GEOLOGY

The Sedimentary Xenoliths from Surtsey: Marine Sediments Lithified on the Sea-Floor

A Preliminary Report

By

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INTRODUCTION

Among the xenoliths in the Surtsey ejacamenta there are numerous sedimentary rocks. These rocks occur most abundantly in the tephra cone of Surtur II; due to erosion of the tephra they gradually become exposed and eventually fall out and roll down the slopes. Numerous blocks, the biggest with a diameter of approximately 1 m, are found N of the lava pool in the Surtur II crater (Plate I A) and most of the present material was collected there in June 1968.

The material was obviously lithified prior to the Surtsey eruption (November 14, 1963) and must derive from sedimentary rocks in the sea-floor where Surtsey now stands. Before the eruption the water depth was about 130 m and the existence of lithified sediments in that position deserves some attention. The locality is situated in the extension of the Central Graben of Iceland, a structure which probably is less than 600,000 years old (RUTTEN & WENSINK 1960) and characterized by glacial and postglacial volcanism. The zone is part of the Mid-Atlantic Rift System, and according to the concept of spreading of the ocean floors, any sediments present should be very young. The main part of the Vestmannaeyjar archipelago is only 5,000—6,000 years old (JAKOBSSON 1968).

The geologic setting implies that the xenolithic material was lithified in the marine environment. Processes of that kind are usually attributed to compaction due to overburden, but according to the properties of the sediments no compaction occurred in this case. Recent observations support the opinion that submarine lithification does take place at or near the water/sediment interface both in carbonate sediments (FISCHER & GARRISON 1967) and in pyroclastic sediments (MORGENSTEIN 1967) but the processes are still much disputed.

SEDIMENT CLASSIFICATION AND DATING

All sediments consist of volcanic material dominated by sideromelane glass, but with regard to depositional conditions they belong to two different groups, one which indicates high-energy transport and another which indicates low-energy transport.

The high-energy type is bedded and laminated, often with convolute or otherwise disturbed lamination and with repeated graded bedding (Plate I A-B). The grain size ranges from silt to pebble, and the material is generally of high sphericity, rounded to sub-angular and close-packed. The grading occurs both within 5—10 cm thick beds and within thin laminae, some mm in thickness. Shell fragments, more or less rounded and often with polished surfaces, are common but no complete shells are found. All characteristics indicate high-energy transport and the mechanism was certainly a turbidity current flow, sometimes with transitions to mudflow.

The low-energy type is a massive sediment in which no bedding has been observed. The grain component is a well-sorted medium to fine sand, and the material is loose-packed and of medium or high sphericity and roundness. Fossils are frequent and range from foraminifers to molluscs, all unworn and well preserved (Plate I C-D). The shells are not in growth position but have been gently treated by the forces of transport and deposition; undamaged foraminiferal tests or thin mollusc shells such as the *Dentalium* in Plate I C occur even without any internal

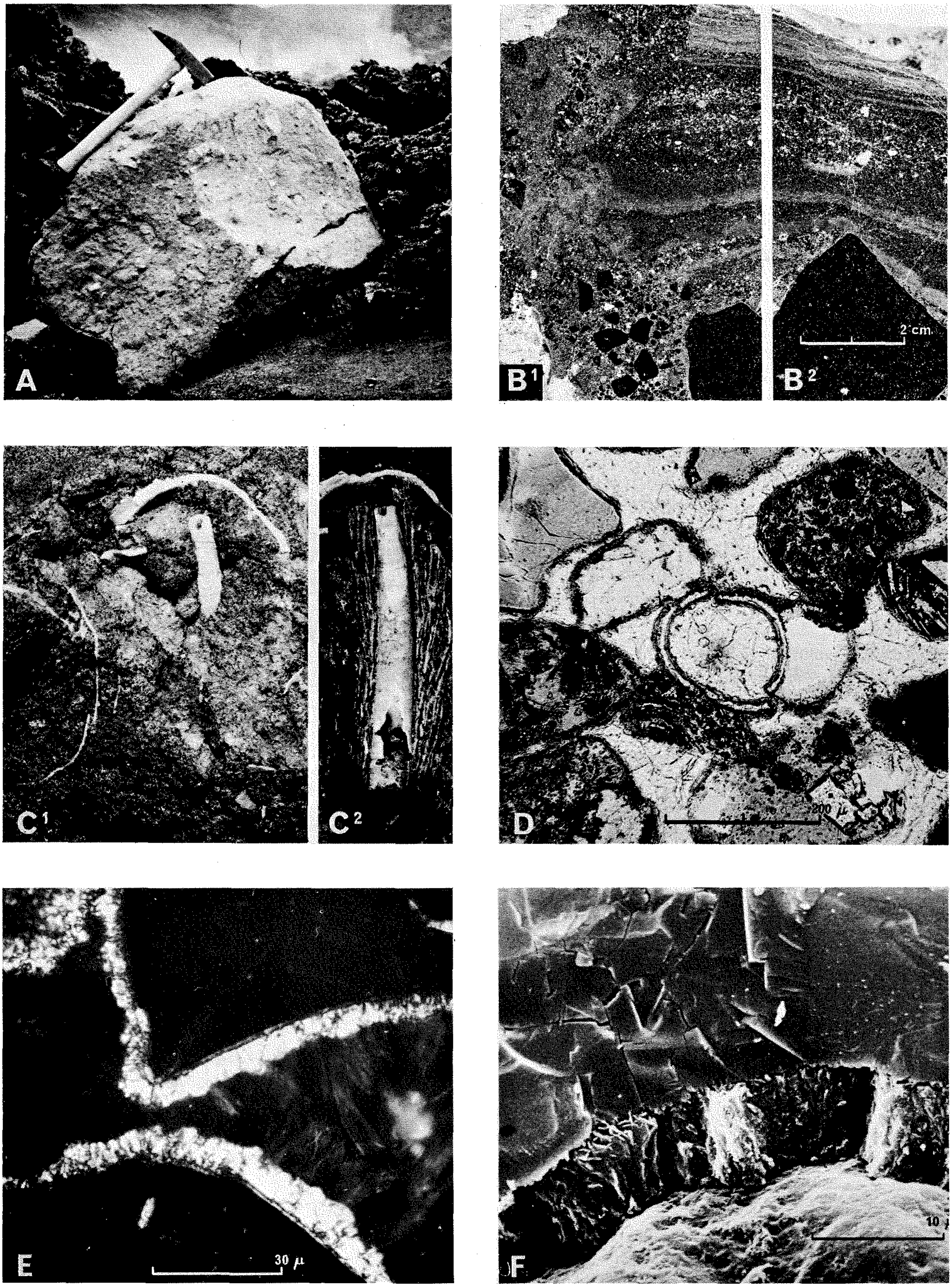

Plate I. A. Sedimentary xenolith with shell fragments and graded bedding near the rim of the lava pool in Surtur II. Hammer handle 35 cm. June 1968. B. Polished surfaces of turbidite with repeated graded bedding and disturbed lamination. B^2 is the surface perpendicular to B^1. C. Massive sediment with thin, undamaged shells. C^2 is the *Dentalium* shell after preparation. There is no sediment in the interior of the shell, the inside is lined with radiating phillipsite aggregates (not visible in picture). Length of shell 28 mm. D. Massive sediment with foraminifer. Cementing isotropic substance fills most of the pore volume except unbroken right chamber of foraminifer. Thin section, plane polarized light. E. Massive sediment with highly birefringent crystalline coating on grains and weakly birefringent pore filling. Thin section, crossed nicols. F. Electron stereoscan micrograph of massive sediment. In lower part of the picture a rounded sediment grain with radiating crystalline coating. No indications of crystals in the siliceous substance which fills pore volume. Freshly broken surface.

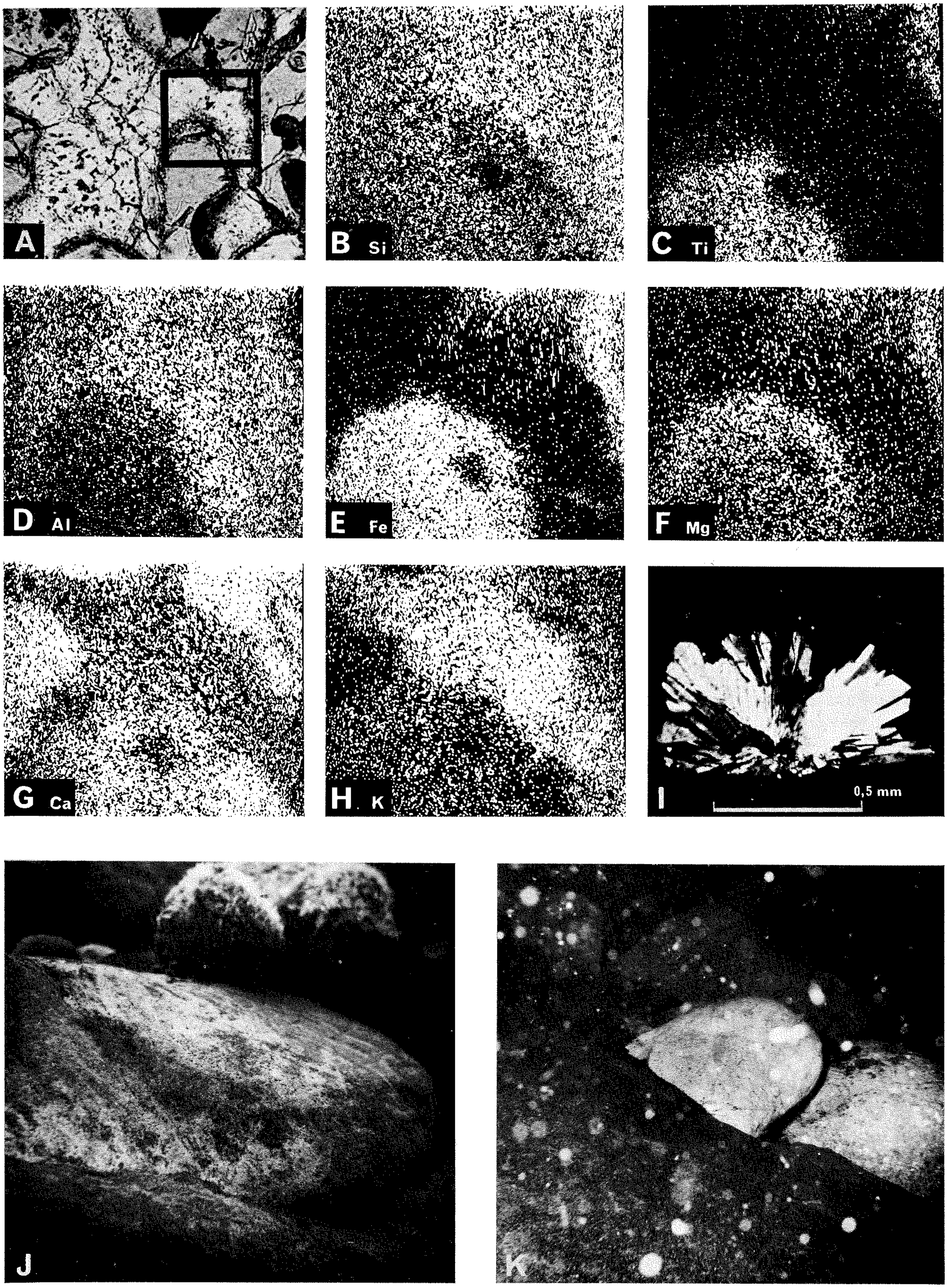

Plate II. A. Massive sediment with isotropic cement. Square in right center scanned for distribution of elements. Side of square 100 microns. Thin section, plane polarized light. B—H. Electron beam scanning images showing distribution of respectively Si, Ti, Al, Fe, Mg, Ca and K. I. Aggregate of Ba-phillipsite crystals from inside of *Dentalium* shell. Thin section, crossed nicols. J. Crest of submarine slope near N end of Surtsey. Transport of material from right to left in picture. Block in center approximately 1.5 m. Depth 12 m, June 1958. K. Further down the same submarine slope as in J. A slow gravity-induced creep goes on in the sand-sized material. Visible part of block in center 0.7 m. Depth 25 m, June 1968.

filling of sediment so it is obvious that no appreciable compaction affected the sediment between deposition and lithification. Evidently lithification was caused by processes not connected with compaction due to overburden.

The high degree of sorting in the massive sediments does not include the fossils of which some are foraminifers of approximately the same size as the sediment grains but with lower settling velocity and some are large mollusc shells which nevertheless are out of growth position and certainly transported. Regarded as sediment particles the fossils do not belong to the hydrodynamic régime adequate for sorting and transport of the grain component proper. A two-stage origin is therefore proposed with a primary sorting of the grains by hydrodynamic forces in a shore environment, and a secondary gravity transport down a submarine slope where a benthic shelly fauna became included and where at depth, deposition of foraminifers became possible.

Of the faunal content it was possible to identify *Cyprina islandica* (L), *Aporrhais pes pelecani* (L), *Pomatoceros* sp. and *Dentalium* sp. The organisms are marine and common in the sea around Iceland today. The calcareous parts still retain their original mineralogy; the *Cyprina* shells are pure aragonite and the tubes of the serpulid worm *Pomatoceros* consist of high-Mg calcite of the composition $(Mg_{.12}Ca_{.88})CO_3$. Both mineral polymorphs are metastable phases which change rapidly during diagenesis to the stable phase low-Mg calcite; the absence of such changes is noteworthy.

A radiocarbon dating of shell material from specimens of *Cyprina* has given an age of 6,000–7,000 years BP (preliminary value).

LITHOLOGY AND CEMENTATION

The clastic material corresponds to the tuffs and hyaloclastics in the Vestmannaeyjar area as described by JAKOBSSON (1968). The main component is palagonitized brown sideromelane glass and opaque tachylitic glass but phenocrysts of olivine and plagioclase are common.

The sediment particles, regardless of their mineralogy and composition, are surrounded by a fringe of highly birefringent crystals, 8–10 microns in size and perpendicular to the grain surface (Plate I E-F). The fringe is missing at the grain contacts and is thus post-depositional, and the fringe/grain boundary is a distinct and smooth surface and not a vague or botryoidal transition zone. The thickness of the fringe is essentially equal on all grains and not related to their mineralogy or composition as a reaction rim or diagenetic recrystallization. It is here interpreted as a crystalline coating of one or more authigenic low-temperature minerals, precipitated from pore solutions and probably belonging to the zeolite group.

The main cementing component is a transparent isotropic substance, sometimes with a very weak birefringence, which fills most of the pore

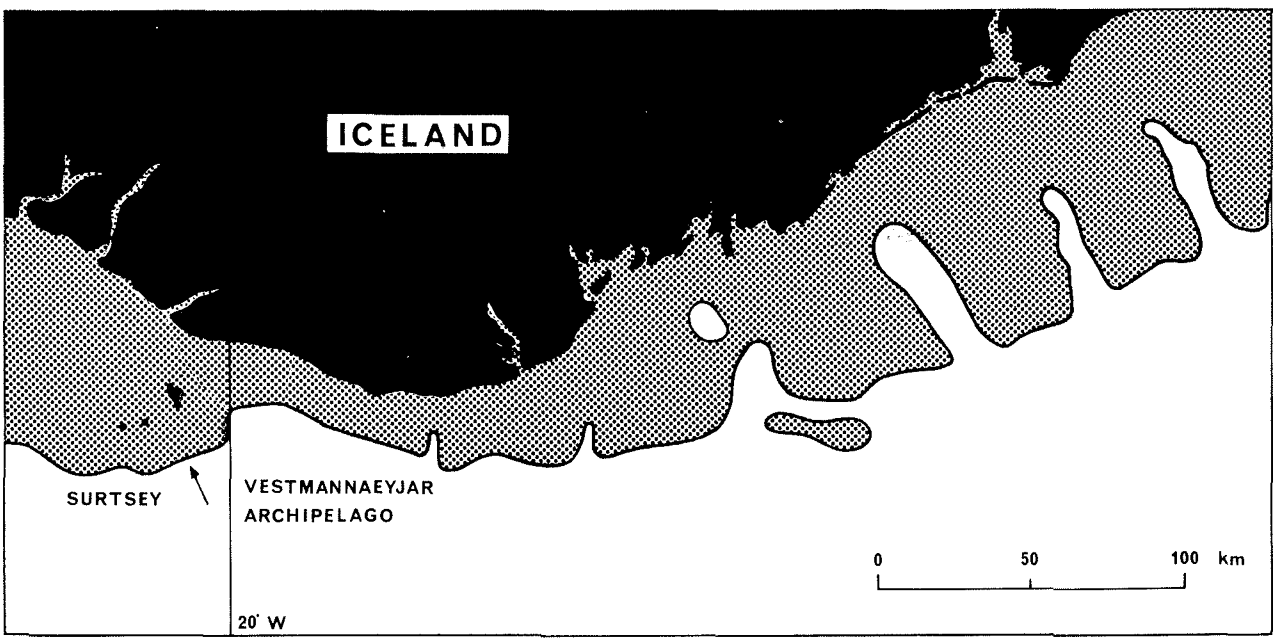

Fig. 1. Morphology of the southern part of the Icelandic insular shelf. The narrowing glacier-sculptured shelf (stippled) broadens abruptly at the Vestmannaeyjar archipelago where postglacial production of pyroclastic material has been considerable. Any previous pattern of transverse sea-valleys in this area is masked by the postglacial sediment sheet. Outer shelf boundary = 100 fathoms = 185 m. From British Admiralty Charts No. 12, 246, 2733 and 2968.

space (Plate I D-F). It is not chemically uniform but has an approximate average composition of 55—60 % SiO_2, 25—30 % Al_2O_3 and 10 % CaO-K_2O with distinct substitution Ca:K. Compared to the sideromelane glass the substance has a higher content of Si, Al and Ca:K while Ti, Fe and Mg are missing (Plate II A-H). It gelatinizes with HCl. The preliminary chemical data suggest wairakite but whether the cement is an ordered mineral or a siliceous gel is still uncertain. No analcite can be identified in X-ray powder diffractograms of the total sediment.

Although it fills the main part of the pore space, including the interior of most foraminiferal tests and other small fossils, the isotropic substance does not occur in larger voids such as the sediment-free interior of a *Dentalium* shell (Plate I C). The inside of this and other empty mollusc shells is instead lined with transparent phillipsite crystals in radiating aggregates, approximately 1 mm across (Plate II I). The phillipsite was identified with X-ray powder diffractometry and the elemental composition determined with electron microprobe analysis (Table 1). The Ba percentage 1.1 % in the phillipsite is very high compared to the Ba content of only 30—100 ppm in the lava and tuff material (JAKOBSSON 1968).

No features indicate *in situ* solution of pyroclastic material and the cementing components must be derived from a source outside the lithified sediments. They probably appeared in the order crystalline coating — isotropic substance — phillipsite.

Table 1

Phillipsite, wt. % (on water-free basis, 1 decimal figure)

SiO_2	58.0
TiO_2	0.1
Al_2O_3	29.6
FeO	tr.
MgO	—
CaO	4.2
SrO	—
BaO	1.1
K_2O	5.8
Na_2O	1.1
	99.9

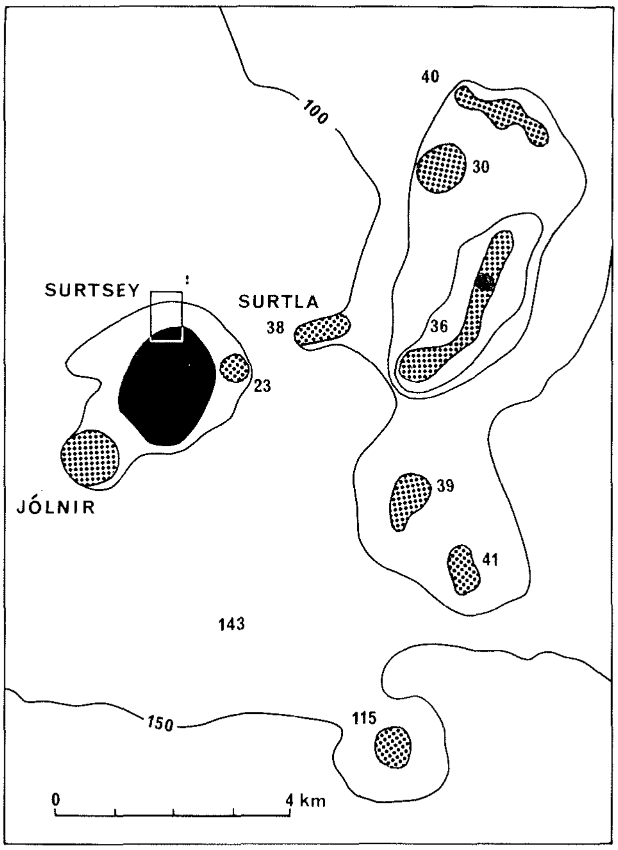

Fig. 2. Bottom topography around Surtsey (from NORRMAN 1969). Above water are only Surtsey and the small skerry Geirfuglasker (black). In addition to Jólnir, Syrtlingur and Surtla there are six conspicuous peaks (stippled) on the sea-bottom, each probobly the remnant of a submarine volcano.

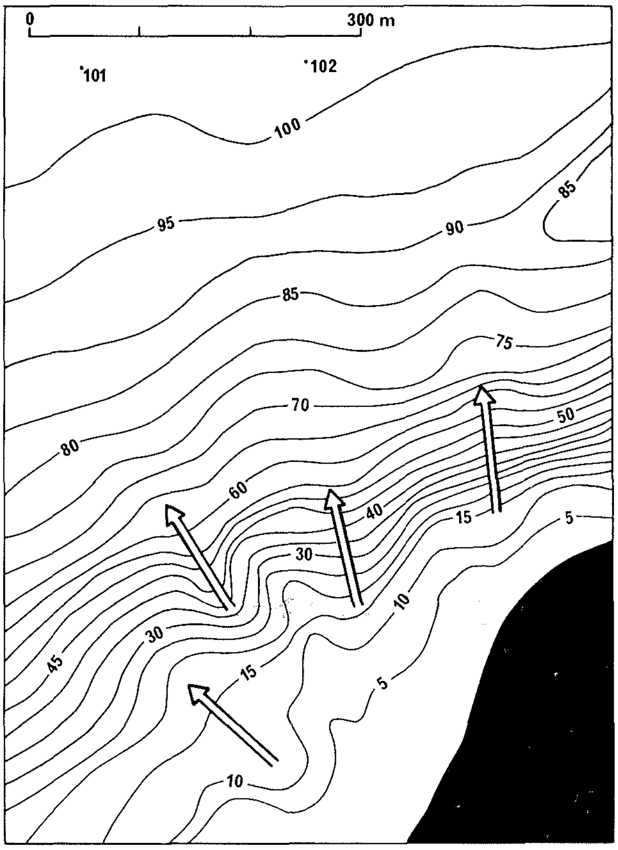

Fig. 3. Offshore morphology at the N end of Surtsey (from NORRMAN 1969). Beach material from SW is building out the ness and in the unstable submarine slope there is a gravity transport of material, constantly as a slow creep and intermittently as submarine slumps or slides. Slump scars and tongues indicated by arrows.

DISCUSSION

From the faunal content it is clear that the sediments found as xenoliths on Surtsey originally were laid down in sea-water, and unless they later were sub-aerially exposed the lithification and other diagenetic processes must have taken place in the marine environment. The water depth of 130 m is just within range of the Holocene eustatic sea-level change, but according to the C^{14} dating the sediments are considerably younger than the lowest stand of the sea-level, —130 m which occurred about 15,000 years ago (MILLIMAN & EMERY 1968). 6,000—7,000 years ago the sea-level was only 10—20 m lower than today, and provided a stable insular shelf, the water depth where Surtsey now stands should have been at least 100 m when the sediments were deposited.

The glacial subsidence of Iceland was however considerable and the highest shore-lines are now at an altitude of 100—130 m. They are supposed to date from "the terminal phase of the glacial period" (JÓNSSON 1957). The maximum glacier growth and glacial depression should be approximately coincident with the lowest stand of the sea, and the subsequent uplift should be expected to lag behind the eustatic sea-level rise, resulting in a somewhat greater water depth than 100 m at the time of deposition. A sub-aerial exposure of the sediments before they were included in the Surtsey eruption is consequently not likely, and this opinion is also supported by the general lack of solution or weathering marks in the material.

The morphology of the insular shelf to the east with its regular pattern of transverse sea-valleys is attributed to the reshaping effect of Pleistocene glaciers (HARTSOCK 1960), but this pattern is abruptly broken by a bulge at the Vestmannaeyjar archipelago (Fig. 1). This is an area where extensive submarine volcanism has taken place; within 700 km² there are at least 60 submarine craters and probably all Holocene (JAKOBSSON 1968). The production of volcanic material during the Surtsey event is estimated to be 1.1 km³ and about 70% of that is tephra (THÓRARINSSON 1968). If this value is taken as representative for all eruptions in the Vestmannaeyjar archipelago, the produced volcanic material which is now eroded away should be sufficient for a sediment cover with a thickness of 90 m over the entire area. Doubtlessly the bulge on the insular shelf is in part due to the pyroclastic sediment sheet from the postglacial submarine volcanism. Within 8 km from Surtsey there are at least 6 peaks on the sea-floor which are remnants of older craters but the only part left above water is the small island Geirfuglasker (Fig. 2). The sediments in the xenoliths represent different niches in an environment characterized by erosion of such former equivalents to Surtsey, and the deposition of corresponding beds can be studied around this island today.

The material in the submarine slopes of Surtsey is unstable and slumps or slides occur frequently (Fig. 3). Such slides may generate mudflows or turbidity currents spreading over the adjacent sea-floor and the deposited sediments should be close equivalents of the xenolithic turbidites. Where the submarine slopes are at the angle of repose and new material is supplied at the top there is a continuous slow creep of material which finally comes to rest at the bottom of the slope. Conditions of that kind prevail for instance at the N end of Surtsey where a constant supply of beach material along the shore from SW is building out the ness (NORRMAN 1968). The slow creep in that slope was observed by the present author during diving operations in June 1968 (Plate II K-L). The material is sorted by wave and current action when transported along the beach, and some sorting is preserved in the gravity transport down the slope. Big mollusc shells as well as small foraminiferal tests can in this way be transported and accumulated together with a sediment of quite different hydrodynamic properties without wear. The massive sediments in the xenoliths were probably formed under conditions similar to these in such a submarine talus.

Low-temperature formation of zeolite minerals in marine sediments with an abundance of volcanic material is well known (ARRHENIUS 1963), but only exceptionally do such processes cause cementation (MORGENSTEIN 1967). The mechanism behind the rapid and advanced lithification in the xenolithic sediments from Surtsey is yet unknown, but without doubt it depends ultimately on the submarine volcanism.

ACKNOWLEDGEMENTS

For helpful discussions and valuable advice I thank Professor Bengt Collini at The Geology Department, University of Uppsala, and Professor Otto Mellis at The Geology Department, University of Stockholm. Dr. Åke Franzén at The Zoology Department, University of Uppsala, kindly identified the marine organisms and Dr. Ingrid Olsson at The C^{14} Laboratory, University of Uppsala, made the radiocarbon dating. I am also in many ways indebted to Dr. John O. Norrman at The Department of Physical Geography, University of Uppsala. Mrs. Marianne Dahl made the microprobe analyses, Mr. Gustav Andersson did the photographic work and Mrs. Dagmar Engström made the drawings.

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