On the Consolidation and Palagonitization of the Tephra of the Surtsey Volcanic Island, Iceland

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I. INTRODUCTION

About one third of the exposed part of Surtsey is made up of tephra, pyroclastics of alkali olivine-basaltic composition, formed in the phreatic eruptions in Surtsey during Nov. 14, 1963 – April 4, 1964. Since the formation of the tephra, samples have been taken in various localities every year (except 1965 and 1968) in order to find out when and how the expected process of consolidation and palagonitization of the tephra would start.

A thorough study of the petrology of the tephra-formation in Surtsey might give important answers to some of the problems of the chaotic subglacial "palagonite formation" of Iceland and to the question of formation of palagonite from basaltic glass in general.

Fig. 1. View of the north coast of Surtsey, looking to SE; August 5, 1970. In the foreground layered tephra with discordance in the layers in the middle of the sequence. To the left, finely bedded redeposit tephra. In the background, mud flows are conspicuous in the northern wall of the Surtur II crater. The field station can be seen at the left edge of the picture.

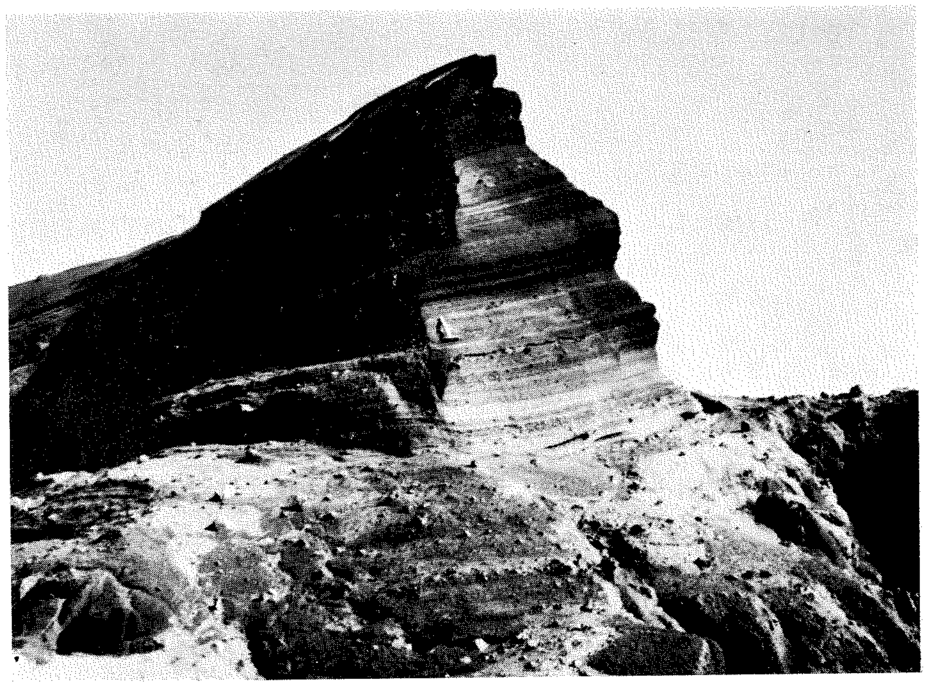

Fig. 2. Wind-eroded profile in the tephra, showing the characteristic layering. Top of eastern crater, August 5, 1970.

The first signs of consolidation in the tephra were seen in 1966, and in 1969 a marked consolidation process had begun, clearly connected to local heating of the tephra. It seems possible to define under what conditions these processes work.

II. GENERAL PROPERTIES OF THE TEPHRA

The tephra formed when the approx. 1150°—1160°C or hotter magma (Sigurgeirsson 1966) was quenched on contact with the seawater. The tephra felt still hot when it fell in the immediate surroundings of the crater, but it was only a matter of a relatively short time, possible only a few hours, before it had cooled down to air temperature. The quenching resulted in phreatic explosions and horseshoe-craters with a diameter of about 400 m and an height of 150—170 m above sealevel were formed. The tephra was deposited in finely-bedded layers (Fig. 1 and 2), each layer representing one shower. The crater and the tephra of the first phreatic phase (Nov. 14, 1963 — April 4, 1964) is for convenience called Surtur I *(S I)* and that of the second phreatic phase (Febr. 1 — April 4, 1964) Surtur II *(S II)*. For further details of the eruption history the reader is referred to the detailed descriptions of Thórarinsson et al. (1964) and Thórarinsson (1965, 1968).

Microscopic investigations on the tephra shortly after deposition (summer 1964) showed that 82—88% vol. was made up of unaltered and unpalagonitized basaltic glass (sideromelane), the rest being fragments of autogenic hyalobasalt and phenocrysts of olivine, plagioclase and Cr-spinel. The sideromelane is light-brown with a refractive index of $n = 1.605 \pm 0.002$. Dispersed in the tephra are grains of opaque glass (tachylyte); in contrast to the sideromelane, the tachylyte is magnetic. It is difficult to measure the density of the glass because of the great number of vesicles, but values around 2.70 g/cm^3 were repeatedly obtained. The tachylyte grains have similar density.

The grain size in five analysed samples varies, with more than 90% between 0.05—5 mm. The grain size curves have in most cases three maxima and are quite distinct from the curves of samples of tephra deposited in the seawater e.g. just north of Surtsey, which are rather wellsorted and have only one maximum. The content of olivine-phenocrysts varies greatly because of eolian differentiation. In the case of Jólnir (an island formed in 1966, which broke down the same year) the olivine content was found to decrease by 50% between two sites in contemporaneously formed tephra-layers at distances of 350 m and 1100 m from the crater.

III. CONSOLIDATION OF THE TEPHRA

The first signs of consolidation were seen in August 1966 in a few places, f.ex. at the top of the eastern mound. It was then possible to take a coherent sample, but it disintegrated when transported. Only the outermost 10—15 cm of the exposed tephra layers were consolidated. No

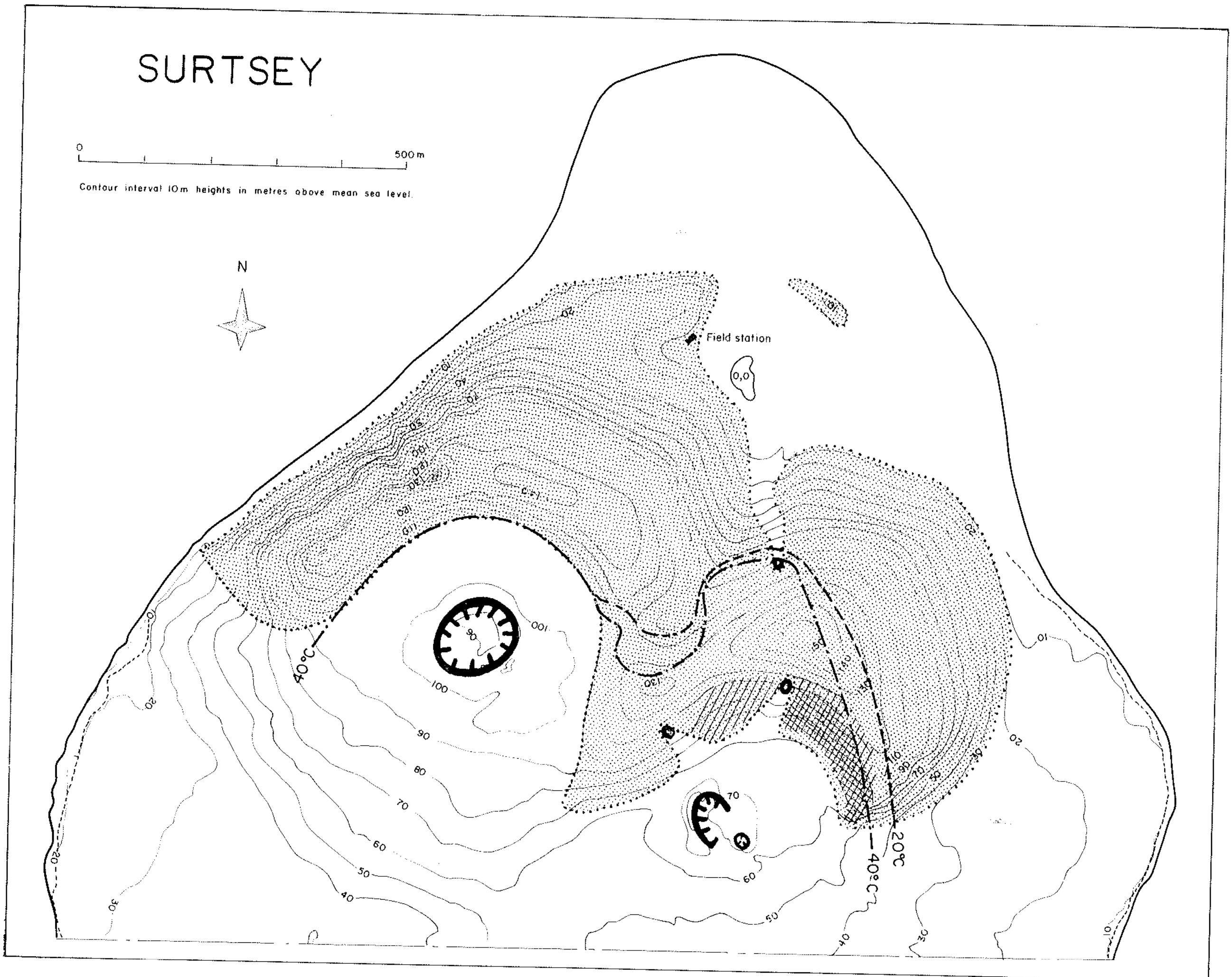

Fig. 3. Map of northern part of Surtsey (after air photographs of 6 July 1968,, Norrman 1970). The area of primary tephra is shaded, lava covers the whole southern part, but the costal plain to the north is mainly made up of sand and gravel. The extent of the thermal field within the tephra area as it was in August 1970 is indicated by the 20°C and 40°C isotherms (measured at the depth of 20 cm). The hatching shows the area of consolidated tephra, close hatching indicates hard tuff.

abnormal heat was observed in the layers. The exposures face SE, which is the main direction for precipitation and since this is also the sunny side, it is possible that the consolidation depends on the frequent oscillations in temperature and moisture on the surface. Microscopic examination of samples from one of the localities did not reveal any palagonitization and it was not possible to see (at 1000x) any cementing substance in the sample. These localities are since 1968 part of the thermal field which will be described below.

In Sept. 1969 a considerable area in the walls of the S I – tephra crater was already consolidated, probably as a result of the heating up of the tephra. In April 1968 Prof. Sigurdur Thórarinsson had discovered that a part of the older tephra crater (S I) was warm. In Sept. 1969 the present author visited the island and the thermal field was surveyed; temperatures between 48°–84°C

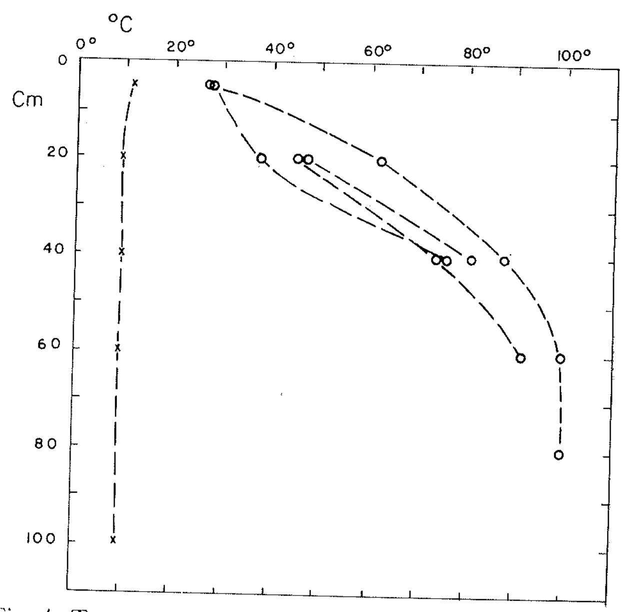

Fig. 4. Temperatures in five 40–100 cm deep holes in the Surtsey tephra (August 1970). Four of the holes are from the thermal field (circles) and one outside the field, at the field station (crosses).

were measured at approximately 5 cm depth in the hottest areas. The tephra in the thermal field was usually slightly wet and in some places steam escaped through the surface. In August 1970 the thermal field was mapped in detail, see Fig. 3, and it now seemed slightly larger than in 1967. At 20 cm depth the temperature was usually between 40°—60°C within the thermal field, but 10°C or lower outside the field. It was attempted to measure the temperature gradient by hammering an iron bar down (Fig. 4). Usually it was not possible to get farther down than about 40—60 cm within the thermal field as the tephra gradually became harder. As is evident from Fig. 4, the temperature gradient is very steep in the uppermost 40 cm of tephra, but as the temperature reaches 100°C the curve seems to flatten out. This could mean that 100°C is maximum temperature, at least near the surface. A small area in the northern part of the field was kept under observation for a few weeks in Aug.—Sept. 1970. At 20 cm depth the temperature was found to vary as much as 35°C at the same locality when measurements were repeated within a few days. Temperatures above 100°C were never obtained. From the above it could be suggested that the tephra is heated up by vapour at 100°C. It is very important to get this clear in order to ascertain at what temperatures the consolidation and palagonitization takes place at depth.

As is evident from Fig. 3 the thermal field surrounds the lave craters and it is therefore probable that the heating up is connected with heat flow through the feeder dykes of the lava craters. The lava crater S II (the westernmost one) was last in action in May 1965, whereas the craters S I ceased lava-effusion in June 1967. Heat flow through the craters continued however, in July 1968 temperatures around 500°C were measured in discharged gases in the S II lava crater, and as late as in Aug. 1970 temperatures as high as 400—500°C were obtained (Ae. Jóhannesson, pers. inf.). The temperatures of gases from the S I craters were somewhat lower.

As mentioned above it seems clear that the tephra, at least near the surface, is heated up by steam at 100°C. This steam can either be vapourized meteoric water which after precipitation seeps down to the 100°C level and then is vapourized, or it can be vapourized seawater which probably is present in the porous underground of Surtsey. In the small area which was kept under observation during Aug.—Sept. 1970 the temperature varied considerably, even from one day to the next. The volume of steam which escaped in this area seemed to increase with increasing temperature. It was not possible to see any connection between the precipitation as measured in this time interval at the weather station near the hut and the variations in the emanation of steam from the area. It could therefore be suggested that the steam is mainly seawater which becomes vapourized at sea level and then emanates through the tephra to become mixed with meteoric water near surface. This would mean that the palagonitization and the consolidation proceeds at 100°C below about ½ m depth with a more or less constant flow of water vapour at this temperature, and probably near atmospheric pressure. This could be ascertained with a shallow, say 50—100 m, borehole.

In Fig. 3 is shown the extent of the consolidated area on the surface in August 1970. A considerable area is semi-consolidated and here it is possible to take good coherent samples with a hammer, and about 7000 m^2 are made up of quite hard rock where a good hammer is needed when samples are taken. Elsewhere within the thermal field the tephra seemed hard and consolidated at 40—80 cm depht.

IV. PALAGONITIZATION

Within the consolidated area which was observed in Sept. 1969 a few small rust-brown patches were found in the tephra, especially where the vapour emanation was strong. The glass grains were distinctly coloured, but usually only on the under side of the grains which turned towards the vapour stream. Under the microscope the outermost 0.05—0.10 mm of the sideromelane grains were found to be altered to red-brown "gelpalagonite" (Peacock 1926, Noe-Nygaard 1940), i.e. isotropous and apparently homogenous palagonite. In many cases the palagonite is concentrically banded, possibly due to fluctuations in temperature and amount of steam. The refractive index is $n = 1.665 \pm 0.002$, i.e. considerably higher than before alteration, in contrast to the palagonite in the tuffs of the older Westman Islands, whose refractive index is lower, usually about 1.56—1.58. Samples from the same area taken in Nov. 1969 and in Aug. 1970 showed a similar degree of alteration (Fig. 5). In these red-brown patches in the tephra, approx. 1—3% vol. of the rock was palagonized. It does not appear that the palagonite is the actual cementing substance. It was possible to take consolidated samples before any palagonitization was visible in the micro-

Fig. 5. The incipient palagonitization of a sideromelane grain in tuff taken in Nov. 1969, about 0.7 mm of the grain is seen. In the glass are a few microlites of plagioclase and olivine.

scope. The cementing substance, if any, can possibly be identified by electron mircoscopy.

The sideromelane and its first alteration product, the red-brown gelpalagonite were analysed in one grain from the sample taken in Sept. 1969 (TABLE 1, I and II), each analysis is the average

TABLE 1

wt %	I	II	III	IV	V	VI
SiO_2	: 46.5	23.6	36.6	146.6	110.0	75.0
TiO_2	: 2.5	4.2	6.5	7.9	1.4	17.7
Al_2O_3	: 16.0	5.2	8.1	50.4	42,3	83.9
*Fe_2O_3	: 12.4	25.2	39.1	39.1	0	0
MgO	: 4.8	3.9	6.0	15.1	9.1	60.3
CaO	: 10.8	2.3	3.6	34.1	30.5	89.4
Na_2O	: 3.3	0.05	0.08	10.4	10.32	99.2
K_2O	: 0.6	0.02	0.03	1.9	1.87	98.4
SUM:	96.9	64.5	100.0	305.5	205.5	

* Total Fe as Fe_2O_3.
I: Electron — microprobe analysis of sideromelane in the grain shown in Fig. 6. II: Do — of palagonite rim. III: Palagonite analysis calculated waterfree. IV: Sideromelane values multiplied with 3.153. V: Difference between IV and III, loss of leached components. VI: Loss in % of original amount.

of 3—4 single counts. The analyses were made on the ARL electron microprobe, using as standard a basaltic glass from Hawaii, kindly provided by R. L. Hay. The palagonite analysis was difficult to make and should only be considered as semi-quantitative. The sum of the analysis is only 64.5% which is suspiciously low, it is, however, not impossible that water amounts to 35%. The sideromelane, which represents the average composition of the magma minus phenocrysts, proved to be very homogenous, whereas the palagonite rim was rather heterogenous. The process of palagonitization appears to be isovolumetric.

As seen from these preliminary analyses all components are depleted in terms of weight per cent, except Fe and Ti and water. Fig. 6 shows how e.g. Ca and Na are lost with palagonitization in a single sideromelane grain. Microlites are unaffected. It would here be interesting to calculate the change in concentration per volume, but as the specific gravity of the palagonite is not yet known this is not possible.

Approximate values of the relative amounts of leached components can, however, be obtained by assuming that the amount of total iron is constant during palagonitization, following the procedure of Hoppe (1940, p. 487). Probably all the iron in the palagonite is found as Fe^{3+} which is rather insoluble, cf. the experiments of Hoppe (op. cit.). On this assumption the values of the sideromelane analysis in Table 1 were multiplied with 3.153 as the iron content of the palagonite is higher by that factor. From the values obtained in this way (IV) are then subtracted the values of the waterfree palagonite analysis (III) and the difference gives the relative amount of each component that has been leached out.

It then appears (Table 1, VI) that the following components are lost in order of relative amounts: Na_2O, K_2O, CaO, Al_2O_3, SiO_2, MgO and TiO_2. Instead, water enters the palagonite, and as mentioned before, probably all the iron becomes oxidized to give the palagonite a rust-brown colour. The above mentioned elements are the same as Hoppe (op. cit.) found by experiments to be leached out of sideromelane in varying amounts at various pH conditions. pH has yet to be measured in the condensate of the steam which flows through the tephra in Surtsey. Microprobe analyses by Hay & Iijima (1968) of sideromelane and palagonite from Hawaii showed that three quarters or more of the K_2O, Na_2O and CaO, half of the Al_2O_3 and about one third of the SiO_2 were lost in the process of palagonitization.

In palagonite tuffs of the older Westman Islands, e.g. in Sæfjall, Ellidaey and Bjarnarey which are 5000—6000 years old (Jakobsson 1968), zeolites and calcite have been precipitated as the result of palagonitization. Of the zeolites, analcime, phillipsite, chabazite and natrolite have been identified. In Surtsey opal along with traces of thenardite (?) was discovered on the surface already in Nov. 1969 in areas with strong emanation of steam. The last-named mineral is possibly formed because of a high content of precipitated seasalts in the tephra. Sigvaldason (1965) has reported encrustations of halite and aphthitalite on lava and tephra in Surtsey. In Aug. 1970 opal was clearly much more abundant. At the time of writing (May 1974) the first zeolite has just been discovered in a sample taken in Surtsey on 28th April 1971; the zeolite is probably chabazite. Both the opal and the zeolite is believed to be the product of palagonitization as these secondary minerals have only been found where palagonitization has occurred and are made up of the principal components leached out of the sideromelane.

Outside the thermal field no consolidation or palagonitization has yet been discovered. This of course does not mean that it is ruled out that these processes can proceed under these circumstances, only that they are slowed down because of lower (atmospheric) temperatures and less moisture.

The ions which are found in solution on the surface of the glass grains as a result of palagonitization will be available to organisms which eventually colonize on the surface of the tephra. In this connection it is of interest to consider that the rock constituents of Icelandic soil are in most parts of the country by 80—95% made

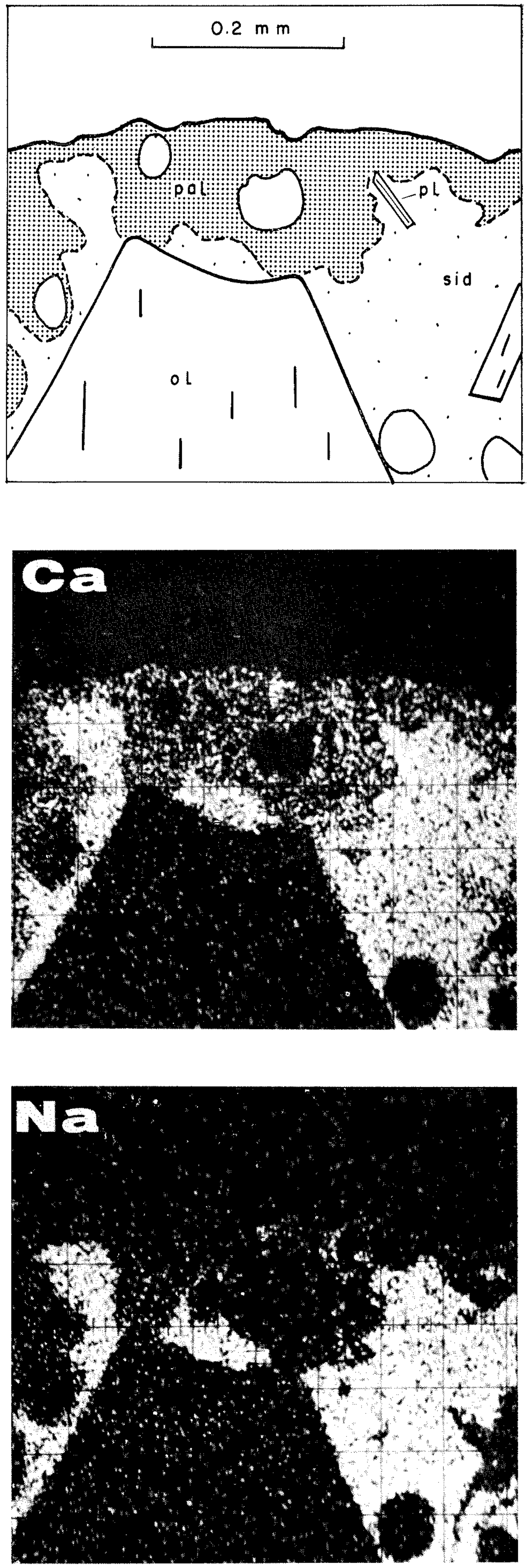

Fig. 6. Electron beam scanning images showing distribution of Ca and Na in a sideromelane grain and its palagonite rim (sample taken in Sept. 1969). For reference see the drawing of the grain at top; sid=sideromelane, pal=palagonite, ol=olivine and pl=plagioclase.

up of volcanic glass, mainly of basaltic composition (Jóhannesson 1960, Sigbjarnarson 1969), the main part of the remainder being crystalized fragments. Provisional analyses of Icelandic soil indicate that the rock constitutents (i.e. the glass) easily undergo chemical weathering (Jóhannesson 1960, p. 10). It seems probable that palagonitization of basaltic glass is an important chemical process leading to the formation of soil in Iceland. If so, the process works at temperatures as low as approx. 0–15°C which are common mean monthly temperatures near the surface in Icelandic soil (Helgason 1961). Average temperatures in tephra at 5 cm depht on the northern coast of Surtsey during April–Augst 1968 varied between 5–17°C (Sigtryggsson 1970).

DISCUSSION

In the case of Surtsey it is possible to follow closely the processes of consolidation and palagonitization of basaltic tephra and describe how they take place under the local physical conditions. So far the story reads as follows:

Nov. 14, 1963 – April 4, 1964: The tephra forms in phreatic eruptions and is composed of fresh basaltic glass (sideromelane) with dispersed fragments of hyalobasalt.

August 1966: Consolidation has started in surface layers in a few places but proceeds slowly.

April 1968: Heating of tephra with emanations of steam discovered in the eastern mound close to the newest lava craters.

Sept. 1969: A part of the tephra is found to be consolidtaed to tuff within the thermal field at surface temperatures of approx. 60°–100°C. Palagonitization has commenced in a few places. Dispersed opal precipitations.

August 1970: The area of consolidated tephra is now about 12.000m², whereas the extension of the thermal field is similar as in 1969. Precipitations of opal common.

April 1971: Consolidation proceeds to give a more dense rock; the first zeolite (chabazite) is discovered in the tuff.

As mentioned above the author did not have the opportunity to visit Surtsey in 1968 but it is probable that consolidation and possibly palagonitization had already started by that time, i.e. only one half to one year after heating up of the tephra.

From the above it then follows that the product of submarine, basaltic, phreatic eruptions near sea-level is finegrained tephra made up of sideromelane glass. This glass is subject to palaganitization, which is a post-eruptional process taking place at relatively low temperatures, cf. Noe-Nygaard (1940), Jónsson (1961) and Hay & Iijima (1968). It is provisionally suggested that palagonitization in the tephra-pile above sea-level in Surtsey proceeds at 100°C in the presence of abundant water, and that the temperature falls gradually in the uppermost ½–1 m of the layers. The surface palagonitization described in this report has proceeded at approx. 6°–100°C and 1 atm. pressure. At these conditions it is only a matter of 3–4 years before dense palagonite tuff (Icel. móberg) is formed with precipitations of opal and chabazite.

Some workers (e.g. Bonatti 1965) have suggested that palagonite is formed at the time of eruption as the result of reaction between the hot melt and water. Both in the case of the Surtsey eruption and the subglacial 1934 Grímsvötn eruption (Noe-Nygaard 1951) it is established that the glass content of the erupted tephra was sideromelane with no traces of palagonite.

The mechanism of the heat transfer of the thermal field has not been established. As mentioned before, the heating is obviosuly connected to the lava craters. It is possible that cooling feeder dykes and small intrusions at high level are the main sources of the heat. Sigvaldason (1968) has suggested that pillow lavas buried beneath the tephra pile serve as the main heat source for the process of palagonitization of pyroclastic material in subaquatic volcanoes of specific structure. In the case of Surtsey the presence of pillow lavas has not been proved. If pillow lava is found at the base of Surtsey it will have been formed in the first days of eruption, i.e. in Nov. 1963. The thermal field was, however, not discovered before 1968 and seems to be closely related to the 1967 lava-craters, it is therefore not probable that the hypothetical pillow lava is the heat source.

Research on the formation of palagonite rocks in Surtsey will be continued during the next several years. All investigations have so far been limited to the surface of the tephra formation. The value of this research could be greatly enlarged by drilling a hole into the tephra in order to find out how palagonite is formed at depth both above and below sea-level.

ACKNOWLEDGEMENTS

This research has been financially supported by the Icelandic Science Fund and the Surtsey Research Society. Prof. A. Noe-Nygaard is thanked for encouragement and for providing laboratory facilities at the Mineralogical Museum, Copenhagen. Dr. G. E. Sigvaldason critically revised the manuscript.

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