GEOLOGY

The Sedimentary Xenoliths from Surtsey: Turbidites indicating Shelf Growth

By

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ABSTRACT

Well-preserved sedimentary rocks from marine strata in the distal shelf occur as xenoliths in the Surtsey tephra. Fossilbearing xenoliths, to some extent affected by subaerial diagenesis, are previously known from Heimaey and Skammidalur. Marine biogenic carbonates (mainly aragonite and Mg-calcites) included in pyroclastic sediments are slowly affected by subaerial exposure; the changes differ from those in carbonate sedimentation areas. Aragonite shells are not dissolved, leaving molds; instead replacement without a void stage occurs. Depletion of Mg from Mg-calcites has not been observed. Upper Tertiary *Cyprina* shells are still aragonite.

The siliceous cement in the xenoliths is formed in two stages: (i) the grains are uniformly coated by a thin crystalline fringe, and (ii) the remaining pore space is filled by a metastable gel-type cement. Gradually the metastable phase is stabilized by crystallization processes.

According to C^{14} dating, sedimentary xenoliths from Surtsey were lithified within the last 6,000—11,000 years, probably in a submarine position. Equivalents of all intervals in a complete turbidity sequence occur in the material; also a massive-bedded deposit which is attributed to slow creep and small slides in submarine slopes. Present-day conditions around Surtsey probably lead to the formation of corresponding sediments.

The shelf in this extension of the Neovolcanic zone is broad and shows no influence of glaciation. It is concluded that an abundance of pyroclastic material from submarine volcanic eruptions in the area caused growth of the shelf by distal addition of fluxoturbidite sequences. Marine strata in the shelf are known to be about 700 m in thickness at Heimaey, and they occur inland at least as far as to Skammidalur.

INTRODUCTION

The Surtsey eruption penetrated the marginal part of the Icelandic shelf south of the Vestmann Islands in an area where the water depth is about 130 m. The locality is situated 33 km off the coast and about 8 km from the outer edge of the shelf, this defined as the 100 fathoms (185 m) depth contour.

Material from the rock sequence in the shelf became included in the ejacamenta during the explosive phases of the eruption, and that material is now found as xenoliths in the tephra. Any consolidation of the tephra on Surtsey has not yet occurred, and the volcanic cones are eroded by wind action, surface drainage, and slides, released by the under-cutting activity of waves. In July 1969 the slopes were lined by gullies and the edge of the crater Surtur II had been cut through in its western part. As the tephra is eroded xenolithic blocks become exposed, and usually they roll or slide down the slopes to a level surface, either in the crater or on the outside. Eventually most of them are covered again by eroded and re-deposited tephra.

Most of the xenoliths are lithified sediments and, according to the perfect preservation of carbonate organisms present in the rocks, they are virtually unaffected by the heat from the eruption. The material presents an opportunity to study well-preserved layers from a marginal shelf area, and the big size of the samples (up to 1 m diameter) is an advantage, especially in connection with the study of sedimentary structures and the distribution of organisms.

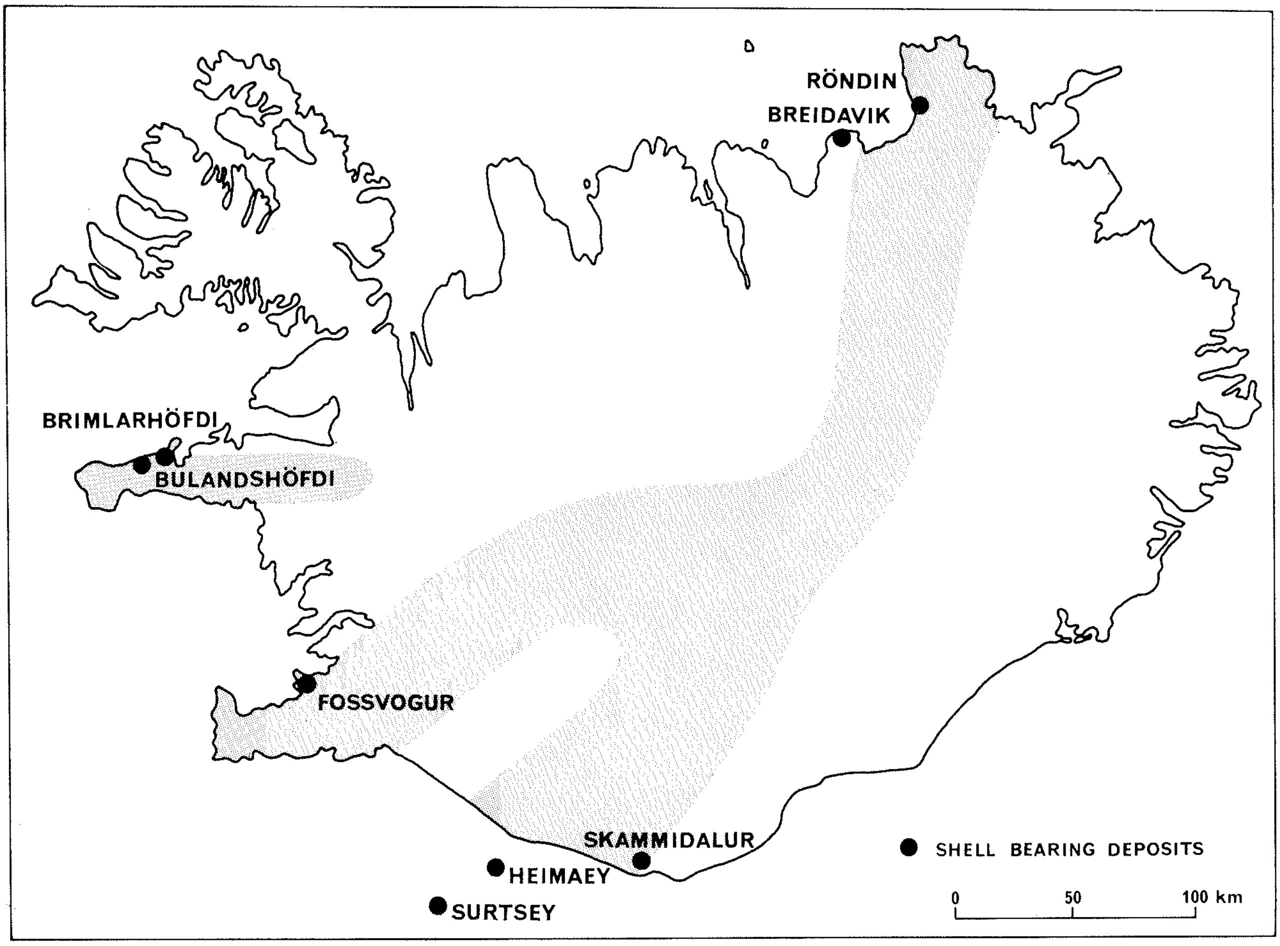

Fig. 1. Iceland with Neovolcanic areas and Pleistocene shell-bearing deposits (in part after ASKELSSON 1960). The shell-bearing deposits all lie within or near Neovolcanic areas.

SEDIMENTARY XENOLITHS AND SUBAERIAL DIAGENESIS

Xenoliths containing marine organisms are previously described from Skammidalur (ASKELSSON 1960, EINAR EINARSSON 1968) and from Heimaey (JAKOBSSON 1968). Both localities are situated in the zone of postglacial volcanism, the Neovolcanic zone, where also the Surtsey eruption took place, and the sediments obviously belong to the same sedimentary sequence. In this connection it is interesting to note that finds of Pleistocene shell-bearing deposits in Iceland generally lie within or close to Neovolcanic areas (map Fig. 1).

Skammidalur lies to the north of the coastal plain in the Mýrdalur district, 6 km from the coast and 75 km from Surtsey. Here a 200 m high scarp of *móberg* (literally "brown rock"; brownish palagonitized tuff and breccia) rises over the plain and the top of the móberg-formation is covered by glaciated lavas. Scattered in the móberg are boulders of sedimentary rocks with a lower Pleistocene marine fauna, i.a. the brachiopod *Rhynconella (Hemithyris) psittecea,* the pelecypods *Nucula tenuis, Mytilus edulis, Cyprina islandica, Venus gallina, Tellina obliqua* and the gastropods *Acteon noae, Nassa cf. prismatica* and *Turritella tricarinata* (ASKELSSON 1960).

JAKOBSSON (1968) reports sedimentary xenoliths in the consolidated tephra of the volcano Saefell on Heimaey, only 20 km from Surtsey. On basis of C^{14} analyses of peat he dates the Saefell eruption to about 5,000 years BP and the fauna in the sedimentary xenoliths is described as Recent. "It was possible to identify ten species of pelecypods, one gastropod and one foraminifer. All these species are found in the sea around Iceland today and at a depth similar to that found around the Vestmann Islands at the present time" (ibid. p. 115).

ASKELSSON (1960) characterizes the xenolithic sediments at Skammidalur as "consisting of rounded pebbles and water-worn sand-grains" but otherwise the sedimentary properties are not discussed.

The volcanic pile at Skammidalur is covered by glacially eroded lava, and is probably not

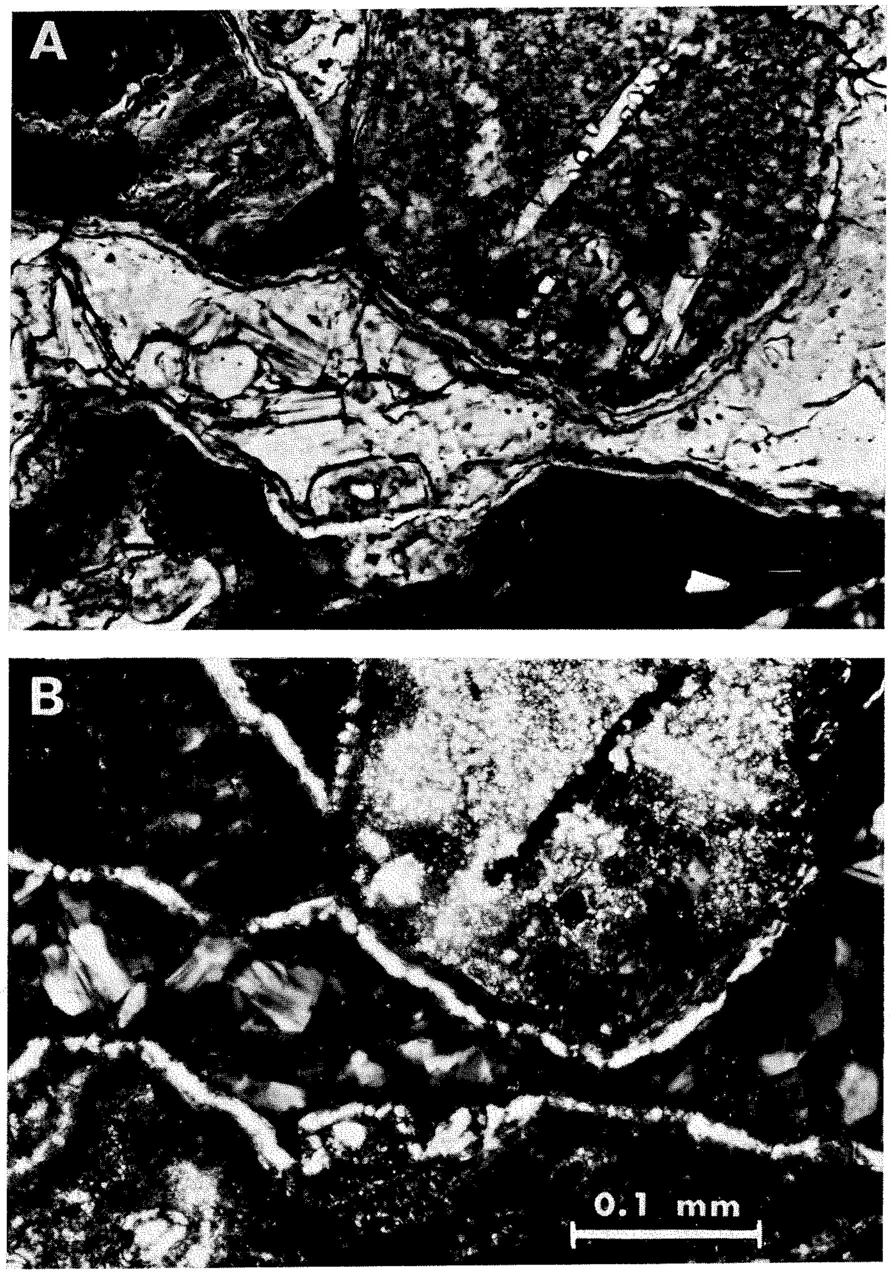

Fig 2. Sedimentary xenolith from Skammidalur. Thin section, A plain transmitted light, B cross-polarized. The cement consists of two components: (1) an epitaxial, isopachous fringe which is missing at grain contacts, and (2) a weakly birefringent siliceous substance, lacking a distinct crystalline fabric. Hand specimens are yellow-brown from subaerial alteration. (Specimen by courtesy of Einar H. Einarsson 1969.)

younger than late Glacial; the Saefell volcano on Heimaey is about 5,000 years old. Consequently, the sedimentary xenoliths found in these deposits have been exposed to subaerial diagenetic processes for a considerable time; their mineralogy and composition may have changed significantly, particularly where they were exposed to percolating groundwater. It is known that mineral assemblages which are stable or metastable under marine conditions may suffer rapid diagenetic changes upon exposure to fresh-water.

There occur in the sedimentary xenoliths three main components which as to origin represent different and specific environments; also conditions for subaerial alteration of these components are basically different. (1) *The pyroclastic grain component,* dominated by volcanic glass. This high-temperature product is not stable at earth-surface temperatures and pressures; the grains in the xenoliths are usually rounded by mechanical wear and they have probably also undergone chemical changes during transport and deposition. (2) *The cement* which is a diagenetic adjustment to post-depositional conditions. Theoretically, minerals formed under such conditions should be more resistant to weathering than volcanic glass. (3) *The biogenic material.* This consists mainly of calcareous parts of marine organisms; mostly mollusc shells and foraminifers and some serpulid worm tubes. The material represents processes controlled by metabolic activity, and diagenetic changes may start immediately after the death of the organism.

Fig. 3. Aragonite shells in coarse sediment from the *Mactra*-zone (Astian), Tjörnes. Polished surface. A black substance replaces the aragonite along growth lamellae in the shells. No intermediate void stage is apparent.

Pyroclastic component and cement

From the palagonitization typical for the *móberg* deposits it is evident that the pyroclastic material is very susceptible to diagenetic alteration (TYRRELL & PEACOCK 1926). The permeability of móberg is high and as a rule drainage is effectuated by groundwater flow (KJARTANSSON 1960). Ionic strength and pH of percolating water probably increases with depth by solution and hydrolysis of glass; so are, for instance, the tuffs on Oahu, Hawaii, progressively palagonitized at depth (HAY & IIJIMA 1968).

The processes that caused palagonitization of the móberg at Skammidalur and lithification of the tephra cone of Saefell also affected the xenoliths. This is apparent even from the colour of the material; the long-exposed xenoliths from Skammidalur are yellow-brown while the fresh sediments found on Surtsey are dark grey or black.

In thin sections the cement in the Skammidalur material corresponds to that described from Surtsey; a birefringent isopachous fringe surrounds the grains, while most of the pore space is filled by a weakly birefringent cement without any crystalline fabric (Fig. 2).

Biogenic material

Marine biogenic carbonates are dominated by the metastable minerals aragonite and Mg-calcites (VINOGRADOV 1953, LOWENSTAM 1954), and several authors have described the diagenetic course of events in areas of carbonate sedimentation (e.g. GAVISH & FRIEDMAN 1969). The first step is generally a loss of Mg from Mg-calcites without any textural changes; this is closely followed by dissolution of aragonite and interparticle cementation by calcite mosaic cement. During these stages partial re-

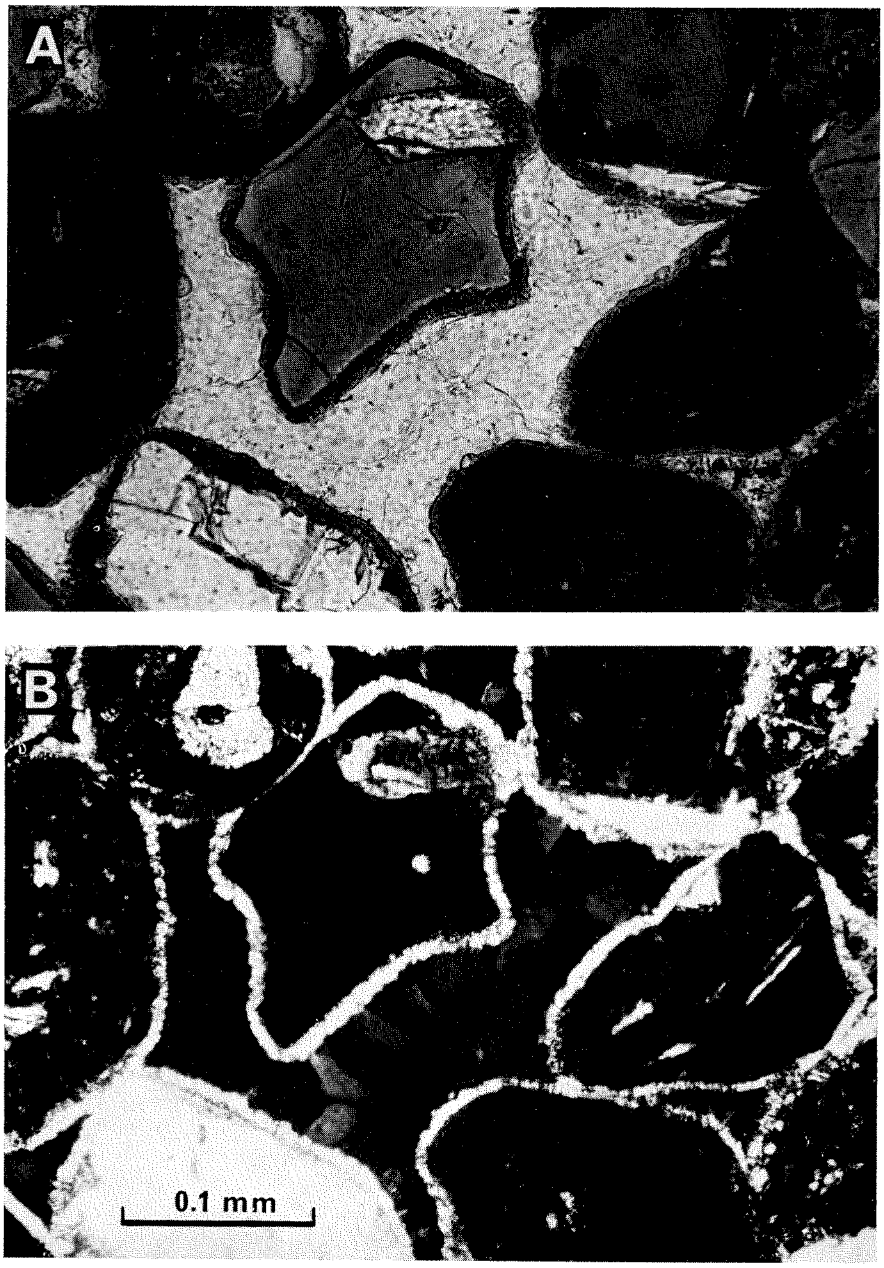

Fig 4. Sedimentary xenolith from Surtsey. Thin section, A plain transmitted light, B cross-polarized. Grains of different composition and mineralogy are all covered by a fringe of even thickness. A transparent siliceous cement which is almost isotropic, fills the remaining pore space (cf. Fig. 2).

placement of quartz and other silicate grains by carbonate also occurs.

It is less well-known what happens to shells and other biogenic carbonates which constitute only a minor component in a pyroclastic sediment. If any depletion of Mg from Mg-calcites occurs under such conditions is uncertain; HAY & IIJIMA (1968) report precipitation of authigenic calcite cement with 10–28 mole % $MgCO_3$ in the tuffs of Oahu, Hawaii, and simultaneous leaching of Mg from biogenic calcites seems improbable.

During diagenesis of carbonate sediments, dissolution of aragonite shells commonly leads to formation of molds which are subsequently infilled by a drusy calcite mosaic (WINLAND 1968). That process has not been observed in the present material, which includes samples of the shell-bearing pyroclastic deposits at Tjörnes (with Breidavík), Fossvogur, Skammidalur and Surtsey.

There occurs, however, a partial replacement of molluscan shells without any intermediate void stage. A black earthy substance which is insoluble in weak HCl, replaces the calcium carbonate; commonly this process proceeds along growth lamellae in the shells, and in sections these may appear striped in black and white (Fig. 3). In an advanced stage the complete shell is replaced by the black material, but this has been observed only in heavily altered xenoliths from Skammidalur.

Except for the replacement process, diagenetic

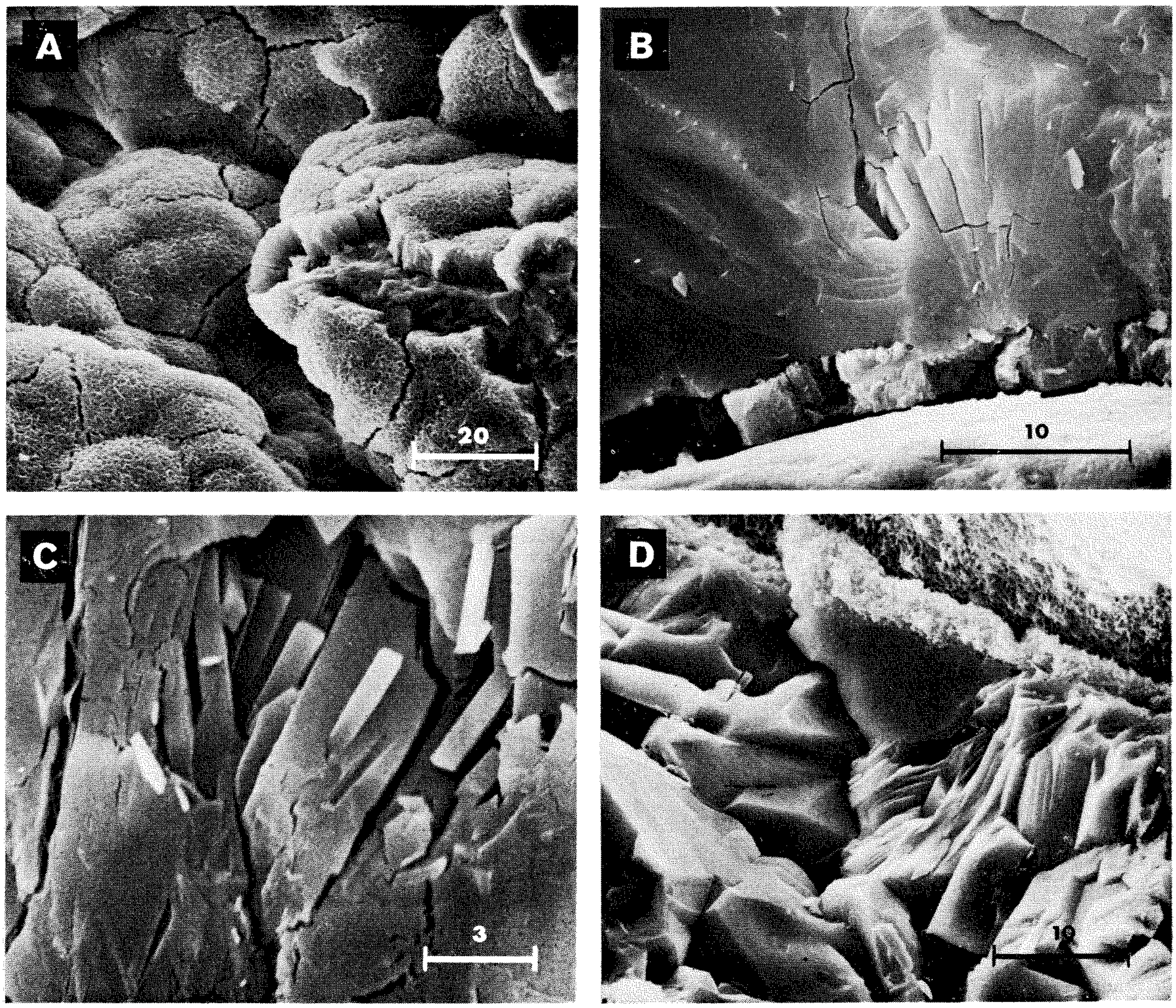

Fig. 5. Scanning electron micrographs of siliceous cement; fractured surfaces. A. Crystalline fringe cement in xenolith from Surtsey. All grains are coated by the uniform fringe; grain in right center is partly exposed by the fracture. The numerous shrinkage cracks are probably a drying effect. No gel-type cement is present in this deposit. Scale bar 20 microns. B. Xenolith from Surtsey. In order upwards: grain surface, crystalline fringe, gel-type cement. (Compare with D.) Scale bar 10 microns. C. Gel-type cement with shrinkage cracks. Small crystals, belonging to the earliest crystalline phase observed, are projecting out of the gel. Scale bar 3 microns. D. Xenolith from Skammidalur. In order downwards: grain surface, crystalline fringe, gel-type cement showing crystal faces. (Compare with B.) Scale bar 10 microns.

changes of biogenic carbonates under these conditions seem to be small; the oldest shells examined belong to the *Mactra*-zone (Astian) in the Tjörnes beds and, according to X-ray diffractometry, these are still pure aragonite.

SURTSEY SEDIMENTARY XENOLITHS

Composition and cementation

In a previous paper (ALEXANDERSSON 1970) it was reported that the sedimentary xenoliths from Surtsey contain *Cyprina islandica, Aporrhais pes pelecani, Pomatoceros* sp., *Dentalium* sp. and various foraminifers, and that the sediments consequently are marine. The calcareous parts of the organisms still retain their original mineralogy (aragonite and Mg-calcite) and have not been diagenetically altered; nor do they show any signs of leaching or dissolution. The same species occur in the seas around Iceland at the present time, and the opinion that the sediments are very young was supported by a radiocarbon dating of *Cyprina* shells which gave a preliminary age of 6,000—7,000 years BP.

The *Cyprina* shells were taken from two blocks and according to the final radiocarbon values these were not of the same age; one block (mainly "outer fraction") was approximately 11,000 years old while the other (mainly "inner fraction") was 6,200 years.*

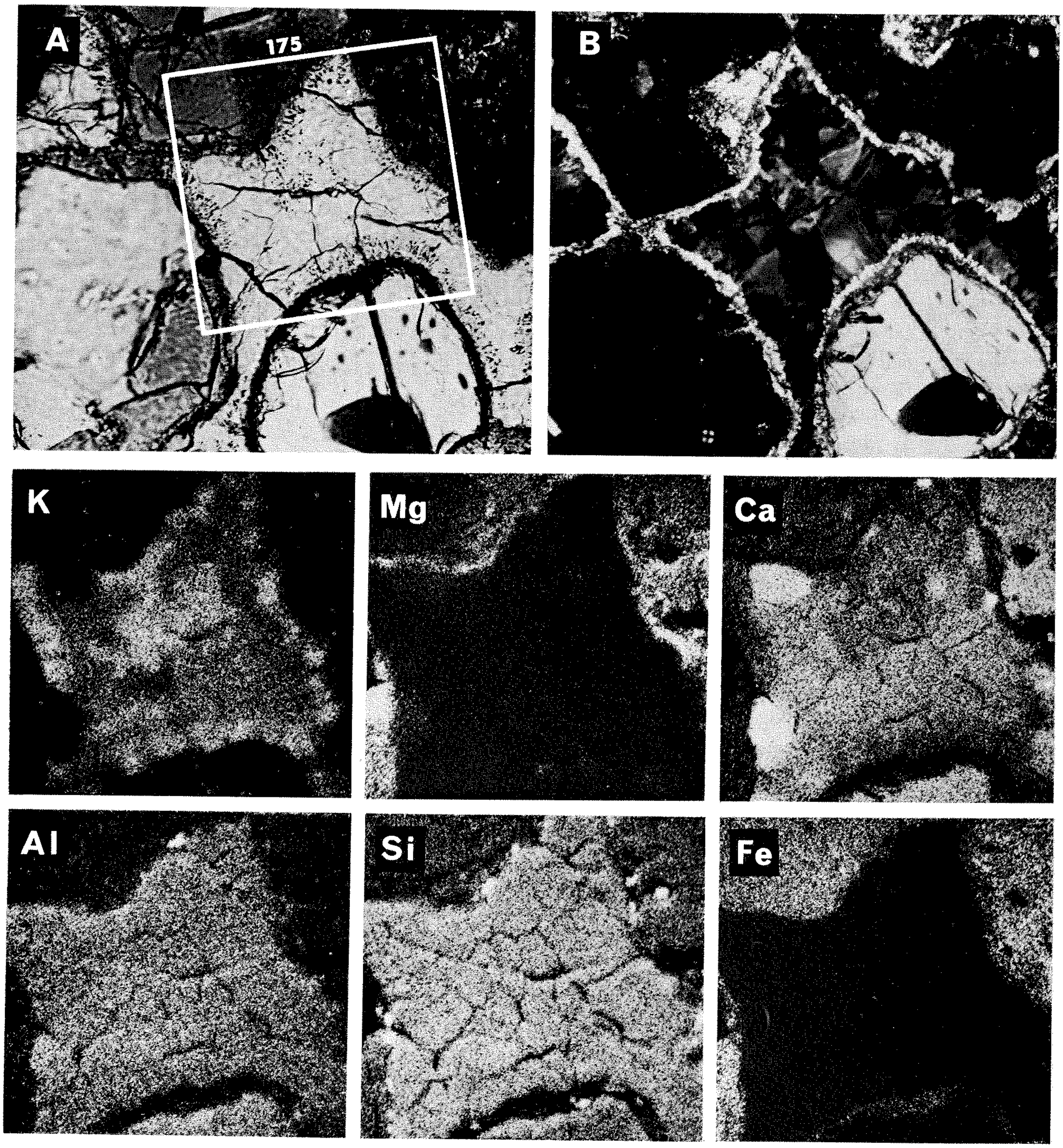

Fig. 6. Elemental composition of gel-type cement in sedimentary xenolith from Surtsey. A Thin section, plain transmitted light, B cross-polarized. Square in A scanned for distribution of elements in scanning electron microscope with X-ray spectrometer; side of square 175 microns. Note the high resolution in the scan pictures; even shrinkage cracks are resolved. The crystalline fringe was lost prior to scanning, during ultra-sound cleaning of the specimen. Only relative proportions are shown; the general intensity level depends mainly on the number of scans made.

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* The C^{14} laboratory, Institute of Physics, Uppsala, Sweden:

	$T_{1/2}$ 5570	$T_{1/2}$ 5730
U-2146 Surtsey 4+20, 6–68, inner $\delta C^{13} = +0.7$ ‰	6010 ± 190 B.P.	6180 ± 200 B.P.
U-2147 Surtsey 4+20, 6–68, outer $\delta C^{13} = -1.6$ ‰	10570 $\pm^{390}_{370}$ B.P.	10870 $\pm^{400}_{380}$ B.P.

The grain component of all sediments is of pyroclastic origin, but with regard to depositional conditions the rocks are of two types: (1) well-sorted massive-bedded sandstones, deposited under low water-energy conditions, and (2) conglomeratic deposits with subrounded pebbles in a sandy-silty matrix, often rippled and with graded bedding and indicating high-energy transport.

The siliceous cement usually consists of two principal components: (1) the crystalline *fringe,* which is a thin coating on the surfaces of the grains, and (2) the *gel-type cement,* a transparent, colourless substance which fills the remaining pore space (Fig. 4). The fringe encloses all grains, including shell fragments and foraminifers, but it is missing at grain contacts. It is formed by birefringent crystals, 4—10 microns in length, which are oriented normal to the coated grain surface (Figs. 4, 5 A—B). According to electron microprobe data the crystals contain Fe-Mg-Ca-Al-Si, but the precise composition, and their mineral form is as yet unknown. In some deposits the fringe is the only form of cement present (Fig. 5 A), and obviously it represents the first stage of cementation. Similar fringes of calcite crystals are described from marine lithification of carbonate sediments (LAND & GOREAU 1970, ALEXANDERSSON 1969). Alizarin red-S in acid solution, which is a stain specific for calcium carbonate (FRIEDMAN 1959, Warne 1962), does not stain anything except the biogenic carbonates in the present material, and it is clear that aragonite or calcite do not take part in the cementing processes.

The second component, the gel-type cement, has no distinct crystalline fabric, although it has a blocky appearance and very weak birefringence in polarized light. According to preliminary electron microprobe data, the average composition is 55—60% SiO_2, 25—30% Al_2O_3, and 10% Ca-Mg-K with substitution between K and Ca-Mg (Fig. 6). The sediment grains in contact have no direct influence on the composition of the cement.

The gel-type cement appears to be an initially amorphous and metastable substance, gradually stabilizing as it goes through several stages of crystallization. The earliest crystalline phase observed consists of minute laths, floating in the amorphous phase like halos around the grains (Fig. 6 A). Such laths are less than 1 micron in width, and 10—12 microns in length (Fig. 5 C); their composition and mineral form are unknown. However, they seem to represent an enrichment in K, and do not occur in the low-K

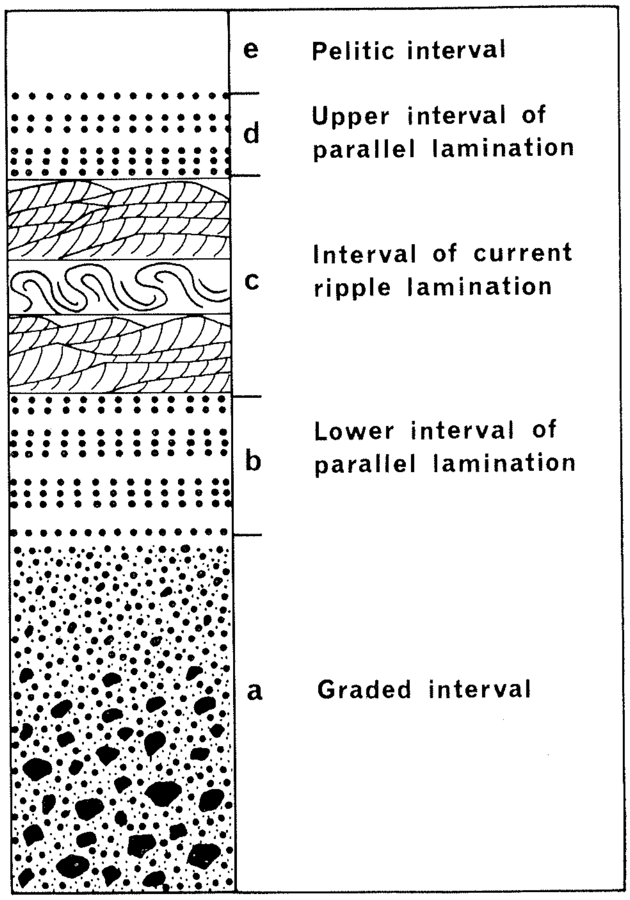

Fig. 7. Successive intervals in a complete turbidite sequence (BOUMA 1962).

phase (Fig. 6 A, and element distribution scans).

Another ordering process affects the gel-type cement as a whole; in the fresh xenoliths from Surtsey this kind of cement typically shows conchoidal fractures without indications of a crystalline organization, while a corresponding fracture in the long-exposed xenoliths from Skammidalur reveals numerous crystal faces (Figs. 5 B and D).

The sedimentary rocks found as xenoliths on Surtsey were probably lithified in a submarine position (ALEXANDERSSON 1970). Submarine lithification of sediments seems to be unusual in the present seas (EWING et al. 1969); only recently has the process been recognized, and the mechanism is not very well understood.

In this connection the preliminary results from Site 115 of the JOIDES Deep Sea Drilling Project are particularly interesting (LAUGHTON et al. 1970). The site lies in 2.893 m of water, 480 km due south of the Vestmann Islands archipelago in the basin between the Reykjanes Ridge and the Rockall Plateau (position 58° 54.4′ N; 21° 7.0′ W); it was drilled on Leg 12, 14—16 July 1970. At 58 m sub-bottom the drill encountered

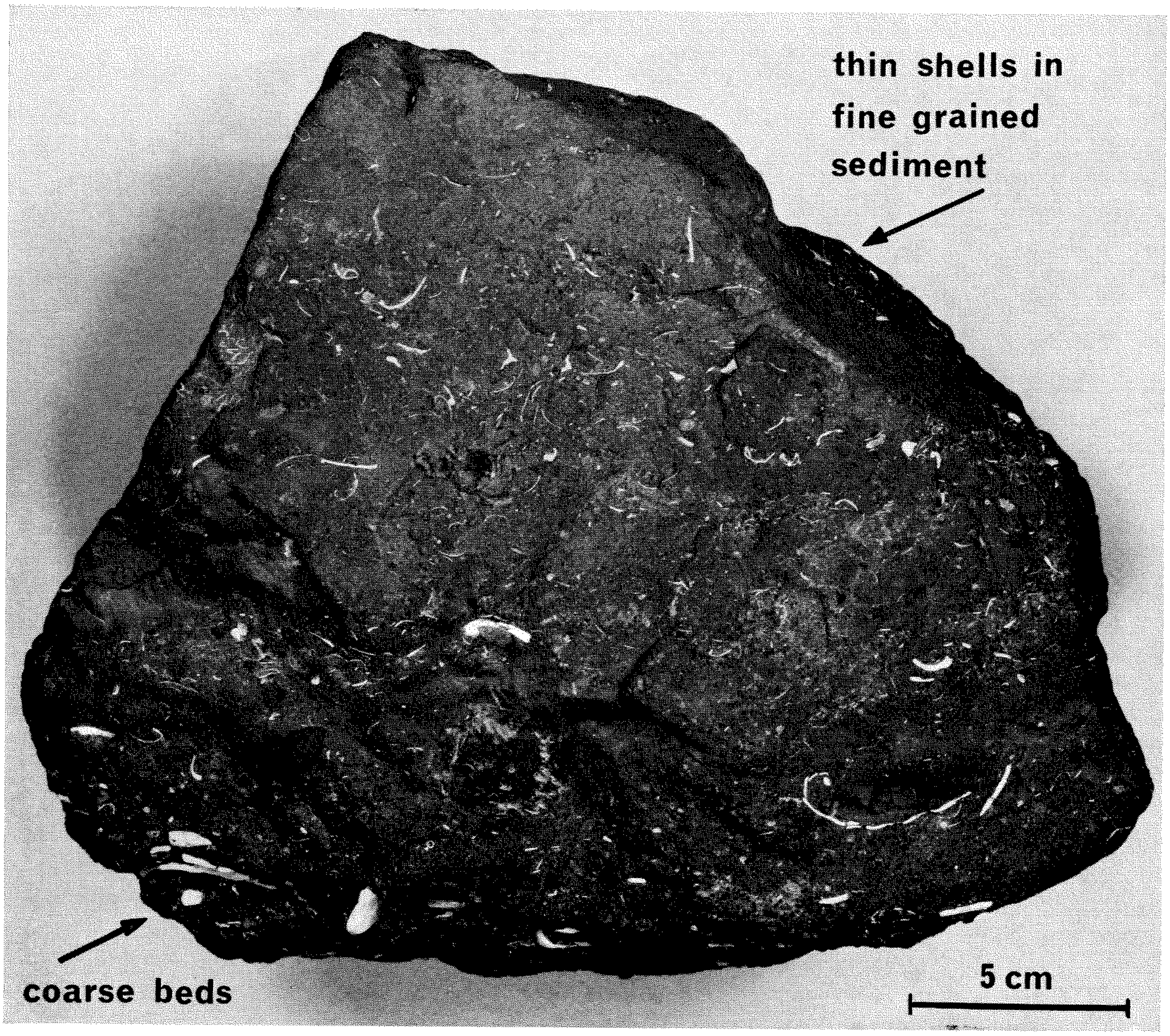

Fig. 8. Graded bedding in xenolithic boulder, Surtsey. Shells indicate pronounced decrease in transport energy; thick shells in lower coarse strata are broken while thin shells in fine-grained sediments are complete.

hard, graded, volcanogenic sandstones, interbedded with thin layers of unconsolidated sediments. The sandstone beds, some more than 1 m thick, persisted to a depth of at least 230 m sub-bottom where the bit was withdrawn. The firmly cemented beds are interpreted as turbidity current deposits of material from Iceland; they were obviously lithified in a submarine position.

Depositional features

A complete turbidite sequence consists of five intervals in a fixed, characteristic succession (BOUMA 1962). From the bottom to the top these intervals are: (a) graded interval, (b) lower interval of parallel lamination, (c) interval of current ripple lamination, (d) upper interval of parallel lamination, and (e) pelitic interval (Fig. 7).

Each of these five intervals is represented in the Surtsey sedimentary xenoliths, of which 80 –90 % is turbidite material (the high-energy sediments). Most common are graded deposits corresponding to interval (a). In these, subrounded pebbles of lava are scattered in a sandy-silty matrix which usually also contains shell fragments but rarely any complete shells. The biggest xenolithic boulders yet observed on the island (about 1 m diameter) belong to this kind of rock. In some cases the grading is distinct, and shells lie orientated on bedding planes; thick shells in coarse beds and thin shells in more fine-grained sediment (Fig. 8).

In other cases the grading is not distinct and sorting is poor. Shells in these beds are broken and many fragments are rounded and with a polished surface (Fig. 9). In the poorly graded

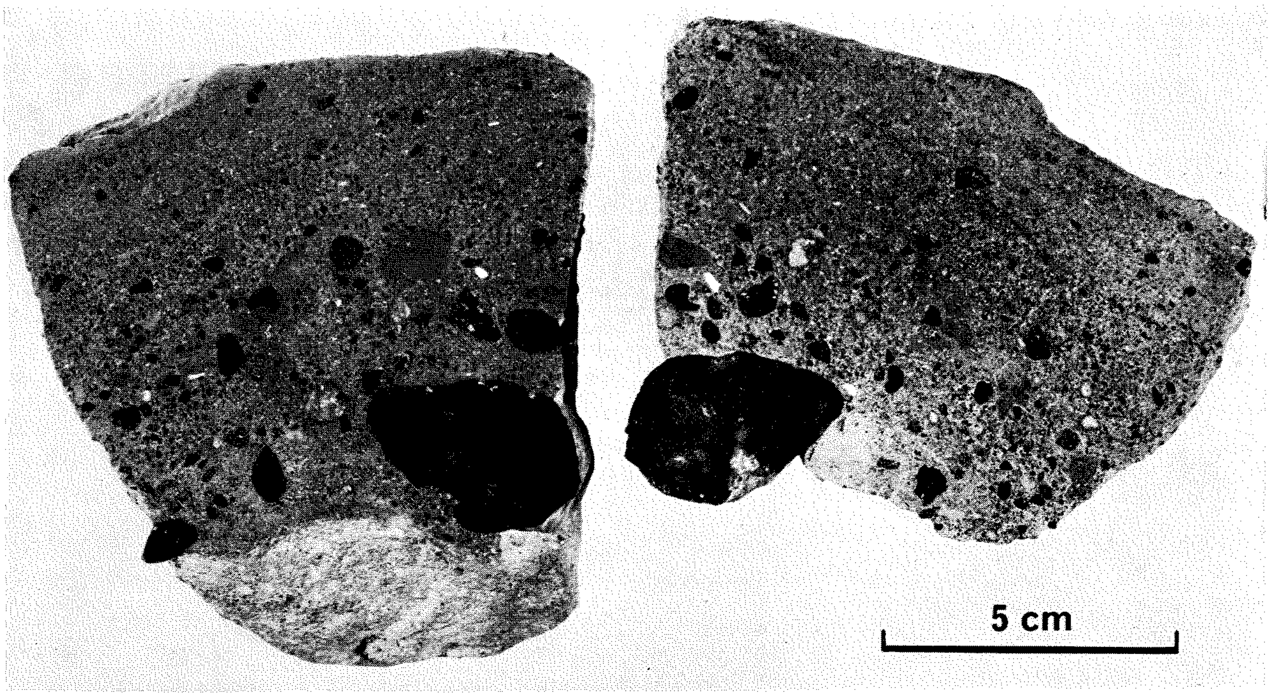

Fig. 9. Xenolith with poorly graded bedding, Surtsey. Cut and polished surfaces. In this kind of deposit (fluxoturbidite) no complete shells occur; fragments are often rounded and smooth.

material it is frequently seen how fragments from the same shell occur close to each other and yet separated by matrix and often pointing in different directions (Fig. 10). Such shells evidently went through the processes of transportation without damage and were broken in connection with the deposition. Shells become orientated in characteristic ways by wave and current action (NAGLE 1967); there is no current orientation of shells or fragments in the poorly graded layers.

It is probable that layers with indistinct graded bedding were deposited from a flow at an intermediate stage between slump and turbidity current, producing a *fluxoturbidite* according to DZULYNSKI et al. (1959). They assume this kind of transport to indicate: (1) a rich supply of material, and/or (2) a steep slope producing slides, and (3) a short distance to the source area and because of that little time for the sorting activity of turbidity currents to work.

The characteristics given by ASKELSSON (1960) for the xenoliths from Skammidalur are

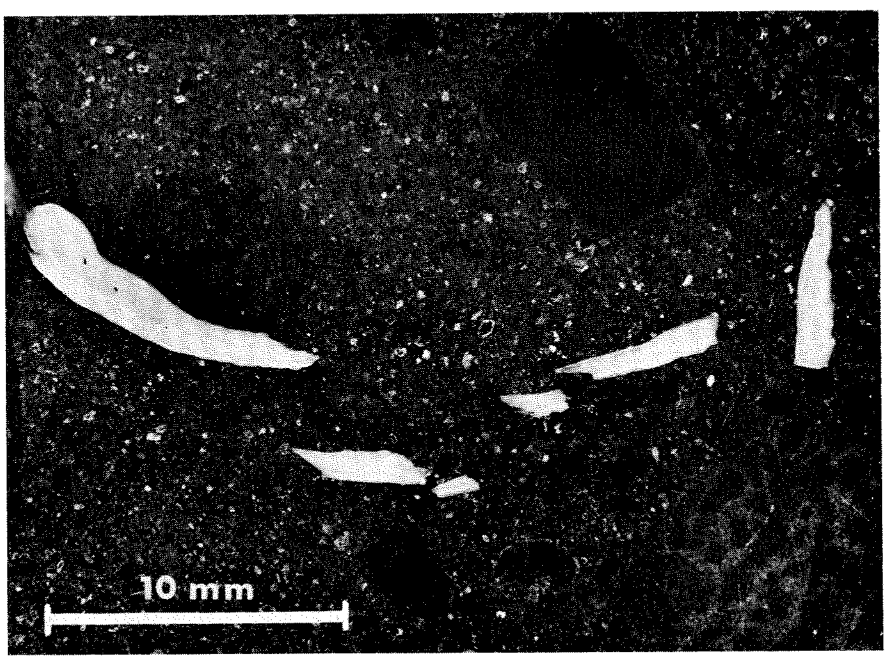

Fig. 10. Shell fragments in xenolith, Surtsey. Polished surface. All fragments are from the same shell; the surrounding material was viscous enough to break the shell just before the movement ceased.

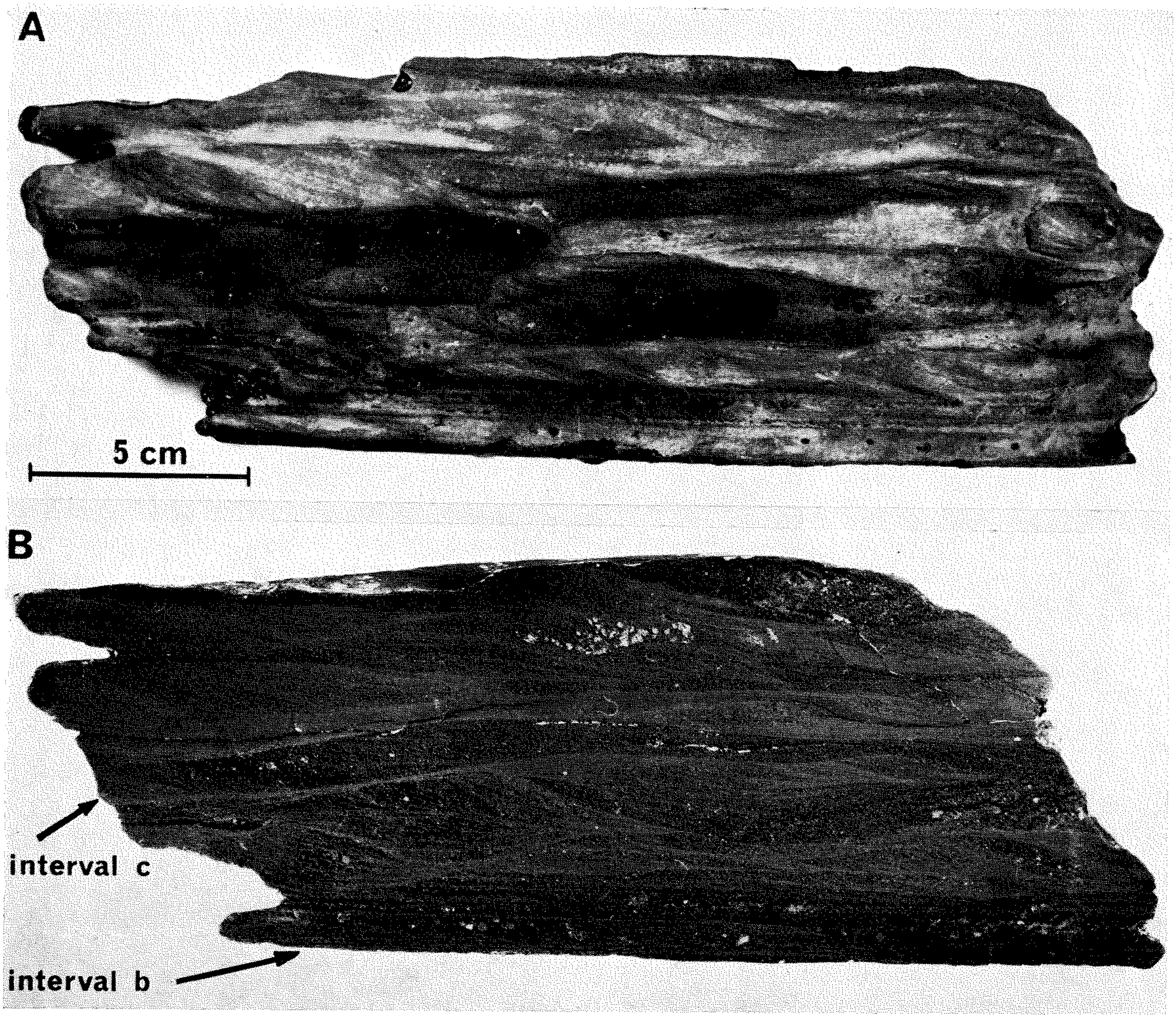

Fig. 11. Xenolith with lamination, Surtsey. A exterior with relief, B cut and polished surface. The deposit is loosely cemented and the block became sculptured by eolian corrasion in an exposed position on Surtur I. The layers correspond to interval b (lower parallel lamination) and c (current ripple lamination).

typical for material from the graded interval in a turbidity sequence.

Sediments with the characteristics of interval (b), lower parallel lamination, and (c), current ripple lamination, occur sparsely on Surtsey and most samples of that kind were found in the tephra cone of Surtur I. The majority of the ripples have a wave length of about 10 cm and a height of about 1 cm; thickness of the beds is usually less than 10 cm (Fig. 11). Convolute bedding is not well developed.

Upper interval of parallel lamination (d), and pelitic interval (e) also occur as thin beds, not thicker than about 10 cm. This indicates a scarcity of clay particles; conditions which are in general agreement with the geologic setting. Load casts and injection structures are common in this kind of material.

Foraminifers with a size of 0.3—0.4 mm occur frequently in horizons where the dominating size of solid particles is less than 0.1 mm. In the same layers the size of scoriaceous fragments with numerous vesiculae may exceed 1 mm (Fig. 12). These different particles have approximately the same hydrodynamic properties and may have settled simultaneously out of the tail of a turbidity current.

The xenolithic sediments which indicate high-energy transport all fit into the fluxoturbidite-turbidite pattern. Outside this pattern fall the well-sorted low-energy sediments, which must have formed under quite different conditions. The grains are rounded, the typical particle size is 0.2—0.3 mm and practically no silt or clay is present. Fossils are complete and unworn; frequently hollow shells are not even filled by sedi-

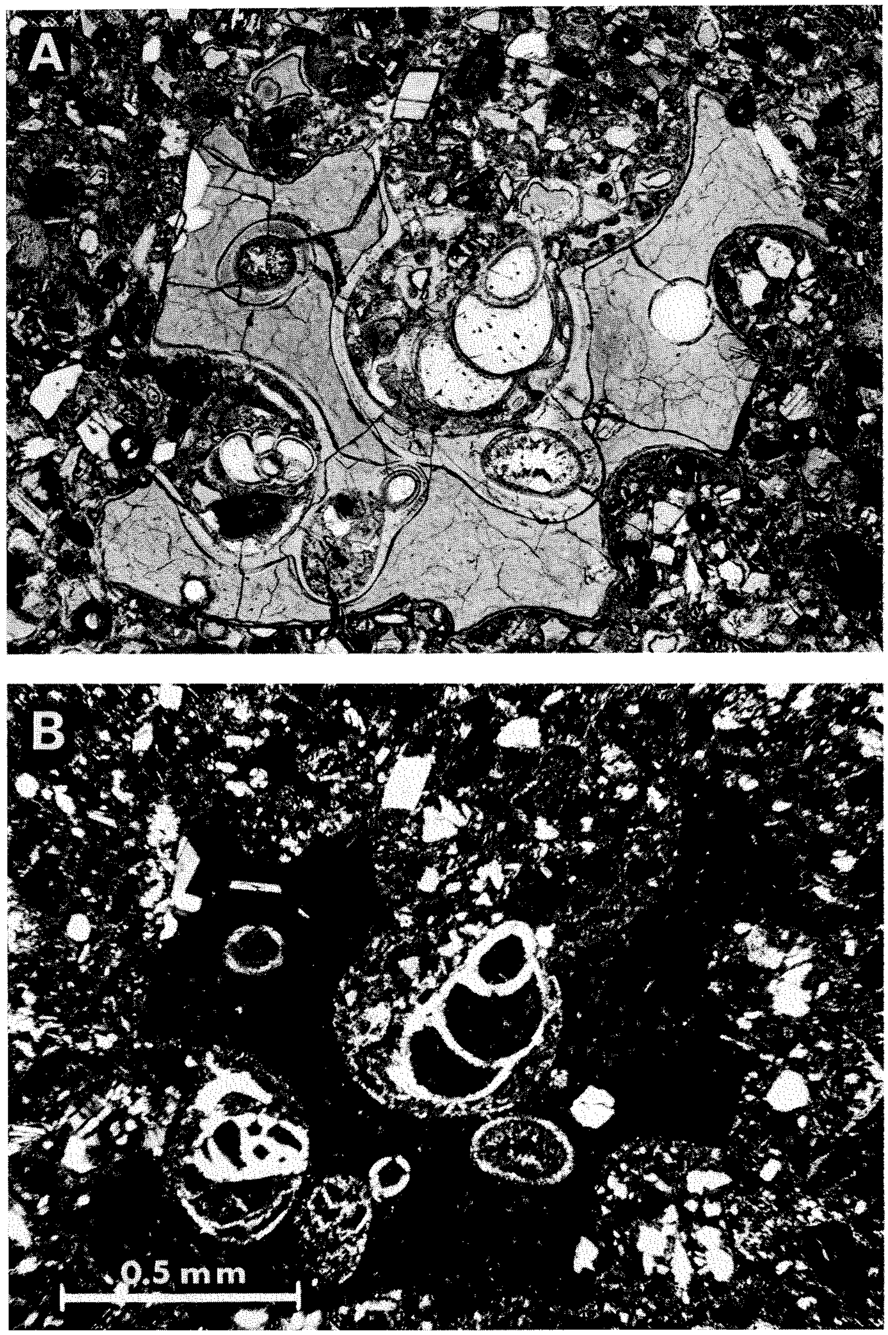

Fig. 12. Sedimentary xenolith from pelitic interval, Surtsey. Thin section, A plain transmitted light, B cross-polarized. The material is a silty pelite with no visible sedimentary structures (pelite = the fraction smaller than 50 μ). Foraminifers are common and occur here squeezed into the vesiculae of a scoriaceous fragment.

ment. The sediments are massive and show no signs of bedding or lamination. Shells are not orientated by wave or current action; they occur randomly distributed and possess widely different hydrodynamic properties. The major part of all identifiable organisms is found in deposits of this kind.

These massive sediments are assumed to represent slow creep of material and small slumps in over-steepened slopes; present-day conditions of that kind have been described from the northern end of Surtsey (NORRMAN 1970, ALEXANDERSSON 1970).

It is noteworthy that sediments indicating deposition under waveaction are not present in the Surtsey xenoliths.

SHELF MORPHOLOGY AND GEOLOGY

The southeastern part of the Icelandic shelf has a very characteristic morphology with a number of transverse sea-valleys running almost from the coast out to the shelf edge. On the submarine topography and the sediments of this area HARTSOCK (1960) reports: (1) Sand covers more than half the area out to the 100 fathoms depth contour. (2) Appreciable portions of the shelf are underlain by bedrock beneath the mantle of sediments. (3) The steep insular slope

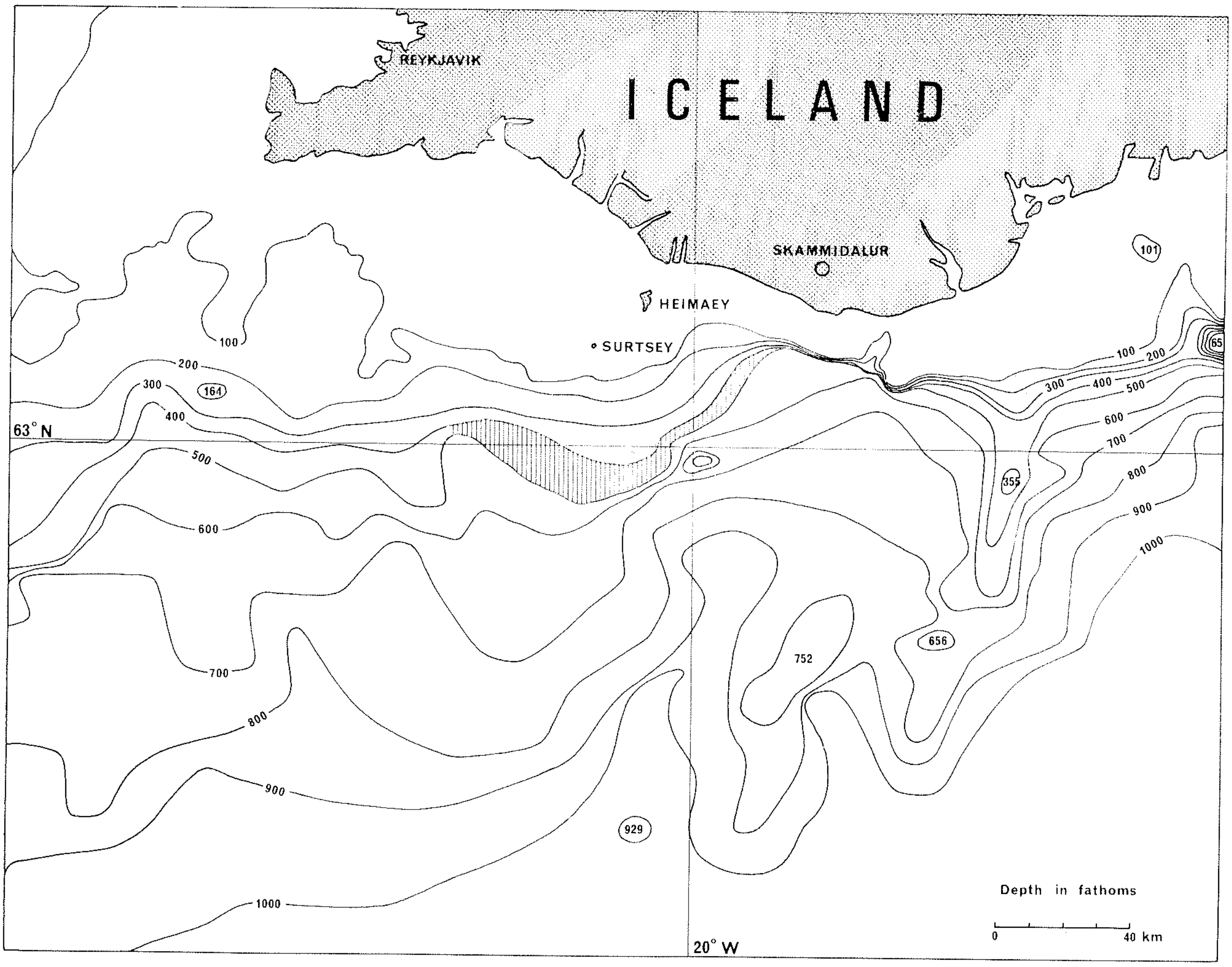

Fig. 13. Morphology and bathymetry of the Icelandic shelf from Skeidarár Djúp to Reykjanes Grunn. After British Admiralty charts 12, 246, 2733, 2968 and HARTSOCK (1960). Dark areas on Iceland = Neovolcanic zones. Vertical ruling in shelf slope = lower level of sedimentary sequence in Heimaey boring.

probably marks a zone of faulting with the southeastern side down-faulted. (4) The ultimate origin of the transverse sea-valleys is not clear; however, it is not improbable that Pleistocene glaciation of the shelf contributed to their present morphology.

Just east of the Vestmann Islands the shelf is only 12—15 km wide, the shelf edge is very distinct and the outer slope drops off rapidly, sloping about 17 degrees. Around the Vestmann Islands and further westward the shelf is 50—70 km wide and the morphology is quite different; there is no pattern of transverse sea-valleys, the outer edge is diffuse and the slope is one degree or less (Fig. 13). On the even shelf plateau numerous steep peaks rise above the level surface; some reach above sealevel and form the islands and skerries of the Vestmann Islands, but most of them occur in submarine positions. JAKOBSSON (1968) reports about 60 submarine peaks in the archipelago; all interpreted as remnants of submarine volcanoes and formed in the same way as Surtsey.

The area lies in the marine extension of the eastern branch of the Neovolcanic zone; an area of postglacial volcanism which traverses Iceland in SW—NE (Figs. 1 and 13). The number of subaerial postglacial volcanoes in Iceland is 150—200 and lava from these covers nearly 12,000 km^2; during the last two centuries eruptions have occurred on an average every fifth to sixth year (THORARINSSON 1960).

During the Surtsey volcanic event at least five main craters were formed (Jólnir, Surtsey I and II, Syrtlingur and Surtla), and it is probable that erosion of these will leave several peaks on the sea-floor. Evidently the number of former volcanoes in the Vestmann Island archipelago is not necessarily equal to the number of peaks on the shelf; even if this were the case the productivity of each eruption is difficult to estimate. However, there is little doubt that volcanism here has been very active and that the Surtsey eruption is the latest in a long series of similar events.

The submarine volcanism seems to be the main source of the material which is building out the shelf in this area. At moderate water depths even basaltic eruptions are explosive and most of the products should be clastic material (cf. the Surtsey event); great water depths or subaerial conditions are required for the production of lava.

The slopes of tephra cones which rise over the sea-floor are rapidly eroded. As seen from Jólnir, Syrtlingur and Surtla, volcanic cones which lack a protective cover of lava are levelled off down to 30–40 m water depth in just a few years (NORRMAN 1970). Submarine avalanches are common in the over-steepened slopes, and the environment should be favourable to the triggering of turbidity currents. Also all conditions postulated by DZULYNSKI et al. (1959) for the formation of fluxoturbidites are present.

All sediments in the xenoliths on Surtsey represent processes which might be expected in a marine environment where abundant pyroclastic material is supplied from not too distant sources. Of such processes, wave- and current-action, slow creep of material and submarine avalanches have been observed around Surtsey at the present time (NORRMAN 1970, ALEXANDERSSON 1970); turbidity currents, which appear to be the main transport mechanism, have not been observed in the field. Sediment cores from the present sea-floor in the area are not available, and to what extent structures indicating turbidity currents occur in the modern sediments is unknown.

The lack of xenolithic sediments which show wave- and current-influence is in agreement with the assumed depositional conditions. Those processes are active at shallow depths; for instance, they are the main agents behind the truncation of the Jólnir-Syrtlingur-Surtla cones. If the final deposition of sediments is due to turbidity currents, coarse material is brought to depths where the hydrodynamic forces are small relative to the grain size, and re-arrangement of material by waves or currents will hardly occur.

Data from a drilling for water on Heimaey in 1964 show that also the proximal part of the shelf to a considerable extent is formed by sediments (Fig. 14). The profile is described by PALMASON et al. (1965) and it is also discussed by TOMASSON (1967) and THORLEIFUR EINARSSON (1967).

The boring began 18 m above sea-level and penetrated 1565 m of rock. The sequence can be

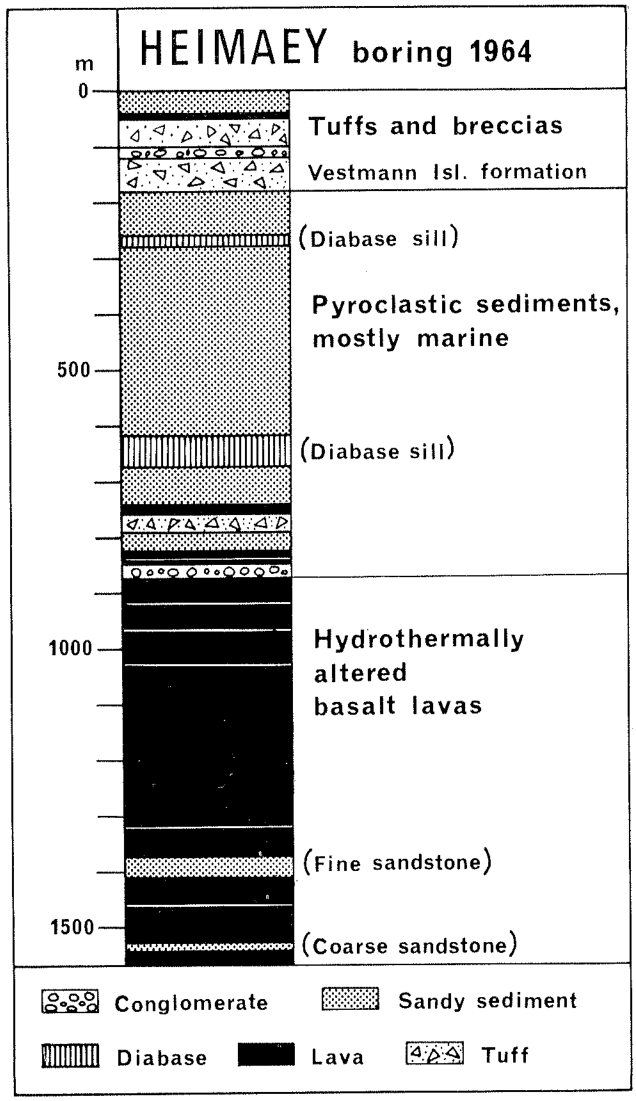

Fig. 14. Generalized profile of the Heimaey boring. After PALMASON et al. (1965) and TOMASSON (1967).

divided into three main units: (1) 0–177 m tuffs and breccias related to the formation of Heimaey (the Vestmann Islands Formation); (2) 177–870 m marine pyroclastic sediments, basal part probably lower Pleistocene; (3) 870–1565 m hydrothermally altered basalt lavas. There is probably a hiatus between the sediments and the lavas which are supposed to be "well down in the Tertiary" (THORLEIFUR EINARSSON 1967).

The low level of the basalt surface (approximately 850 m below sea-level) can be explained as due to a depression of the basalt plateau. This would mean an extreme development of the central Icelandic graben; a tectonic structure which elsewhere is supposed to be very shallow (e.g. TRAUSTI EINARSSON 1960 and 1967, THORLEIFUR EINARSSON 1967, RUTTEN & WENSINK 1960).

On the other hand, if the 500 fathoms (925 m) depth contour along the shelf to the east is extrapolated westwards, its continuation will lead almost exactly to Heimaey, and it is possible that the Heimaey boring is situated south of a buried extension of the shelf-bordering fault-line (Fig. 13). In that case the sedimentary sequence in the boring might represent a wedge of sediments, derived from sources to the west, and growing in an easterly direction on the down-faulted block, south of the shelf-bordering scarp.

The majority of available data can be interpreted both ways, but the presence of subsurface marine strata at Skammidalur 6 km inland indicates clearly that a sedimentation basin once existed in this part of the Neovolcanic zone. The surface deformation in the rift zones of Iceland includes both widening of the rifts (BODVARSSON & WALKER 1964, DECKER et al. 1971), and tectonic subsidence (TRYGGVASON 1968, 1970); the development of a basin of that kind is therefore a very probable process.

CONCLUSIONS

The sedimentological evidence supports the explanation that the Neovolcanic zone in the vicinity of the Vestmann Islands gradually subsided while being filled by pyroclastic sediments of a local origin. Marine strata occur inland at least as far as to Skammidalur, where they underlie the Pleistocene Móberg Formation (ASKELSSON 1960). At Heimaey the marine sequence has a thickness of about 700 m (PALMASON et al. 1965).

Due to a rich supply of material the insular shelf in the area grew by distal addition of sediments. Outside the Neovolcanic zone, 50 km to the east, no such growth occurred. The xenolithic sedimentary material from Surtsey indicates that transport to a great extent was gravity-controlled and lead to the formation of fluxoturbidite and turbidite sequences. Equivalents of all intervals in a complete turbidity sequence have been found in the xenoliths. Corresponding processes are probably active in the present-day environment and to some extent they have been observed around Surtsey.

Previously reported data (ALEXANDERSSON 1970) imply that lithification of the sediments may take place soon after deposition. Such sediments, which occur in the Surtsey xenoliths, differ from deposits affected by subaerial diagenesis, and lithification is supposed to take place in a submarine position. Compaction due to deep burial is not a primary cause.

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