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ZEOLITE ZONES IN GEOTHERMAL AREAS IN ICELAND

Hrefna Kristmannsdóttir
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„Zeolite '76"

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ABSTRACT

Zeolites formed in basaltic flows and hyaloclastic rock sequences in Icelandic geothermal areas have been mapped and investigated.

In the low-temperature geothermal areas (rock temperature < 150°C in the uppermost 1 km.) four distinct zeolite zones are found. The zeolite zones correspond to a rock temperature interval. In the order of increased rock temperature the zones are 1) chabasite, 2) mesolite/scolecite, 3) stilbite and 4) laumontite zones. Analcime is not confined to a distinct zone.

In most of the high-temperature geothermal areas (> 200°C in the uppermost 1 km.) zeolites are formed in the uppermost part of the upflow zone at rock temperatures below 250°C. At even higher rock temperatures analcime and wairakite are found. The sequence of zeolites is normally not sharply defined in the upper levels of the high-temperature areas due to the sharply rising temperature gradients. Mordenite, heulandite, laumontite and analcime are the zeolites most commonly found in the high-temperature geothermal areas. In a few of the high-temperature geothermal areas zeolites are almost lacking.

INTRODUCTION

Geothermal areas in Iceland have been investigated for the last thirty years and deep drilling has been performed in some of the areas. Mineralogical investigation of the altered rocks has been greatly intensified over the last five years. The geothermal areas in Iceland are divided into two distinct groups (e.g. Pálmason, 1974) The low-temperature areas which are found in Quaternary and Tertiary rock formations and the high-temperature areas which are in the recent volcanic zones (Figure 1). In the low-temperature areas the temperature is below 150°C at 1 km depth, whereas in the high - temperature areas the temperature is higher than 200°C at this depth.

Figure 1

In all the high-temperature areas the dominant rock formations are basaltic hyaloclastites and basalt lavas. This is also the case for the low-temperature areas found in the Quaternary rock formation; however, in the low-temperature areas in rocks of Tertiary age the country rocks are mainly basalt lavas with sedimentary intercalations. The geothermal fluid is generally water of meteoric origin with a comparatively low content of dissolved solids (Arnórsson, 1974). However, in some geothermal areas the water is saline and contains considerable amount of dissolved solids. The chemistry of geothermal water from several areas is shown in Table 1. The most common cause of saline water in Icelandic geothermal systems is direct mixing with sea-water or an outwash of chlorine trapped in marine formations (Arnórsson and Tómasson, 1970). In the most extreme case, in the Reykjanes high-temperature geothermal area (Björnsson et al, 1972, Tómasson and Kristmannsdóttir, 1972), the water has the same salinity as sea-water. The pH of most geothermal water is high, 9 to 10 at 20°C in the meteoric originated water, and 7 to 8 in the saline water. The geothermal water of Leirá in Borgarfjörður is special in that it is CO_2 - rich.

Table 1

Rocks in high-temperature areas are young and have never been deeply buried. The alteration caused by the circulation of the geothermal water overshadows completely any former deuteric or low-temperature alteration. In the low-temperature areas, the alteration minerals often reflect a complex thermal and geological history of the area. The effects of the present geothermal system are not as obvious as they are in the high-temperature geothermal areas.

In the hydrothermally altered rocks zeolites are found mainly as minor constituents in small veins and amygdule fillings. The zeolites are also found as devitrifaction products of volcanic glass. However, in one of the Icelandic geothermal areas (Húsavík), zeolites have quantitatively replaced the original rocks.

Zeolitization In Geothermal Areas

Low-temperature areas

Low temperature geothermal areas are found in Quaternary rocks which boarder active volcanic zones and also in Tertiary rock formations mainly in the northern and western parts of the country. Zeolites are apparently in all temperature regions up to 200°C in the deepest drillholes at the areas.

The geothermal areas within and in the neighbourhood of Reykjavík are among the most intensively investigated low-temperature fields in the Quaternary rock formation. Here the rock formations are alternately hyaloclastites and basalt lavas in the uppermost 1000 m. Between 1000 m and below that depth to at least 2000 m basalt lavas are dominant. The maximum temperature obtained is 146°C at 2200 m depth in one of the areas, but in other areas the maximum temperatures vary from 100-120°C. Figure 2 shows a simplified geological section in a drillhole from one of the geothermal fields in Reykjavík, together with estimated rock temperatures and the distribution of secondary mineral species. In all the Reykjavík geothermal fields the occurrence of zeolites is closely related to

Figure 2

the prevailing rock temperature. The zeolite zones found are: An uppermost chabazite zone, a mesolite/scolecite zone, a stilbite zone and a lowermost laumontite zone, listed as a function of increasing temperature and depth. Other alteration minerals are not directly related to the prevailing temperature. Relict alteration is found in an aureole around two nearby Quaternary volcanic centers. The intensity of the alteration in the different Reykjavík areas is governed by their relative distance to these volcanic centers. Epidote is always relic, and its retrograde transformation to prehnite has been observed. The clay minerals are partly relic and partly formed by the most recent low-temperature geothermal activity.

Figure 3

In Figure 3 a similar diagram is shown for a 2187 m deep drillhole near Thorlákshöfn in southwest Iceland (see Figure 1). This area is on the boarder of the western volcanic zone in southern Iceland and can be considered as a border-case between low- and high-temperature geothermal areas. According to the previously stated definition it is, however, classified as a low-temperature area. In the uppermost 300 m the rocks are recent basalts; below that depth hyaloclstites alternate with basalt lavas to about 1900 m, with dominant basalts below. Dolerite dikes intrude the other rocks, mainly below 1100 m depth. The maximum temperature obtained is 190°C at 2100 m depth. Chabazite and thomsonite occur above 450 m, and laumontite below 800 m to 2100 m, accompanied by mordenite and analcime at 800-1000 m depth. Zeolites are nearly absent at 450-800 m depth. The degree of alteration is comparable to the uppermost smectite-zeolite zone, which is found at rock temperatures below 200°C, in the high-temperature areas (Krismannsdóttir and Tómasson, 1976). The occurrence of epidote and mixed-layer clay minerals in the deeper levels of the section indicate the beginning of the next alteration zone.

Walker (1960) mapped a well-defined zoning of the zeolitization of Tertiary formations in eastern Iceland. The zeolites in geothermal areas in the Tertiary formation show a very similar zoning, although the analcime zone is seldom sharply defined. The uppflow zones of water in these areas are mainly governed by tectonic features and have normally a limited horizontal extention. The effect of circulation of geothermal water on the zeolitization is mostly seen by a disturbance of the zeolite zones around the main aquifers.

Figure 4 Figure 4 shows the occurrence of secondary minerals in a drillhole from an area near Akureyri (see Figure 1). The maximum temperature of the geothermal water is 96°C. A disturbance occurs in the zeolite zoning at approximate 620 m depth; at this same depth there is an inflow (23 l/s) of 94°C hot water to the drillhole.

The geology of the Húsavík thermal area in northeast Iceland and the geochemistry of the thermal water have been described elsewhere (Árnason and Tómasson, 1970). The area is transected by a fault system with a vertical displacement of 600-1000 m. The uppermost 1100 m are sediments intercalated by smaller amounts of basalt lavas. The sediments are partly marine. Basalt lavas underlie the formation. The chlorine content of the water is from 400-1800 ppm and the temperature of the geothermal water is from 45-100°C. The zeolites have nearly quantitatively replaced the original sedimentary rocks, especially the most fine grained. A small amount of primary pyroxen remains but plagioclase appears to be completely replaced. The appearance of the zeolite zones seems to be similar to that observed in other low-temperature areas. The mesolite/scolecite zone is quite clearly defined. The laumontite zone is also quite distinct in the sediments, but in the basalts it is not sharply defined. A separate stilbite zone seems to be lacking, but stilbite is found scattered below 400 meters depth.

The geothermal area on Leirá, Borgarfjörður in western Iceland contains CO_2- rich water, which is reflected by the paucity of secondary zeolites. Laumontite is scattered below 700 m at temperatures above 120°C, and analcime is present in only a few samples below 1000 m at temperatures of 130°C and higher.

High- temperature areas.

A regular sequence in the appearance of zeolites is seldom found in the high-temperature areas. This is mainly due to the steep thermal gradient in the uppermost few hundred meters of the fields and also to inflow of cold groundwater into the upper part of the system.

Zeolites (except analcime/wairakite) occur mainly in the uppermost strata in the high-temperature areas at temperature up to 200-230°C and depths of 300-500 m. Analcime and wairakite are scattered in and below the zeolite zone up to rock temperatures as high as 300°C.

Zeolites have been observed in most of the high-temperature areas, however, they are scarce in some areas and completely lacking in one.

Figure 5, 6 Figures 5 and 6 show the mineralogical data of two drillholes in the Krafla and Nesjavellir high-temperature areas (Figure 1). A more detailed description of the Nesjavellir area has been published previously (Kristmannsdóttir and Tómasson, 1974). The investigation of the Krafla field is in progress, and only preliminary results from the first two shallow drillholes (1200 m) have been published (Kristmannsdóttir, 1975).

In the Krafla area all zeolites except analcime and wairakite are formed in the upper levels (200-300 m) at temperatures up to 230°C. Analcime and wairakite are scattered at greater depths and at temperatures up to 300°C. The magnitude and degree of alteration and the alteration zones found from the distribution of the clay minerals, prehnite, epidote, and quarts are generally compatible with the prevailing temperature conditions, at least in the uppermost 1200 m of the profile. At greater depths, fresh impermeable dikes and smaller intrusions are more dominant in the section. Minerals which are stable at much lower temperatures (smectite, mixed-layer clay minerals, chabazite, phillipsite) coexist with high-temperature minerals formed at the contracts of the intrusions (parawollastonite, andradite, hedenbergite). In some of the drillholes there is a fairly regular sequence of zeolites with depth: heulandite, mordenite, laumontite, and analcime/wairakite. Epistilbite is also found in the heulandite zone. Phillipsite occurs in the laumontite zone and also in the deeper intrusive rocks. The zeolitization found in the hydrothermally altered rocks in the Krafla area is typical of that in most other Icelandic high-temperature areas.

The Nesjavellir area is exceptional as it shows much less and a lower degree of hydrothermal alteration than other high-temperature areas with similar range of the rock temperature. In this geothermal area zeolites (other than analcime) are found at rock temperatures of 250°C and higher. The zeolites are commonly observed to 1000 m depth. Calcium silicates such as gyrolite and reyerite, are found at the same depth as the zeolites. Zeolite zoning is not well defined, but it shows a trend similar to that found in Krafla. There is strong evidence for a recent displacement of this area (Kristmannsdóttir and Tómasson, 1974) that may explain the poor fit between the amount and degree of the alteration, the present secondary mineral paragenesis, and the prevailing temperatures.

Experimental studies by Liou (1970, 1971) of Ca - zeolites show the same sequence of zeolite species to by formed by increasing temperatures as in the Icelandic geothermal areas. The equilibrium temperatures (at the same range of total pressure) for conversion from one Ca-zeolite to another are somewhat higher than those observed in the geothermal areas. Contaminants in the geothermal fluids will affect the equilibrium temperatures for formation of zeolites. In the experiments the aqueous fluid pressure is equal to total pressure, which is not neccessarily the case in the geothermal areas. Lower aqueous fluid pressure and higher contents of dissolved solids in the geothermal fluids would tend to lower the temperatures of formation of the zeolites.

Studies of zeolites (e.g. Seki, 1966, 1973, Miyashiro and Shido, 1970) are in agreement with the range of stability observed for those species in the Icelandic geothermal areas.

CONCLUSION

The distribution of zeolites in Icelandic geothermal areas is characterized by the following factors; The original rocks are basaltic lavas and hyaloclastites in all different types of geothermal areas, except those in Tertiary settings where basalt lavas are predominant. In basaltic rocks the occurrence of individual zeolites is influenced by rock composition. For example, heulandite and stilbite are mostly found in tholeiites, while analcime is virtually absent. Successive zones characterized by chabazite, mesolite/scolecite, and laumontite are found in all areas. The permeability of the rocks, the age of the geothermal area and the rock formations, and the composition of the geothermal fluid are all factors that influence the degree and amount of the alteration. The rock temperature is, however, the most important single factor governing the degree of alteration.

Figure 7 Figure 7 collects all available data about the occurence of zeolites in the Icelandic geothermal areas and relates the characteristic zeolite zones to the temperature conditions at which they are formed.

The occurrence of the zeolite species within the main zeolite zones in Icelandic geothermal areas is also shown in Figure 7. In the figure the temperature range of each zeolite zone is indicated.

Experimental data for stability and formation for some of the leading zeolites (e.g., Liou, 1970, 1971; Seki 1966, 1973) are in fairly good agreement with the range of temperatures at which zeolites formed in the Icelandic geothermal areas.

Table 1. Chemical composition of water from several Icelandic geothermal areas.

	Syðra-Laugaland near Akureyri Drillhole No. 5	Húsavík Drillhole No. 1	Leirá Drillhole No. 4	Reykjavík Drillhole G-23	Nesjavellir Drillhole No. 5	Reykjanes Drillhole No. 8
°C	89,5	94	87	100	261	270
pH/°C	9.81/20	7.4/20	8.10/20	9.60/20	7.69/261	6.27/270
SiO_2	106	80	149	130	559.6	592
Na^+	47.5	840	133.4	48	129.9	9854
K^+	1.2	18.7	16.1	1.2	24.2	1391
Ca^{++}	2.9	176	22.6	1.5	0.14	1531
Mg^{++}	0.15	10.6	1.20	0.24	0.05	1.15
CO_2(tot)	16.2	13	119.4	51	738.1	1427
SO_4^{--}	33.8	82	59.6	27	64.2	28.7
H_2S(tot)	<0.1	n.d.	0.26	n.d.	210	31.5
Cl^-	10.6	1633	135.7	19	5.8	18827
F^-	0.41	0.2	2.05	0.4	1.6	0.1

n.d. -not determined

National Energy Authority data and Arnórsson, 1974.

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FIGURE LEGENDS

Figure 1. A simplified geological map of Iceland showing the location of the high-temperature areas and the low-temperature geothermal areas mentioned in the paper.

Figure 2. A simplified geologic section, the occurrence of zeolites and other secondary minerals and the estimated rock temperature by depth in a drillhole in one of the low-temperature fields in the Reykjavík area.

Figure 3. A geologic section, occurrence of secondary minerals and estimated rock temperature in a drillhole near Þorlákshöfn.

Figure 4. A geologic section, occurrence of secondary minerals and estimated rock temperature in a drillhole in a low-temperature area near Akureyri.

Figure 5. A geologic section, occurrence of secondary minerals and estimated rock temperature in a drillhole in the Krafla high-temperature area.

Figure 6. A geologic section, occurrence of secondary minerals and estimated rock temperature in a drillhole in the high-temperature area at Nesjavellir.

Figure 7. Zeolite zones found in the Icelandic geothermal areas. The distribution of individual zeolite species within the zones is indicated. Also shown is the approximate temperature at the zone borders.

Fig. 1

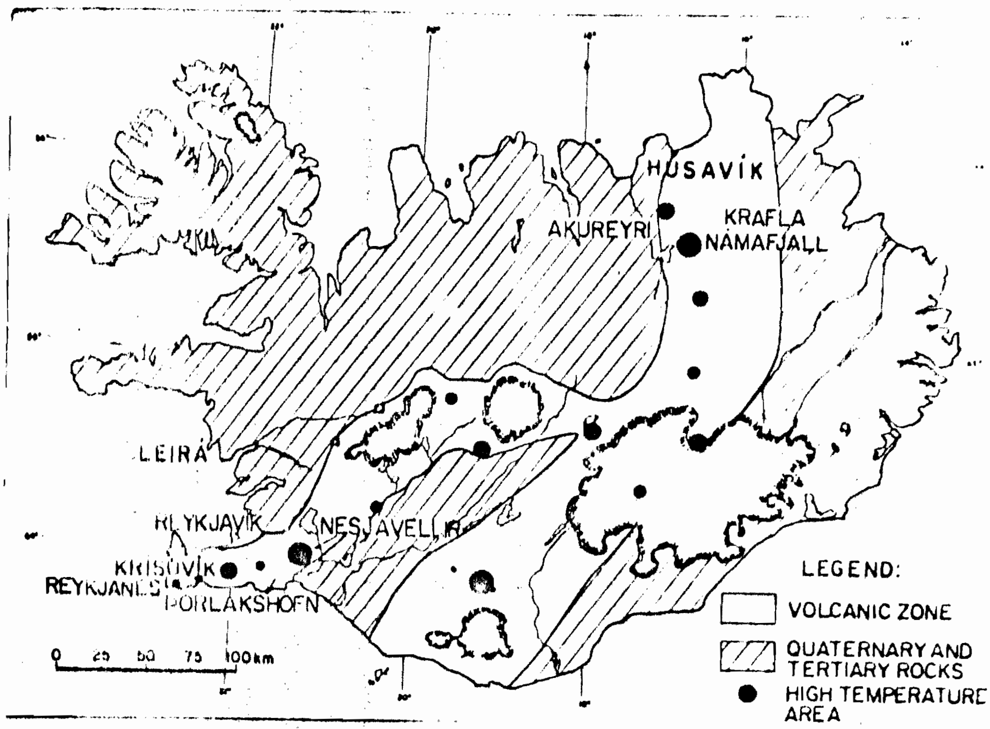

Fig. 2

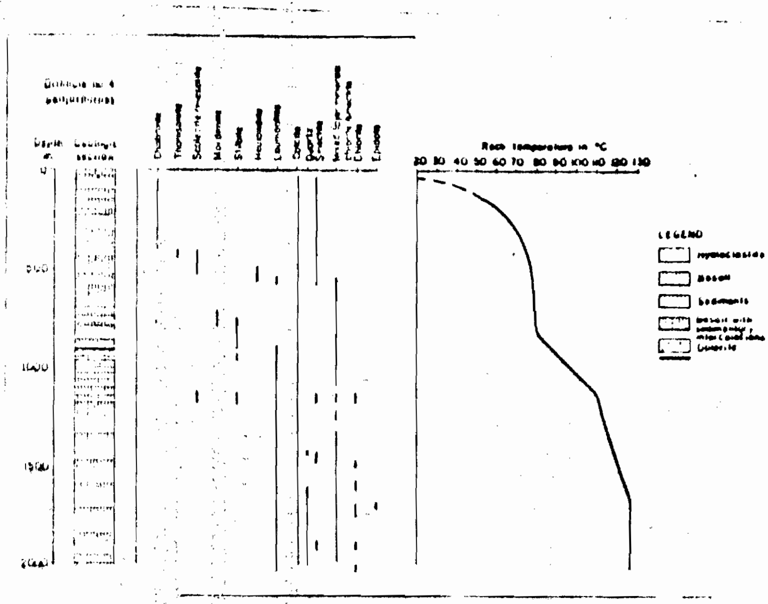

Fig. 3

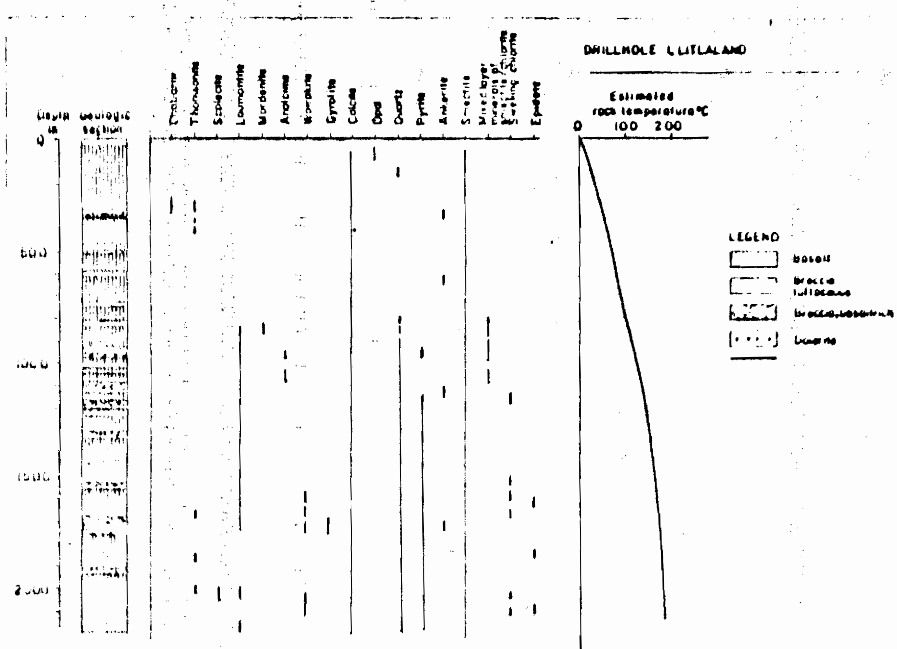

Fig. 6

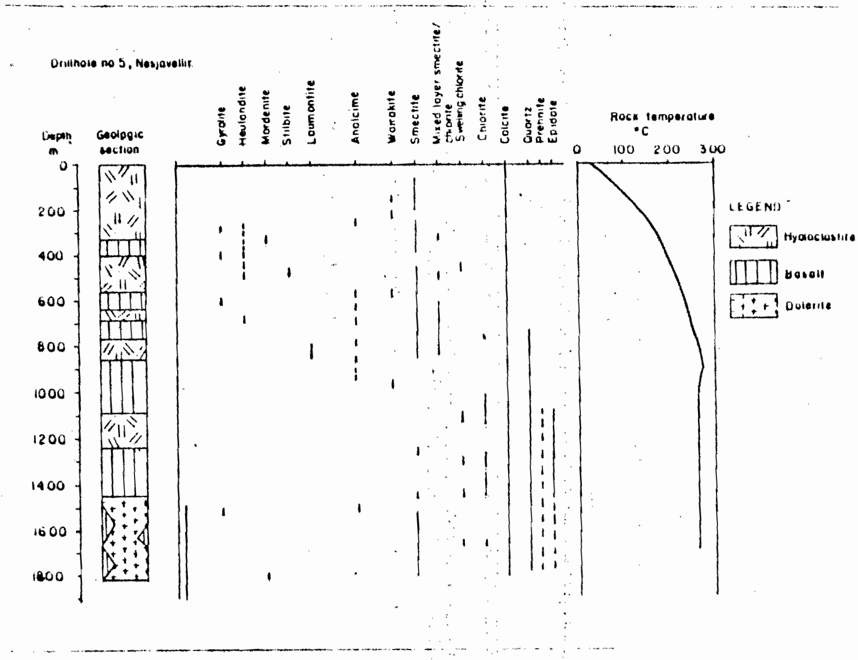

Fig. 4

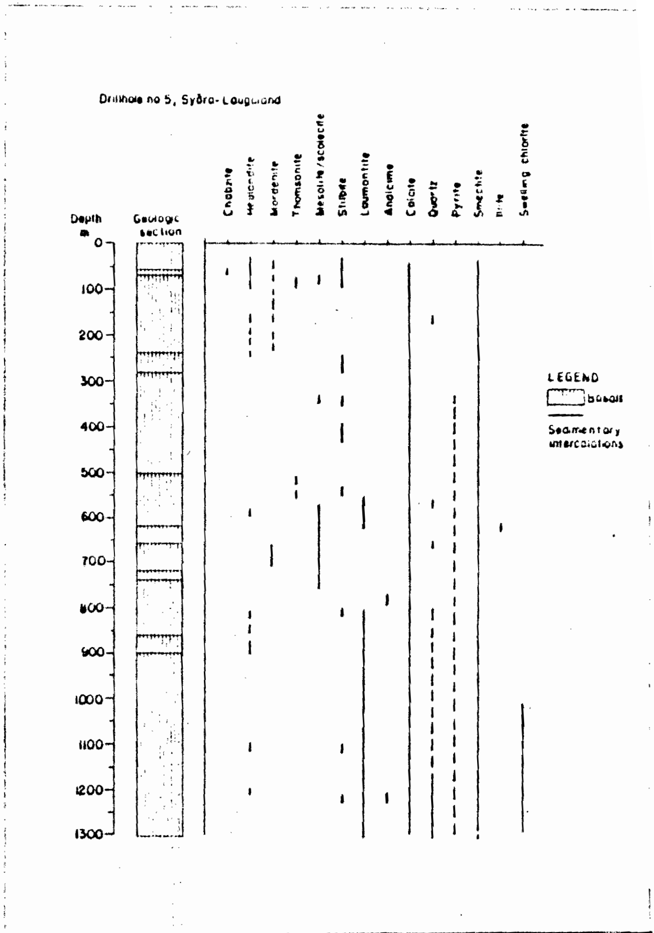

Fig. 5

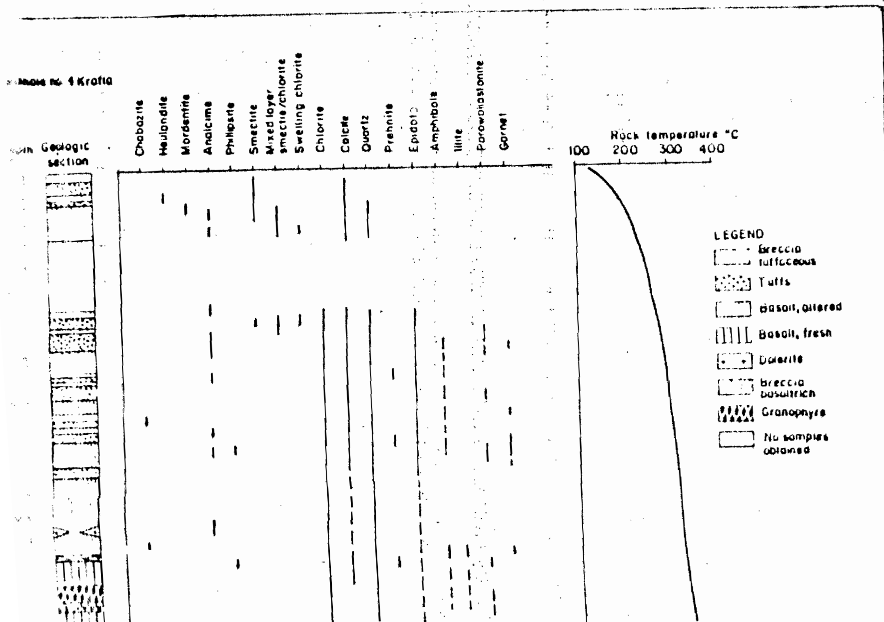

Fig. 7