 and L-2. On the other hand only slight difference can be seen between water samples from 105 m and 212 m depth in well LL-03. This could be due to water flow upwards from aquifers at lower levels. The silica concentration in LL-03 points to a water temperature of 70-77°C. In well L-1 the silica concentration points to a temperature of 46°C and mixing with cold groundwater. The alkali temperature, in well LL-03 gives similar results as the measured temperature or 63-66°C.
Analyses are lacking from the lower system in LL-03 between 635-920 m. The wells L-1 and L-2 are shallower and do not reach down to the lower system.

Most of the feed points in the upper water conducting system in LL-03 (Fig. 4) do not yield much water. They seem to be connected to horizontal flow in interbeds in the vicinity of the the low resistivity fissure zone striking N70°E (Fig. 2a)
The feed point at 105-110 m depth is connected to an interbed of reworked hyaloclastitic tuff. The feed point at 910-920 m was cemented (chapter 3.1). It is located just above a dyke.

Table 2. *Chemical composition of the water from wells L-1, L-2 and LL-03.*

Sample No.	Well L-1 0680259	Well L-2 76 m 03770025	Well L-2 106 m 03770026	Well LL-03 105 m 10770154	Well LL-03 212 m 10770155
°C	47	50	50	63	69
pH/°C	9.6			9.53/21	9.78/21
SiO_2	42	58.4	59.4	76.9	79.5
B	0.62				
Na	71.0	65.4	64.0	99.1	105.8
K	0.8	1.15	1.06	1.43	1.64
Ca	3.1	3.4	3.1	5.8	6.3
Mg	0.04	0.14	0.08	0.04	0.07
CO_2 total	27.8			34.1	21.1
SO_4	54.8	61.4	63.4	91.0	101.9
H_2S	<0.1			<0.1	<0.1
Cl	39.7	44.0	46.2	64.5	76.3
F	1.3	0.53	0.48	0.87	0.93
Solubles	219			356	393
Calcedone temp.	46°C			77°C	70°C
Alkali temp.	55°C	63°C	62°C	63°C	66°C

3.4 Conclusions

The bedrock at Laugaland is of Plio- Pleistocene age and the hot water yield of the rock is poor.

In well LL-03 two main water-conducting geothermal systems occur (Fig. 4). The upper system is found in the 50-220 m depth interval and has a temperature of 60-75°C. It yields more water than the the lower system which is located at 635-920 m depth and has a temperature of 90-92° C. At least one of the feed points in the lower system is connected to a dyke at 932-944 m. On the other hand, well LL-03 has not intersected the water-conducting ffracture zone which was expected to have N70°E direction.

Fig. 2 shows the current thermal model og the Laugaland field (Grímur Björnsson et. al. 1993) assuming a hot water aquifer along the major fracture zone. The location of well LN-03 is shown in the figure.

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Laugaland í Holtum - Well LL-03
Composite Log

21-JAN-1999

Site:	Laugaland í Holtum	*Rig:*		*Casing:*	14" to 16.2 m
Well:	LL-03	*Total depth:*	1308 m	*Bit size:*	15" to 16.2 m, 7 7/8" to 1308 m

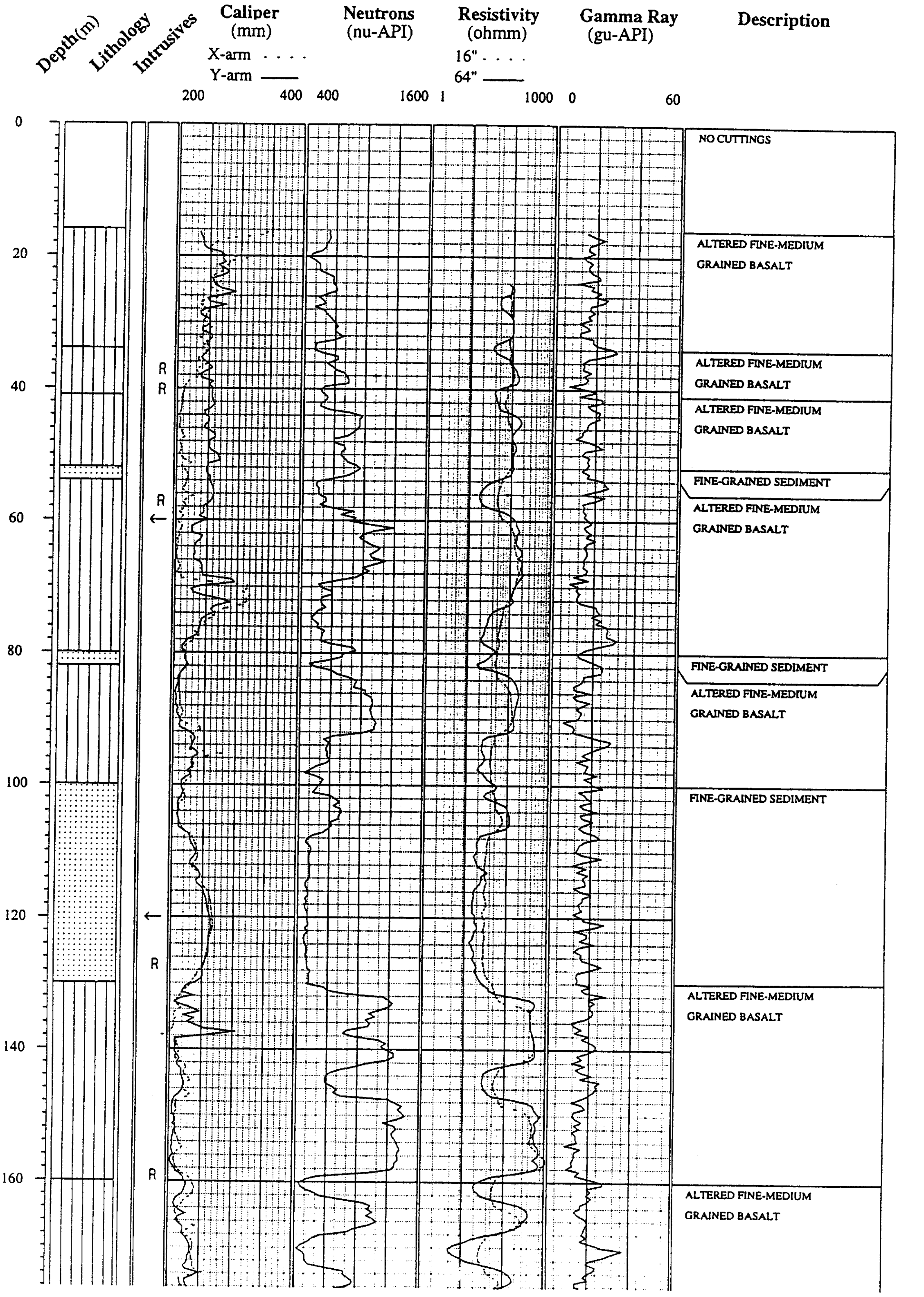
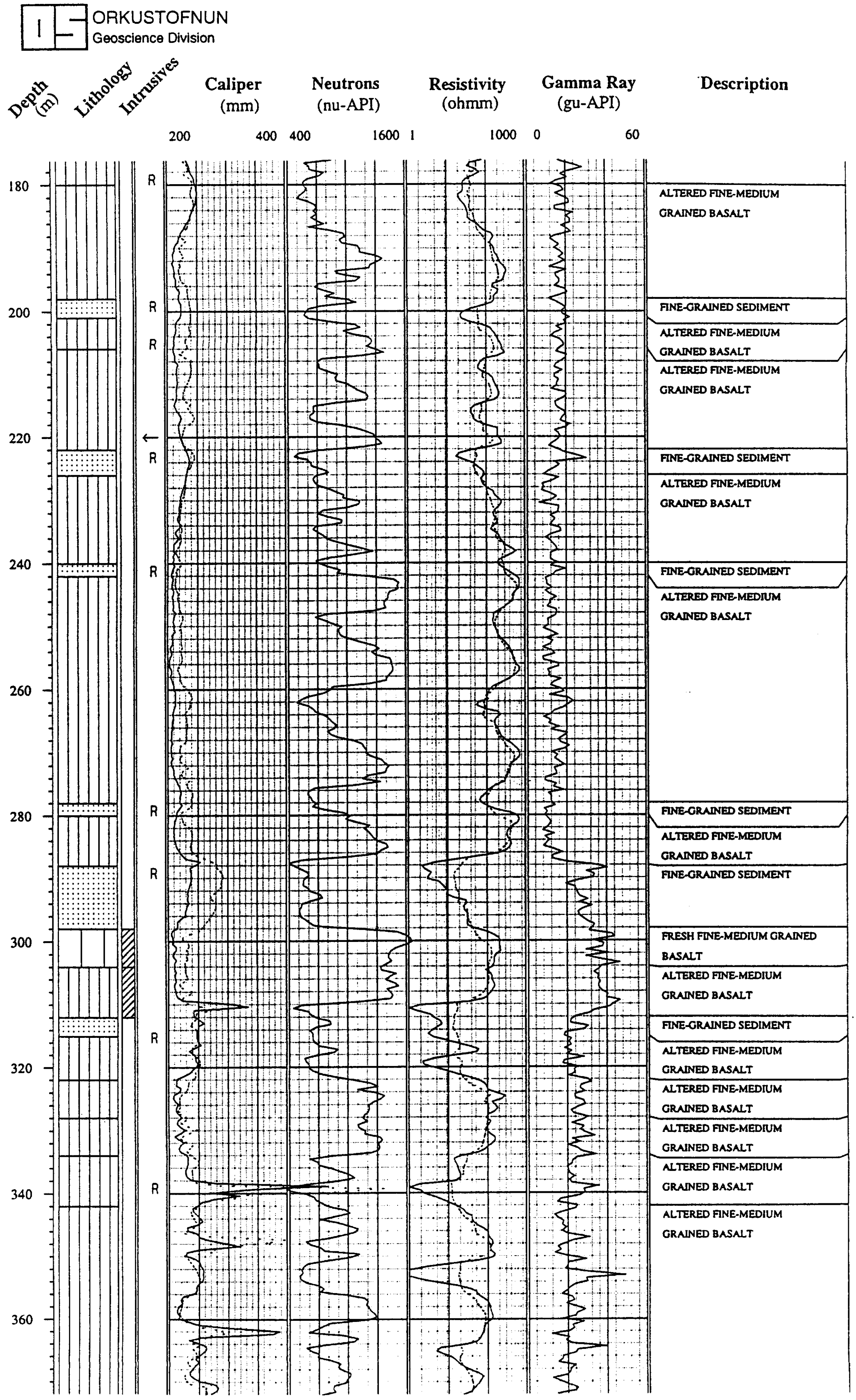


Figure 3. Composite log from well LL-03.



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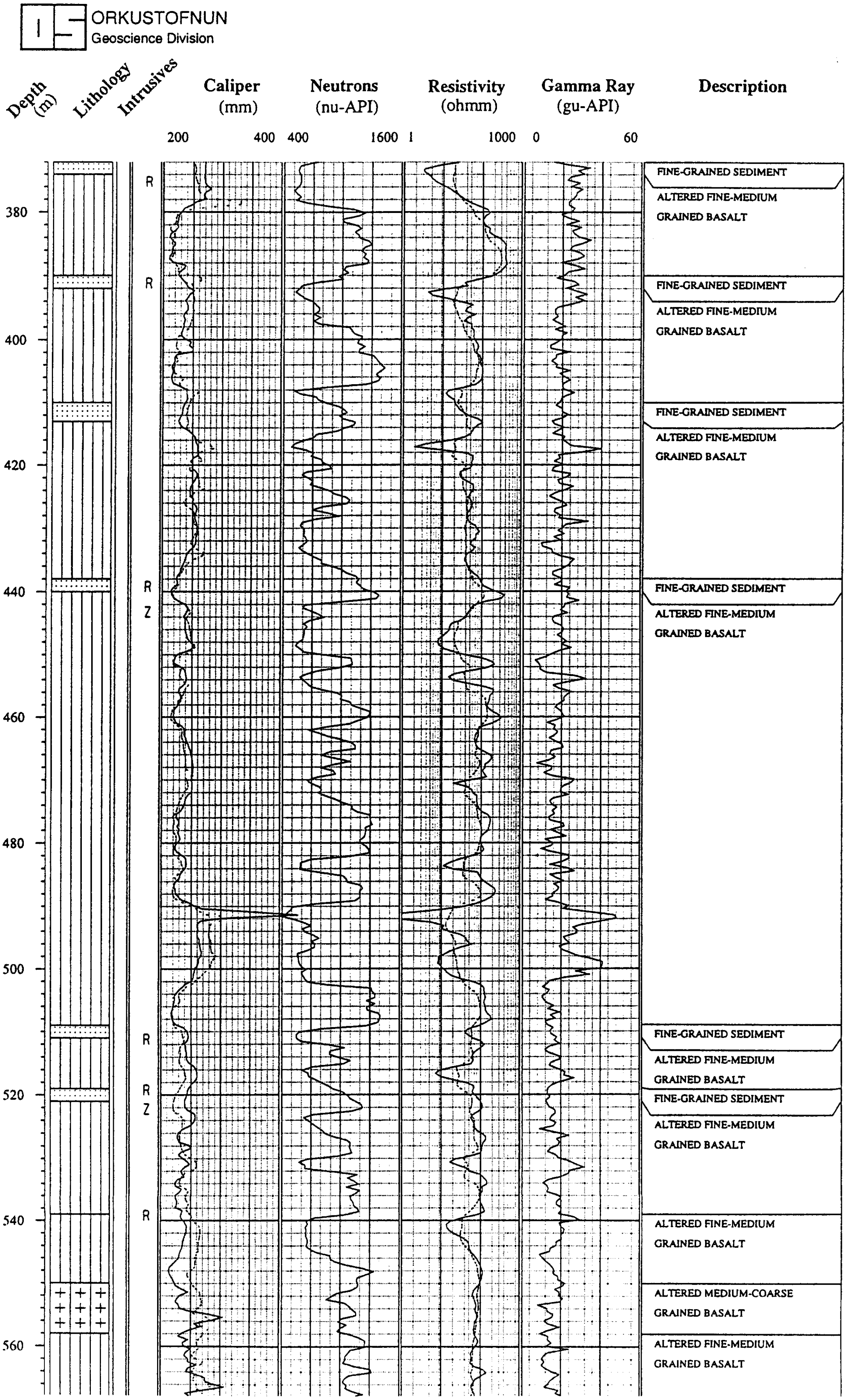

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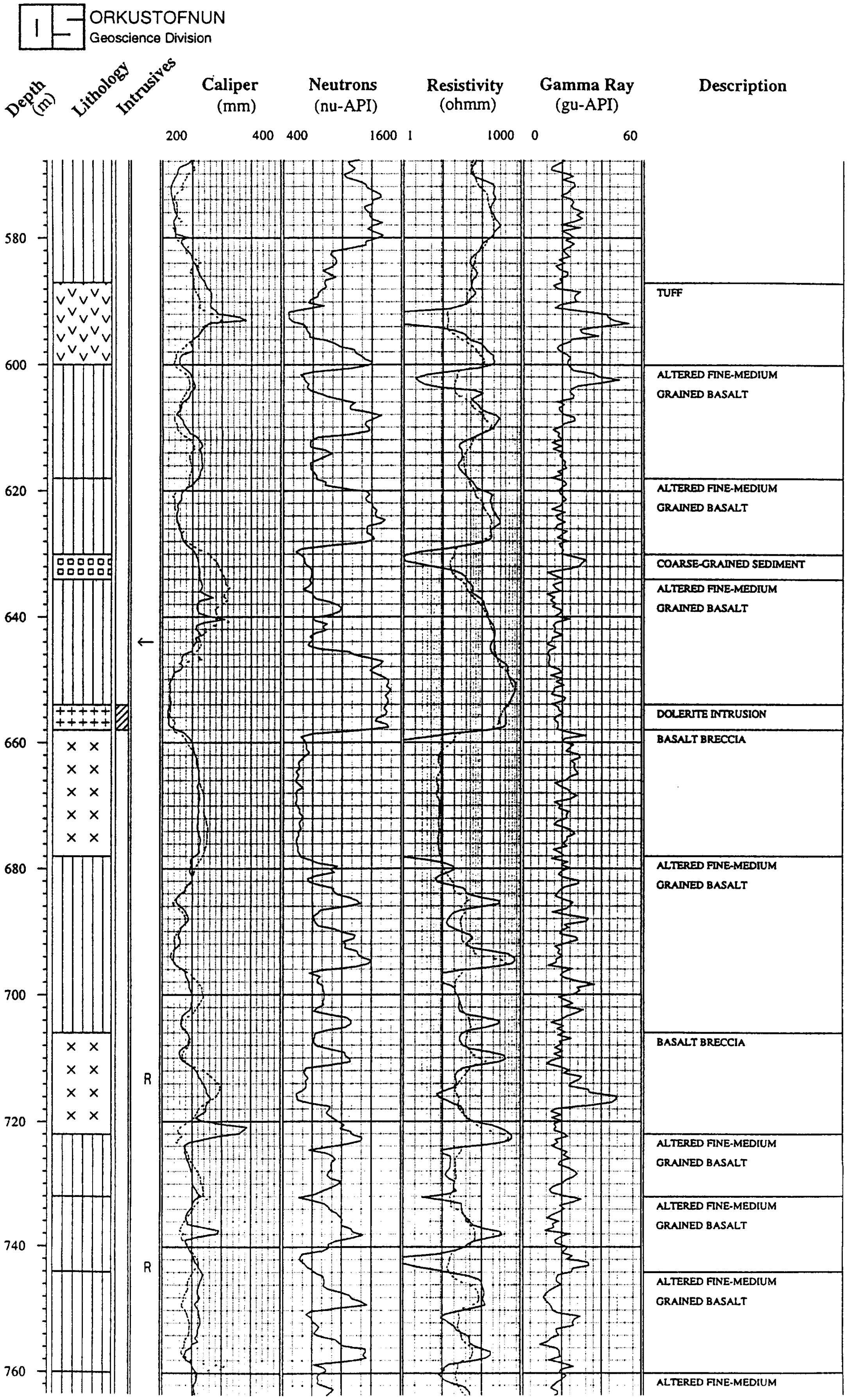
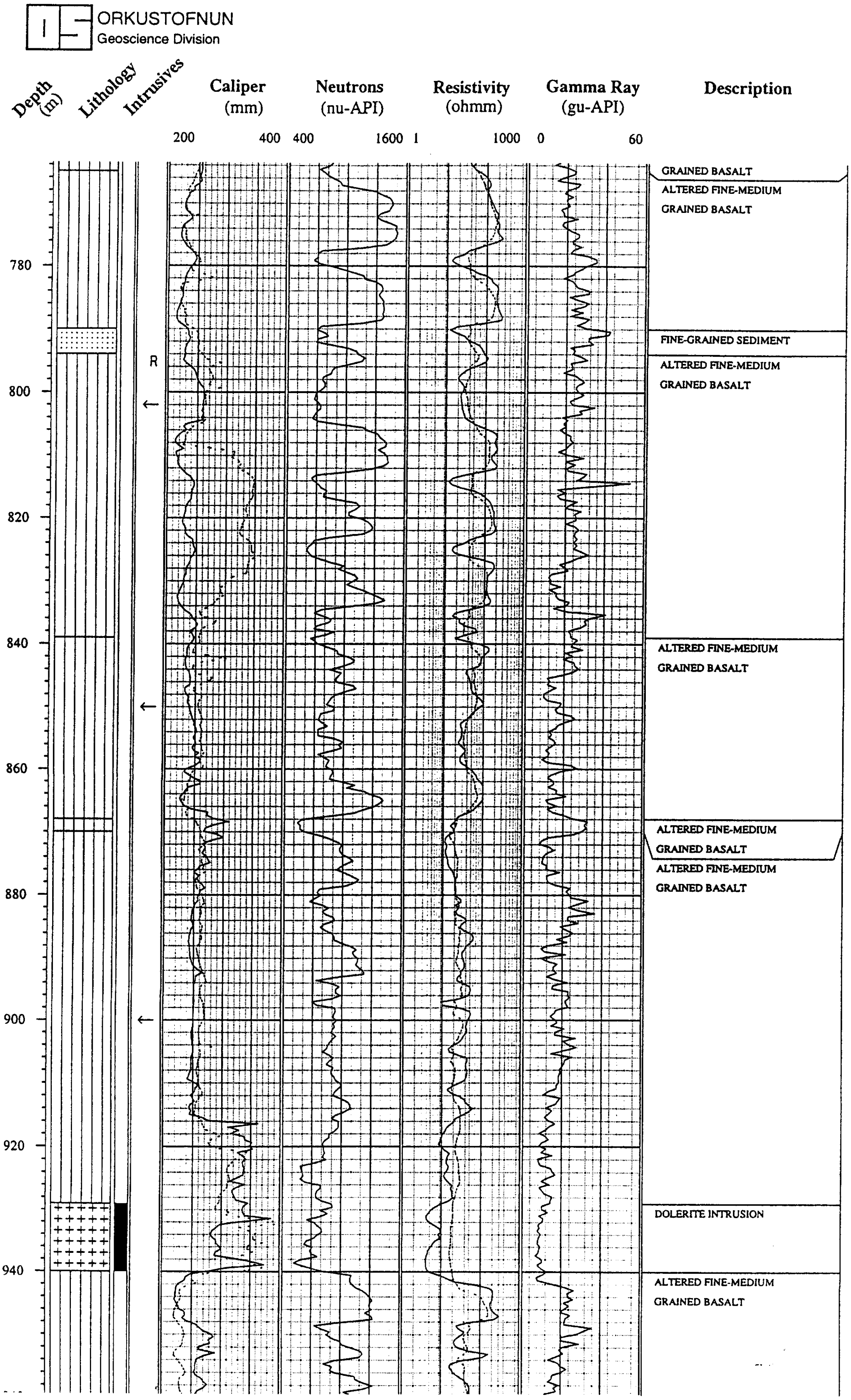


Figure 3. Composite log from well LL-03.



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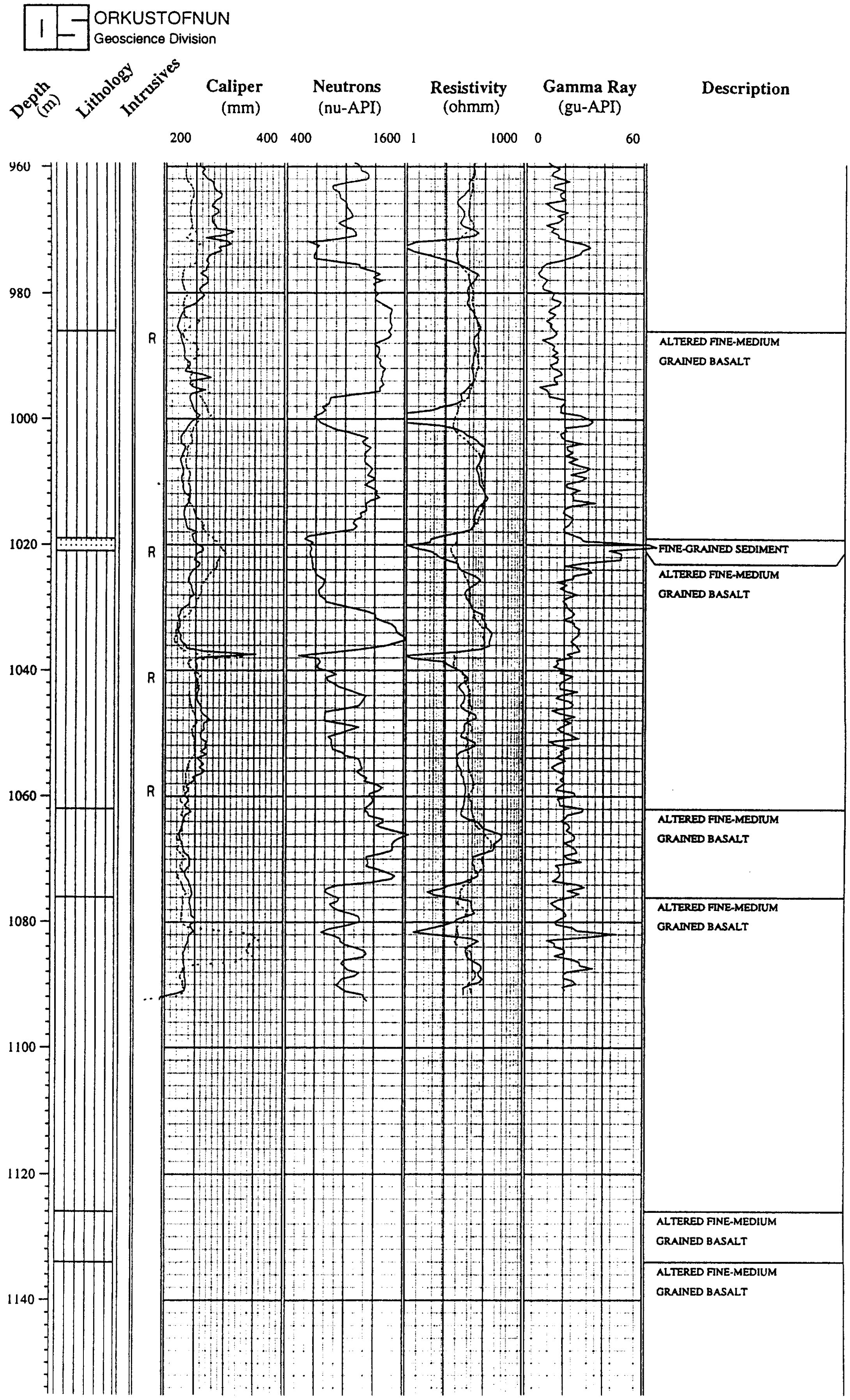

Figure 3. Composite log from well LL-03.

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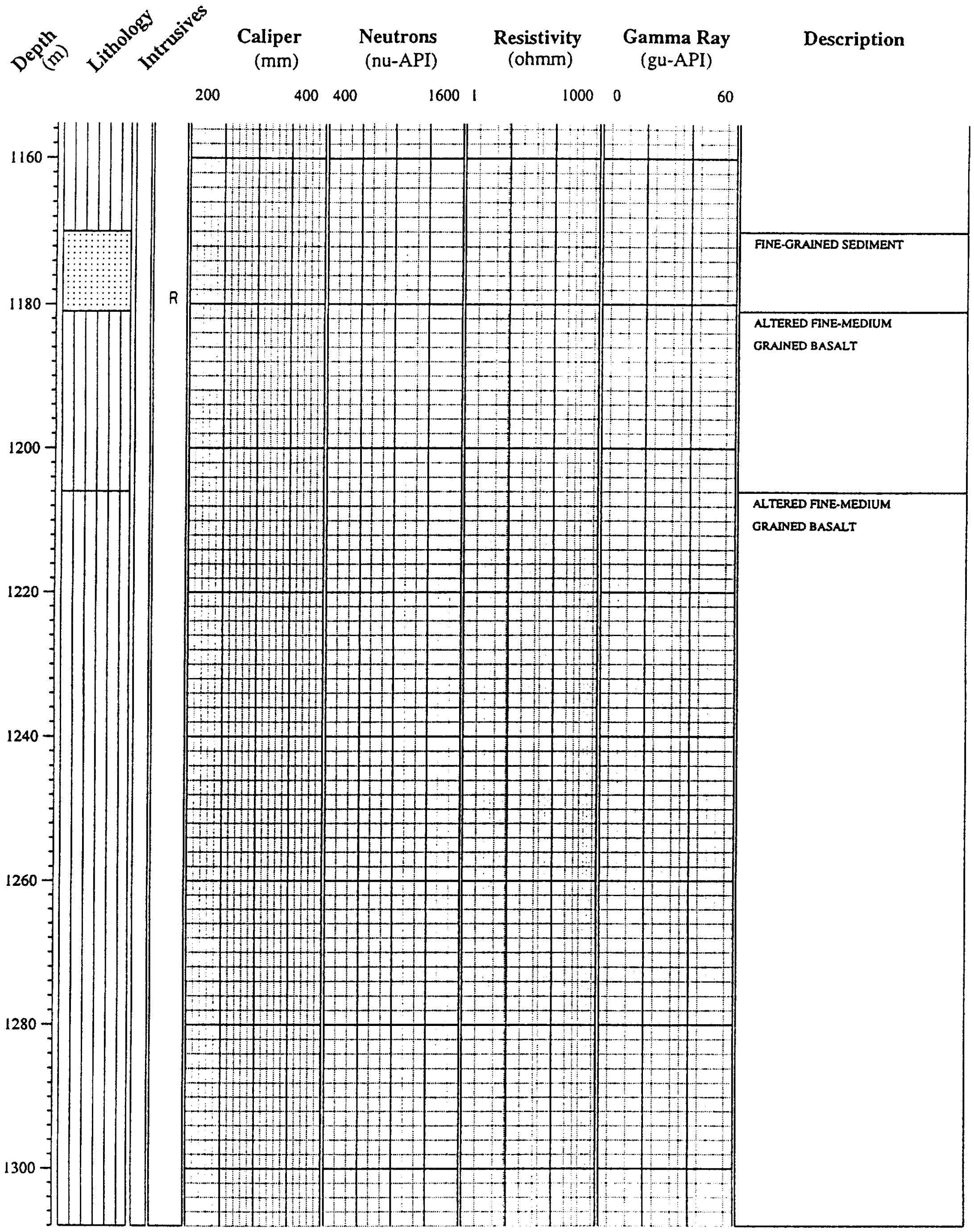

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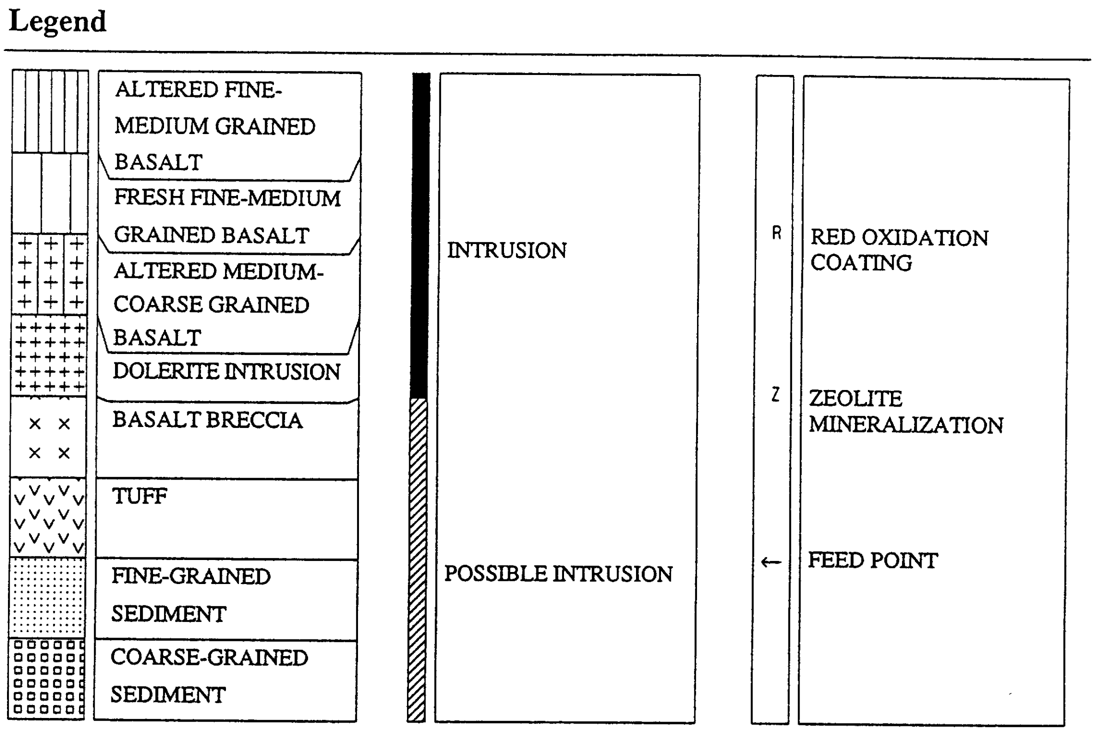

Legend for Figure 3.

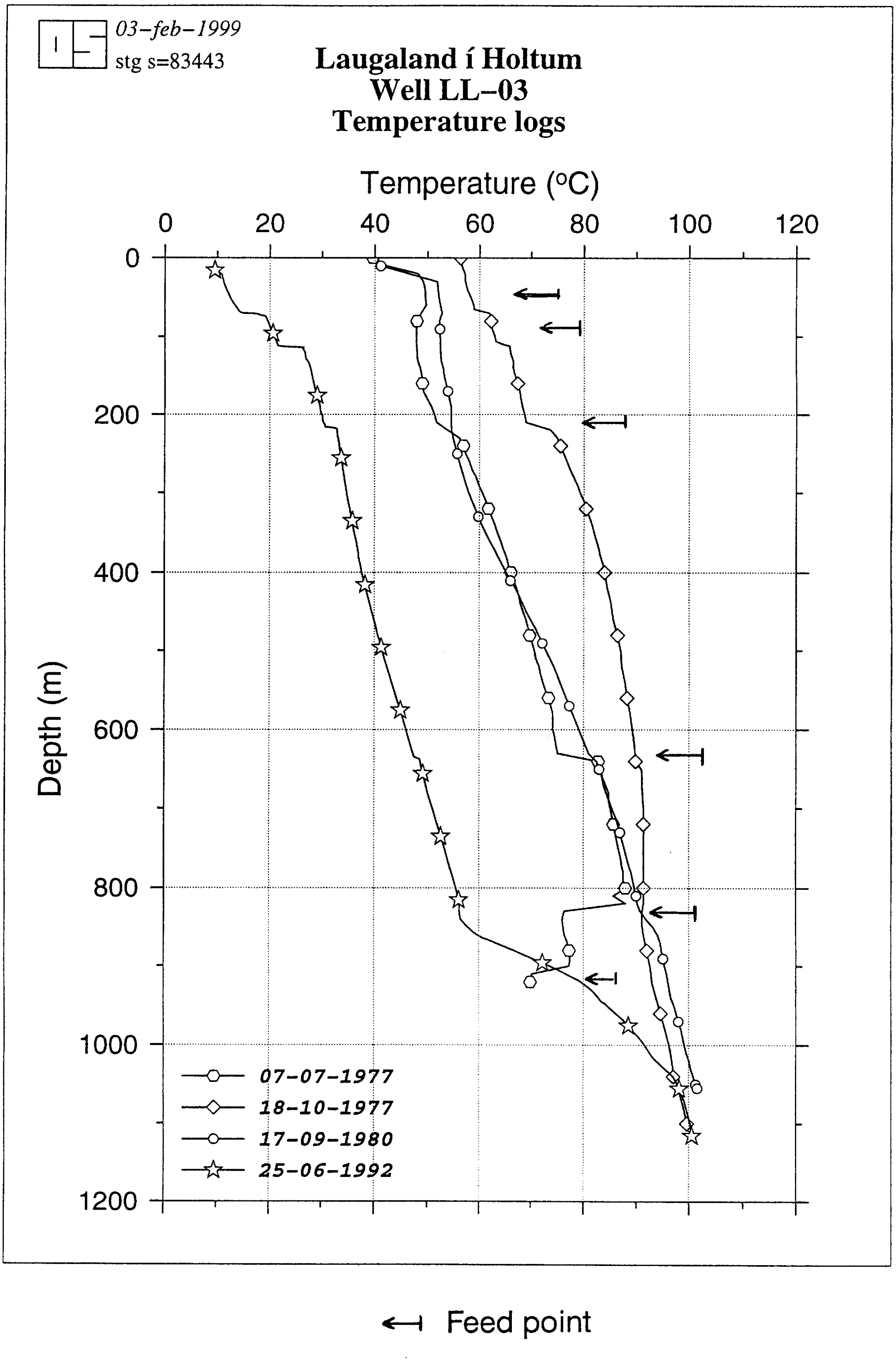

Figure 4. Temperature logs from well LL-03.

4. REFERENCES

Grímur Björnsson, Gudni Axelsson, Jens Tómasson, Kristján Sæmundsson, Árni Ragnarsson, Sverrir Thórhallsson and Hrefna Kristmannsdóttir 1993: Hitaveita Rangæinga. Jardhitarannsóknir 1987-1992 og möguleikar á frekari orkuöflun. (Rangá District Heating Utility. Geothermal research 1987-1992 and possibilities for increased energy production). Orkustofnun, Reykjavík, report OS-93008/JHD-03 B, 74 pp. (in Icelandic)

Gudmundur Ó. Fridleifsson and Steinar Thór Gudlaugsson 1998: Borehole LN-10 Thorlákshöfn. Geological report. Orkustofnun, Reykjavík, report OS-98071, 14 pp. (Prepared for Norsk Hydro)

Lúdvík S. Georgsson, Haukur Jóhannesson, Margrét Kjartansdóttir and Einar Gunnlaugsson 1978: Laugaland í Holtum. Jardhitakönnun og borun holu 3. (Laugaland í Holtum. Geothermal exploration and drilling of well 3). Orkustofnun, Reykjavík, report OS JHD 7802, 53 pp. (in Icelandic)

Lúdvík S. Georgsson and Steinar Thór Gudlaugsson 1984: Laugaland í Holtum. Vidnámsmælingar og mælingar í holu LWN-4 sumarid 1983. (Laugaland í Holtum. Surface resistivity measurements and measurements in borehole LWN-4 in the summer of 1983). Orkustofnun, Reykjavík, report OS-84042/JHD-07, 24 pp. (in Icelandic)

Lúdvík S. Georgsson, Audur Ingimarsdóttir, Gudni Axelsson, Margrét Kjartansdóttir and Thorsteinn Thorsteinsson 1987: Laugaland í Holtum. Hola GN-1 í Götu og vatnsvinnsla á Laugalandssvædinu 1982-1987. (Laugaland í Holtum. Borehole GN-1 at Gata and production of water from the Laugaland field 1982-1987). Orkustofnun, Reykjavík, report OS-87022/JHD-04, 65 pp. (in Icelandic)