Studies of the Surtsey tephra deposits

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ABSTRACT

Similar to other tuff-rings Surtur I, Surtsey, is characterized by a major unconformity interpreted as the result of large-scale slumping owing to possible formation of a ring fault at depth.

The last deposits of the phreatomagmatic activity of Surtsey indicate that they are either the result of very good or of relatively little magma/-sea-water contact. The first type of deposit is characterized by base surge deposits that show phenomena like syn-sedimentary formation of mud-flow channels, gravity flowage ripples, and joints. The base surge deposits consist mainly of vesiculated tuffs. Vesiculated accretionary lapilli are indicative of very rapid accretion in wet eruption clouds. The second type of deposit contains cauliflower bombs and lapilli that received their particulate size prior to contact with water. During subsequent contact with water the surface of the particles was chilled and solidified to form sideromelane whereas the interior stayed fluid slightly longer and formed tachylite. Many cauliflower bombs impacted while still having a fluid interior and consequently they deformed.

INTRODUCTION

Various aspects of the phreatomagmatically formed tephra of Surtsey have already been studied by Jakobsson (1972); Sheridan (1972); Thorarinsson (1965, 1968); Thorarinsson et al. (1964) and Walker & Croasdale 1972). In this study, performed on Surtsey in June 1972, some additional features will be reported concerning mainly the youngest deposits of phreatomagmatic origin of Surtur I and Surtur II.

UNCONFORMITIES

At the SE edge of the Surtur I crater rim a major unconformity is exposed (fig. 1, 2). The older tephra layers underlying it dip with approximately 10° towards the crater and are covered by ash layers that dip on average 30-40°, locally up to 72° towards the crater centre. Angular fragments of partly bedded tuffs lie on the lowermost part of the unconformity and indicate their being the result of a slide or slump. These fragments are overlain by approximately 1 m of unbedded tuff that may have accumulated by grains sliding or rolling down the slip face. This bed dies out upslope rather rapidly and is, in turn, overlain by bedded tuffs, some of which are vesiculated (see below) whereas some other beds show faint low angle cross-bedding directed upslope. The beds successively step onto older tuff layers. Locally, here the unconformity reaches dips of up to 72°, these beds, in part, are plastered against the older tuffs.

The unconformity can be traced along the rim edge up to a level where the younger tuffs completely drape over the older ones so that no indication of the unconformity is seen anymore (fig. 3).

A similar unconformity is exposed, locally, in the SE wall of Surtur II.

It has been pointed out recently (Lorenz 1973) that many tuff-rings display unconformities indicative of slumping as a result of subsidence along a ring-fault at depth. Examples in Iceland are Hverfjall, Lúdent and Hrossaborg.

The unconformities on Surtsey are interpreted likewise and would, in the case of Surtur I, indicate a ringfault of a diameter of approximately 250-300 m near the surface.

During its final stages of activity the adjacent tuff-ring Jólnir developed subcircular ring-faults of a diameter of 400 and 600 m respectively — in May 1967 but stopped eruption only at the end of August 1967 (Thorarinsson 1968). This

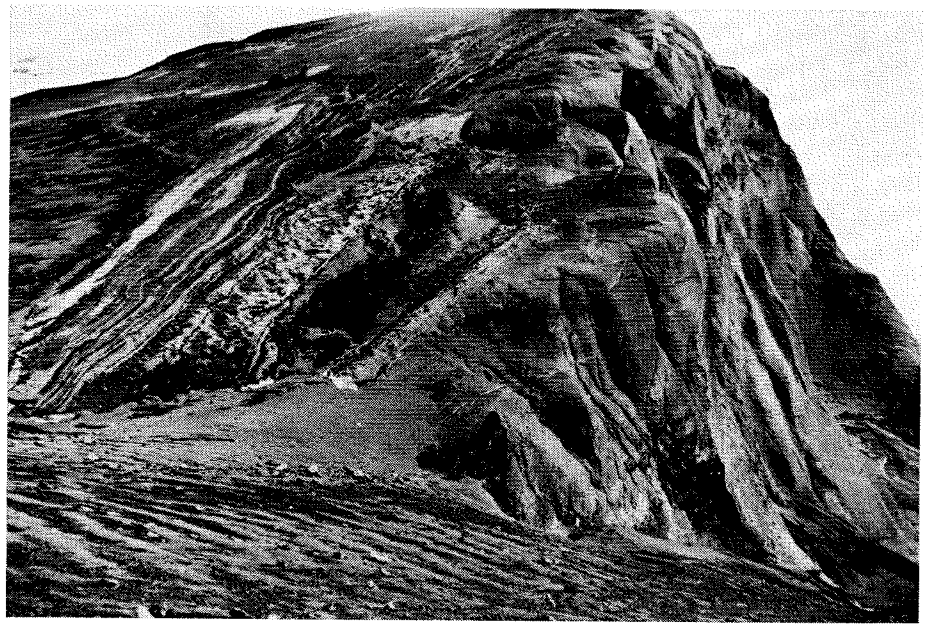

Fig. 2. Unconformity at SE edge of Surtur I rim.

clearly indicates instability at depth that results in subsidence; ash-layers from the following eruptions then cover the faults and drape over the older beds.

PYROCLASTIC DEBRIS BELOW THE UNCONFORMITY OF SURTUR I AND SURTUR II

The older tephra of both Surtur I and II are well exposed in the cliffs at the E and W side of Surtsey. They are rather monotonous, well bedded, rather homogenous in grain-size variation and thickness of beds. Many of the tuffs are vesiculated indicating a base surge origin. The few included blocks or bombs rarely indent the underlying beds; most of them, therefore, were emplaced by base surges.

The layers above the unconformities, however, display a much greater variety in grain-sizes and block and bomb content and are discussed below.

VESICULATED TUFFS

Vesiculated tuffs, i.e. tuffs or lapilli-tuffs with vesicles between the particles, occur in two varieties on Surtsey. The first one is rather coarse grained and largely confined to the older tuffs exposed in the cliffs. Owing to the grain size of the lapilli-tuffs the vesicles are irregular in shape and 0.1-1 cm in diameter. The second type is found in the ash layers above the unconformity of Surtur I. Differential erosion and preservation of these tuffs owing to recent rise of heat and consequent hardening and palagonitization (Jakobsson 1972) provides an excellent change to study these beds in detail.

The vesiculated tuffs are, in general, 1—6 cm thick and contain vesicles 0.1-2 mm, rarely 1 cm in size. The walls of the vesicles are rather smooth; small zeolite crystals frequently are attached to them but are also found in the interstitial pore space of the rocks (Jakobsson 1972). Palagonitization, identified by the brown colour,

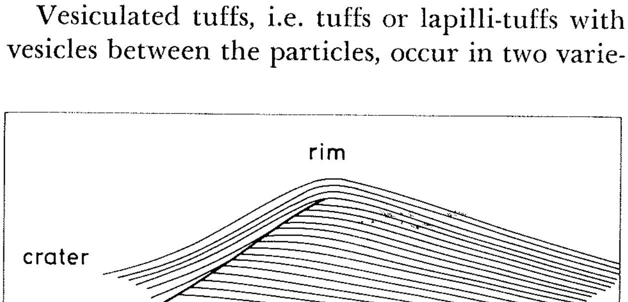

Fig. 3. Schematic cross-section through rim of tuff-ring similar to Surtur I E rim.

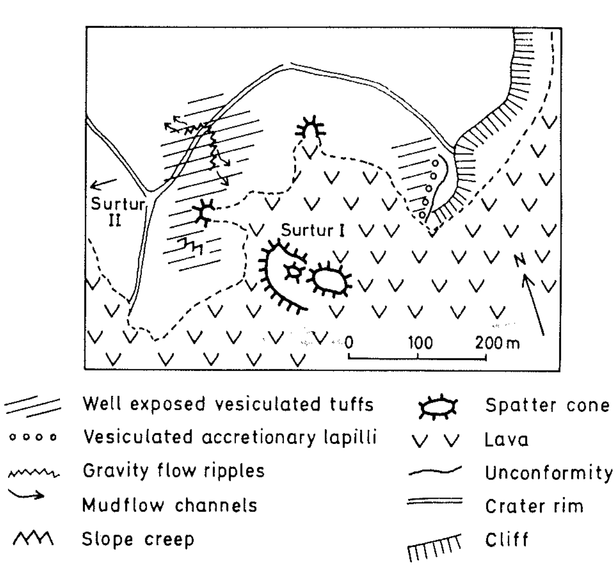

Fig. 1. Index map of Surtur I.

Fig. 4. Mudflow channels at upper part of Surtur I NW inner slope.

effects the ceiling of many vesicles, especially the larger ones, earlier than the main part of the rock. If heat keeps rising long enough on Surtsey palagonitization of the whole rock will ultimately give rise to amygdaloidal tuffs.

Vesiculated tuffs are an excellent indicator of phreatomagmatically formed base surges (Lorenz 1974) which are known to have taken place on Surtsey (Moore 1967, Thorarinsson et al. 1964).

MUDFLOW CHANNELS

On the W rim of Surtur I there is a graded vesiculated tuff layer, a few cm thick, that can be traced from the inner crater wall over the rim onto the outer wall. On the rim where the bed dips less than 20° there are no associated surface phenomena. On both the inner and outer crater wall, however, this vesiculated bed displays mudflow channels at dips greater than 20° (fig. 1). At an angel of approximately 20° there are only small and faint channels 1-3 cm wide. At a dip of approximately 25° they are more frequent, wider, and deeper. Typical mudflow channels are 6-8 cm wide, several cm deep (up to 5 cm), and have marginal ridges, 1–3 cm high, that are lined with finegrained ash to give a smooth surface. Some channels unite to form larger ones (fig. 4) and some show meandering. Inside the channels there are faint ridges their convex side pointing downslope. Accretionary lapilli and the overlying also vesiculated bed fill and cover the channels the latter without showing any depressions above the channels at its own surface. This clearly indicates that the channels formed immediately after deposition of the vesiculated tuff, and that the ash layer gave off excess water and formed the mudflow channels prior to deposition of the next younger layer. It is assumed that this particular bed approximately contains 20–30 vol% of water at the time it was deposited by a base surge (Lorenz 1974).

At dips greater than 35° (at the inner slope) the whole bed broke up into fragments several cm to 20 cm in size and began to slide down the slope as a mass of these fragment (fig. 5). Some of the fragments even indicate that prior to sliding the bed formed small gravity flowage ripples of a type described below. The slide also affected some of the underlying, coarser-grained beds. Even farther down the slope some remains of larger mudflow channels, up to 50 cm wide, can be recognized on this particular bed.

RIPPLE LAYER

One ash layer, 6–8 cm above the just described one, is also developed as a graded vesiculated tuff and is 1–4 cm thick. It contains particles up to 5 mm at its base whereas at the top the ash is very fine-grained. In the upper 0.3 to 1 cm there are vesicles up to 1-2 mm in diameter. Some vesicles are inclined downslope and indicate a small degree of shear movement owing to slight downslope flow. In the lower part of the bed the vesicles may be interconnected and reach 0.5 cm in size.

At the top of the rim there are no surface phenomena associated with this bed. Several tens of meters down the outer slope where the slope reaches an angle of 15-20° there are faint signs of ripples elongated parallel to the slope. With increase in slope angle the ripples become more pronounced (fig. 6) and asymmetric. Their wavelengths are 3-8 cm, the amplitudes up to 1 cm with the downslope sides being steeper and shorter than the upslope sides. With increase in slope angle the wavelength of the ripples decreases slightly.

From the rim towards the crater this bed increases in grain size slightly. And the vesicles become fewer and finally disappear nearly completely probably as a result of the increasing ease of escape of the gas phase in the coarser ash. The ripples also are less well developed on the uppermost part of the inner crater wall and disappear completely downslope.

The overlaying bed covers the ripples without showing irregularities at its own surface indicating that the ripples formed prior to its deposition. Ripples of this type associated with vesiculated tuffs were already interpreted as the result of very wet ash being deposited on a slope by a base surge and consequently starting to flow downslope because of its high water content (Lorenz 1970). Beds of this type are also considered to have contained, at the time of their deposition, 20-30 vol% of water (Lorenz 1974).

JOINTS

Approximately 1 m above the unconformity as well as in the W part of the Surtur I crater bowl pyroclastic beds, both vesiculated and non-vesiculated, show joints antithetic to slope and bedding (fig 1, 7). These joints are similar to those described by Fürlinger (1972) in slaty quartzphyllities and interpreted by him, likewise, as a result of slope movements. This jointing is restricted to specific bed sequences and covered by undisturbed ash layers. These beds, therefore, already must have acquired a certain degree of consistency and hardness to react in such a manner prior to deposition of the younger beds. Hardening of the ash immediately after its deposition and some drying, again probably due to a specific water content (Carr 1969), is suggested to explain this mechanical behavior.

VESICULATED ACCRETIONARY LAPILLI

Approximately 3 m above the unconformity at the SE edge of the Surtur I crater rim there is a layer 3-5 cm thick, and dipping 30-40° towards the crater centre. This bed contains many accretionary lapilli. They vary in size from 0.5-3.5 cm and contain as a core a piece of basalt. The outer layer, 1-6 mm thick, consists of vesiculated tuff the vesicles reaching 0.2–0.5 mm in diameter, rarely 1 mm (fig 8-9). The accretionary lapilli are found in flat accumulations the largest accretionary lapilli lying downslope and the smaller ones having accumulated behind them upslope. This seems to indicate their having rolled and slid downslope to some extent.

Halfway up the inner slope, i.e. slightly farther away from the source of eruption, the accretionary lapilli of this bed, which at this locality dips with approximately 40° towards the crater, become smaller in size, reaching only 1.5 cm, and the amount of vesicles in the outer layer decreases. Even higher up the slope the vesicles nearly disappear and the accretionary lapilli decrease to 0.5-1 cm in size.

At this last locality only, the vesiculated tuff bed underlying the accretionary lapilli shows

Fig. 5. Slide of mudflow-channel-layer at upper part of Surtur I NW inner slope.

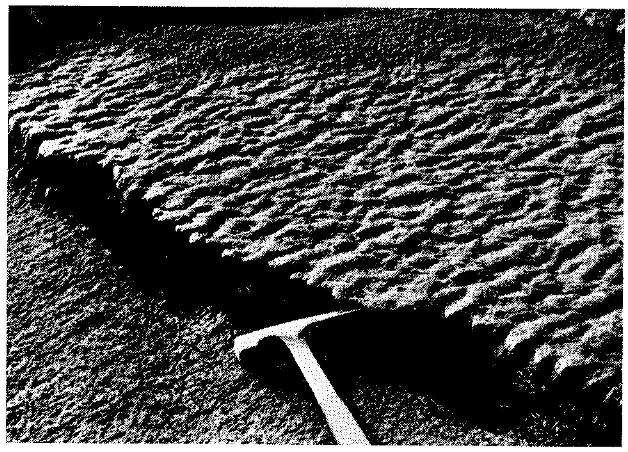

Fig. 6. Ripple layer at uppermost part of NW outer slope of Surtur I.

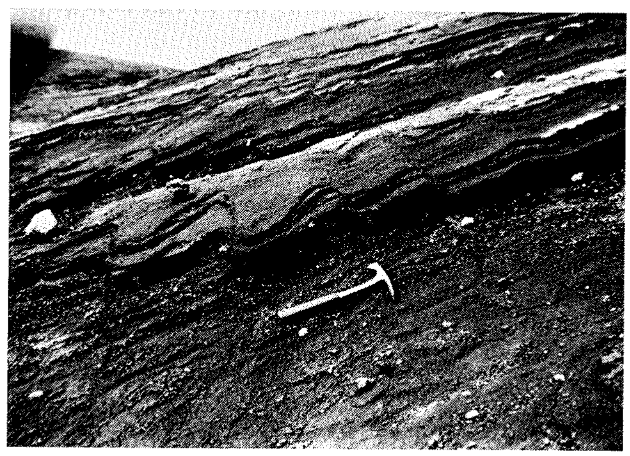

Fig. 7. Joints at upper part of NW inner slope of Surtur I.

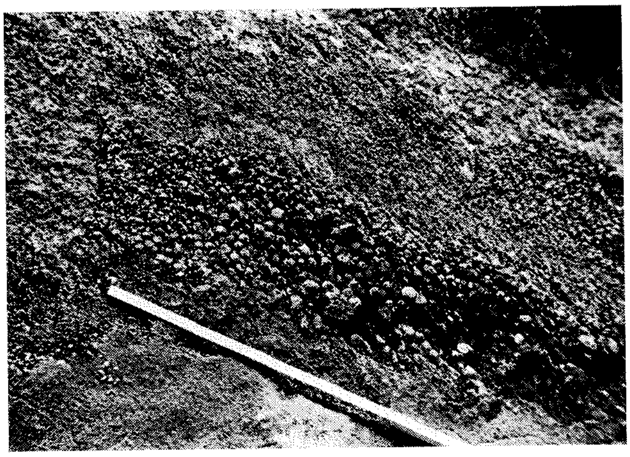

Fig. 8. Accumulation of vesiculated accretionary lapilli approximately 3 m above lower part of unconformity, SE edge of Surtur I rim, left side is upslope.

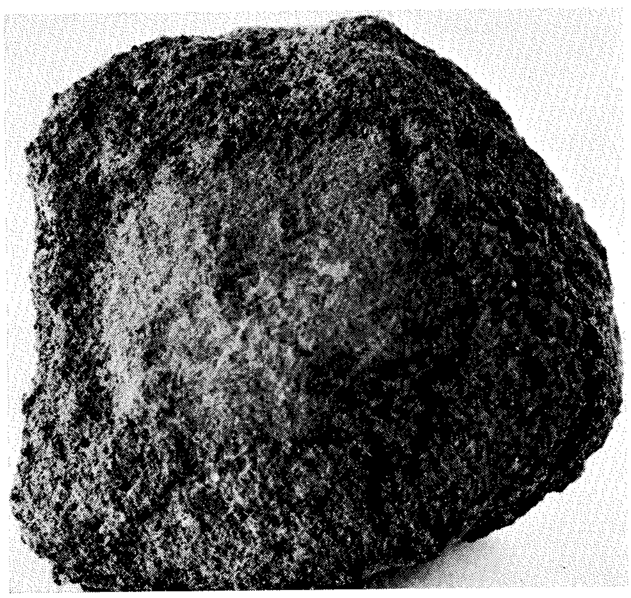

Fig. 9: Vesiculated accretionary lapilli, same locality as fig. 8, diameter of lapilli is 2.5 cm.

pronounced linguoid flowage ripples the lee sides of which are oriented downslope. These ripples are also thought to have formed as a result of gravity flowage owing to a very high content of water in the newly deposited vesiculated base surge deposit.

Elsewhere vesiculated accretionary lapilli have been observed only at the tuff-rings Hverfjall and Ludent, and in palagonite tuffs at Askja. Their formations points to very rapid accretion of ash around a core within a very wet eruption cloud (maybe even within a base surge), i.e. an eruption cloud of phreatomagmatic origin like the Surtsey eruption clouds (Lorenz, 1974).

CHANNELS

Relatively few radial base surge channels are found exposed on Surtsey (fig. 12). 3 channels exist at the N rim of Surtur II and are 3-5 m wide and 10-20 cm deep. The largest channel, however, is exposed in the small ridge NE of the Surtsey hut. It is approximately 20 m wide and has a maximum depth of 1 m. The tuffs and lapilli-tuffs within the channels are characterised by a decrease in thickness and grain-size of the individual layers towards the margins of the channels.

IMPACT STRUCTURES

Below the unconformities most blocks and bombs do not show impact sags in the underlying beds. This indicates that they were emplaced by base surges.

There are a few beds above the unconformity of Surtur I, especially near the top of the SW rim, with many bombs and blocks that indented the underlying beds on impact, i.e. they landed ballistically (fig. 10). The bedding sags are commonly elongated with their long axes oriented radially to the crater centre of Surtur I. This would indicate that the blocks and bombs were ejected from Surtur I. Jakobsson (1972, personal communication) points out, however, that the ash of the youngest layers of Surtur I, at least in part, was erupted from Surtur II. The only explanation in this case would be that the blocks and bombs, after having been ejected from Surtur II onto the upper inner crater wall of Surtur I, started to slide down the slope to a small extent.

Where the bed has just been eroded the blocks and bombs are still attached to the ground (fig. 10) and surrounded by a rim that represents the deformed remains of the ash layer into which the ejecta impacted. These crater rims, therefore, must have been compacted and hardened on impact in order to be more resistant to erosion. Such impact sags are indicative of wet, cohesive ash were the bedding is preserved but deformed plastically upon impact (Lorenz et al. 1970; Waters & Fisher 1970).

CAULIFLOWER BOMBS

In the final tuff layers of both Surtur I and II there are many cauliflower bombs whereas hardly any were observed in the older tuffs in both cliffs.

Cauliflower bombs were first described by Nakamura & Krämer (1970) from a maar in the Eifel (Germany) where they especially mention their "characteristic particulate structure: the scoria is broken up locally (around the rim and in wedges) into subangular fragments, but these fragments are weakly to firmly welded together". Nakamura & Krämer also point out that this structure is "Included in the product of phreatomagmatic explosions" which is confirmed by the author's studies. So far they are known from most maars in the Eifel and Massif Central and tuff-rings in Iceland.

Typical cauliflower bombs (fig. 11) are, in general, round and have a surface resembling cauliflowers (term suggested by H. U. Schmincke 1971). Similar to breadcrust bombs fractures extend for a few mm or cm into the bombs. The crust is thus devided into subangular to round, bud-like fragments that adhere weakly to firmly to the bomb depending on the extend of continuity with the bomb. At the bottom of some fractures of a few cauliflower bombs vesicles are elongated at right angle to the length of the fracture indicating that the fractures were formed while the interior of the bomb was still fluid. Some threads of pele's hair, up to 1 mm long adhere to the walls of the fractures and rarely extend across the fracturs from wall to wall. Cauliflower bombs from Jólnir, collected by the author in June 1966 on Surtsey also display many small threads of pele's hair.

The surface of the cauliflower bombs consists of a layer, one to several mm thick, of shiny sideromelane whereas the interior is made of tachylite. Vesicles in the sideromelane layer increase in size from the surface towards the interior of the bombs and are rather round whereas the more frequent vesicles of the interior part of the bombs are slightly irregular in shape and much more frequently interconnected.

All this indicates that the surface of the bombs was formed while the interior was still fluid and exsolved gas. The surface was chilled and solidified very rapidly as pointed out by the existance of the sideromelane crust.

Many cauliflower bombs on Surtsey have the typical surface pattern on one side only, the other side being rather flat. Impacted bombs, investigated in situ, clearly show that the flat side is the side with which the bombs had impacted and which consequently deformed. Extremely deformed bombs may reach 16 cm in maximum diameter and only 3-4 cm in minimum diameter. This deformation could only have taken place if the interior of the bomb had not yet solidified at the time of impact so the whole bomb reacted plastically. The surficial crust, the result of a certain degree of chilling, could not prevent deformation of the whole bomb, i.e. chilling could not have been very intense. On the other hand, however, chilling must have been intense enough

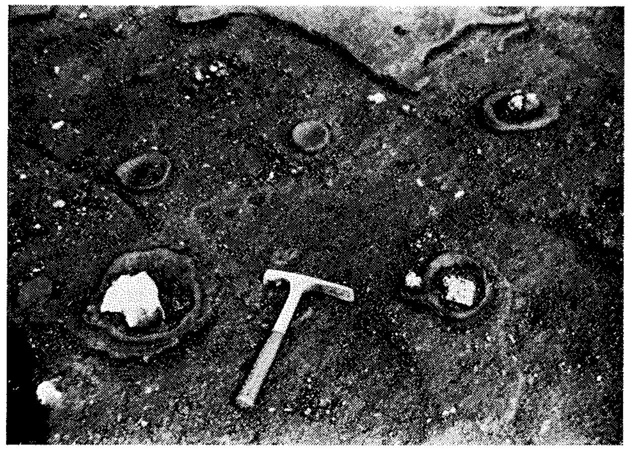

Fig. 10. Impacted blocks and bombs with impact craters at upper part of NW inner slope of Surtur I.

Fig. 11. Cauliflower bombs from final phreatomagmatic layers of Surtur II.

Fig. 12. Small channel in NE upper slope of Surtur I rim.

to prevent disintegration of the bomb during flight and impact.

Rarely the bombs contain small fragments of basalt of slightly different state of crystallization and/or vesiculation. Cauliflower bombs of the Eifel and Massif Central maars typically contain many chips of country-rocks that were caught up in the eruption channel during intense wall-rock spalling ,prior to formation of the bombs. In the eruption channel of tuff-rings that have a shallow magma/water contact level wall-rock spalling seems to be much less intense than in maars (Lorenz 1973), and probably therefore, fewer xenoliths are incorporated in the respective bombs.

These and other studies in Iceland, Eifel and Massif Central suggest that cauliflower bombs only form if there is not a very good contact between magma and water, or not very much water contacting the magma. The magma erupts inside the eruption channel forming the bombs which only subsequently contact water and become chilled. On Surtsey rapid chilling accounts for the sideromelane crust and the typical surface pattern whereas the fluid interior still exsolved gas and solidified slightly less rapidly after impact forming tachylite.

DARK LAYERS

Near the top of Surtur II rim and on the ridge between Surtur I and II there is a coarse dark layer, 20-30 cm thick, that is very rich in bombs, blocks, and vesicular black juvenile lapilli. The blocks consist in part of basalt pillow fragments, marine sediments etc. In addition to many cauliflower bombs there are a few cow-dung bombs, some of them reaching a maximum diameter of 1.25 m.

Approximately 4 m higher up on Surtur II W rim there is a second dark layer, 0.5-1 m thick and very rich in cauliflower bombs and vesicular black juvenile lapilli. In addition to the cauliflower bombs and cow-dung bombs some ordinary basaltic scoriaceous bombs with smooth or bread-crust surfaces are found. Country-rock fragments from the sea-floor are frequent too.

The juvenile lapilli of these two layers contrast to the ones of the other lapilli-tuffs of Surtsey in so far as they are, in general, several cm in size, and relatively more vesicular. The core is made up of vesicular black tachylite, whereas the rim consists of 1 to several mm thick, shiny, yellowish-brown sideromelane, that is slightly less vesicular than the tachylite. Thus even these lapilli were chilled rapidly only at their surface whereas their interior cooled and solidified less rapidly. The interior resembles ordinary cinder, i.e. the magma was in the process of high-level vesiculation and eruption when the eruption products contacted some sea-water. The relatively small amount of sea-water consequently chilled only the surface whereas the interior of the lapilli was less effected.

The ordinary basaltic bombs, cow-dung bombs and cauliflower bombs as well as the vesicular black juvenile lapilli all indicate that during their formation there was only little contact between sea-water and magma. Thorarinsson (1965, 1967) in fact, points out that magma could only reach the surface of the tuff-ring Surtur II after the sea could not breach the crater rim anymore. Close to the end of the phreatomagmatic activity the crater rim was breached repeatedly by the sea. Juding from the final deposits there must have been two periods where the magma nearly reached the surface and, at this shallow level, contacted during its own eruption only a minor amount of sea-water. The already formed bombs and lapilli then were chilled rapidly only to the extent that their surfaces solidified into sideromelane whereas their interior stayed fluid slightly longer depending on the size of the particles.

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