LAVA-COOLING OPERATIONS DURING THE 1973 ERUPTION OF ELDFELL VOLCANO, HEIMAEY, VESTMANNAEYJAR, ICELAND[1, 2, 3]

by

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U.S. GEOLOGICAL SURVEY OPEN-FILE REPORT 97-724

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EDITOR'S INTRODUCTION

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Diversion of Lava Flows: A Brief Review

In order to protect public and private property from being destroyed by lava flows, various plans and actual attempts have been made in the past on volcanoes to stop or divert lava flows, including Mount Etna, Sicily, Italy; Kilauea and Mauna Loa volcanoes, Hawaii, Hawaii,and Eldfell volcano, Heimaey, Vestmannaeyjar, Iceland (Bolt and others, 1977; Blong, 1984; Appendix No. 2). The lava-cooling operations on Heimaey, Iceland were, however, the most extensive ever attempted, and the two excellent accounts of the operations that were published in Icelandic by a geophysicist and two engineers are translated into English in this open-file report. Birgir Jónsson (1993) also published a report on the use of dikes to divert lava flows; he mentioned past attempts in Italy, Japan, Iceland, Samoa, and Hawaii, but devoted most of his paper to presenting a case study of the 1973 eruption on Heimaey.

Lava-diversion attempts have been carried out in Hawaii on several occasions (Moore, 1982; Macdonald, 1972; Macdonald and others, 1986; Lockwood and Romano, 1985; Heliker, 1992; Appendix No. 2). The U.S. Army Air Corps carried out aerial bombing of lava flows from Mauna Loa in 1935 and 1942; the results were considered inconclusive, because the lava flow stopped at about the same time as the bombing operations. On 1 December 1975, 8 April 1976, and 4-5 May 1976, the U.S. Air Force carried out bombing experiments on Mauna Loa lava flows and craters using various types and sizes of bombs.

Moore (1982), in a U.S. Geological Survey open-file report, discusses lava-diversion barriers on Mauna Loa volcano and provides a comprehensive list of references pertaining to diversion of lava flows in Hawaii. The 1986 and 1987 effusive eruptions from Pu'u O'o on the East Rift Zone of the Kilauea Volcano Hawaii, destroyed several homes in the Kalapana area. In November 1986, attempts were made by local firemen to prematurely chill and divert lava flows around one home by spraying freshwater from the municipal water system onto the advancing margin (John Lockwood, 1987, personal communication), but the attempt failed because of the volume of lava. [As of late 1997, lava flows from the East Rift Zone continue to overrun homes and land in Kalapana and environs.]

Translation of Icelandic Reports

Because of the success of the Icelanders in their massive lava-cooling operations during the 1973 eruption of Eldfell volcano within the town of Vestmannaeyjar, on the island of Heimaey, in the Vestmannaeyjar archipelago, Iceland, I decided that English translations of two relevant reports by Icelandic scientists and engineers on the lava-cooling operations would be useful to volcanically active regions, where access to water (river, lake, or ocean) could provide the basis for lava-cooling operations. Several developed locations on the island of Hawaii could be candidates, including lava flows from Mauna Loa into Hilo and environs, lava flows from Hualalai along the Kona coast, etc. The two translations, one from a newspaper article, the other from an engineering journal, provide English-speaking scientists access to these important reports.

The first report appeared in the Reykjavik newspaper *Tíminn* [The Times] on Saturday, 19 January 1974, pages 8, 9, and 13 (Þorbjörn Sigurgeirsson, 1974). The newspaper article is based on a lecture given by Prof. Thorbjörn Sigurgeirsson (1917-1988) at the Nordic House (Norrænna húsið) in Reykjavík, Iceland, on 4 November 1973, approximately 4 months after eruptive activity ceased on the island of Heimaey, Vestmannaeyjar, Iceland (fig.1). Thorbjörn Sigurgeirsson, in January 1967, had previously carried out limited experiments on the north coast of Surtsey, Vestmannaeyjar, where water was sprayed onto a lava flow that was advancing into a lagoon near the scientific observation hut, Pálsbær [named for Prof. Paul S. Bauer (1904-1977) of American University, Washington, DC, co-founder and financial benefactor of the Surtsey Research Society]; the experiment proved that an advancing lava-flow front could be prematurely solidified, thereby impeding further advance of the lava as long as the flow rate was not too high. When the volcanic eruption on Heimaey threatened the town of Vestmannaeyjar, and it appeared likely that the harbor would be closed off by lava flows, Thorbjörn Sigurgeirsson became a strong proponent of spraying sea water on the lava flows to prematurely cool the lava flow fronts. The congealed lava would perhaps create a barrier to the upstream lavas, thereby sparing the harbor and also lessening the damage to public and private structures in Vestmannaeyjar.

In his lecture, Thorbjörn Sigurgeirsson, who, at the time, was a professor of physics at the University of Iceland's Science Institute, draws from his personal observations and experiences during the course of the catastrophic volcanic eruption on Heimaey between 23 January 1973 (start of the eruption) and early July 1973 (end of the eruption). The lava-cooling operation began on 7 February 1973, and ended on 10 July 1973. The original lecture published in *Tíminn* included five photographs. Figures 2 and 3 are index maps to the volcanic archipelago (Vestmannaeyjar) and Heimaey and to the Town of Vestmannaeyjar on Heimaey, respectively, that I have included in this introduction to provide reference maps for scientists unfamiliar with the geography of Heimaey and its geographic place-names. Thorbjörn Sigurgeirsson (1974) also published an account in English about the lava cooling operations on Heimaey in a travel magazine.

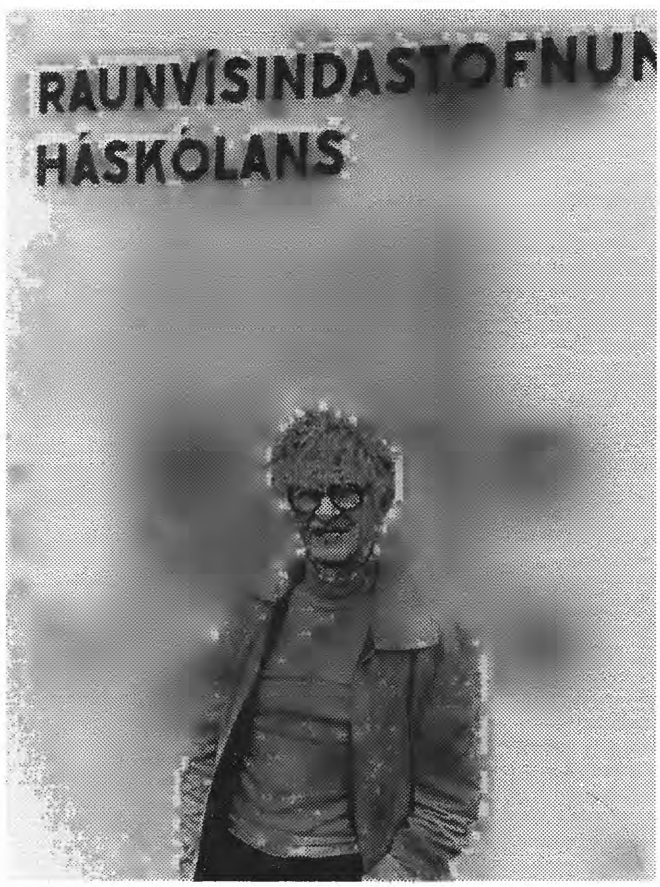

Figure 1. Photograph of Próf. Þorbjörn Sigurgeirsson (1917-1988) in July 1983 outside the Science Institute of the University of Iceland. Photograph by Richard S. Williams, Jr., U.S. Geological Survey. The Tíminn article included a different photograph of him.

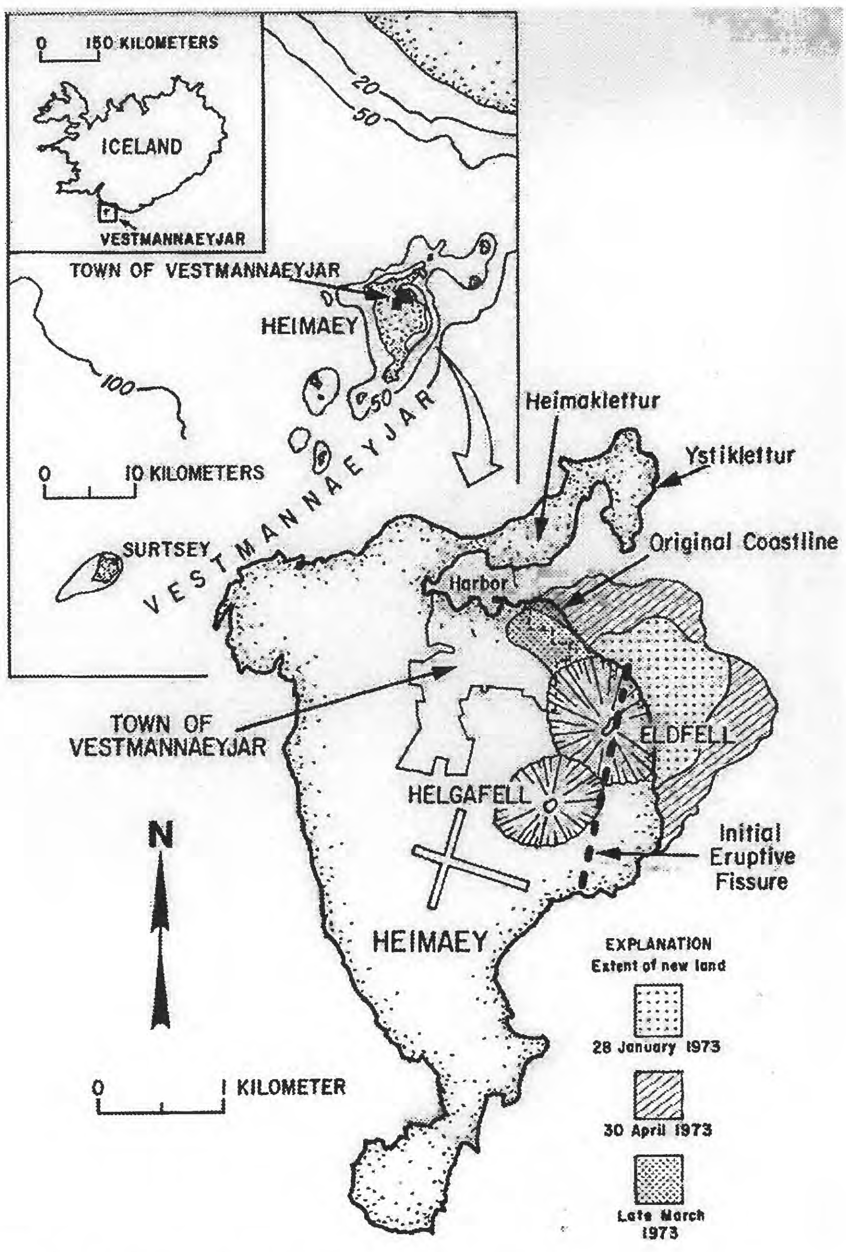

Figure 2. Index maps of Iceland, the Vestmannaeyjar volcanic archipelago, and the island of Heimaey with the fishing community of Vestmannaeyjar. (Modified from Williams and Moore, 1976 a, b and 1983, and the National Land Survey of Iceland, 1979.)

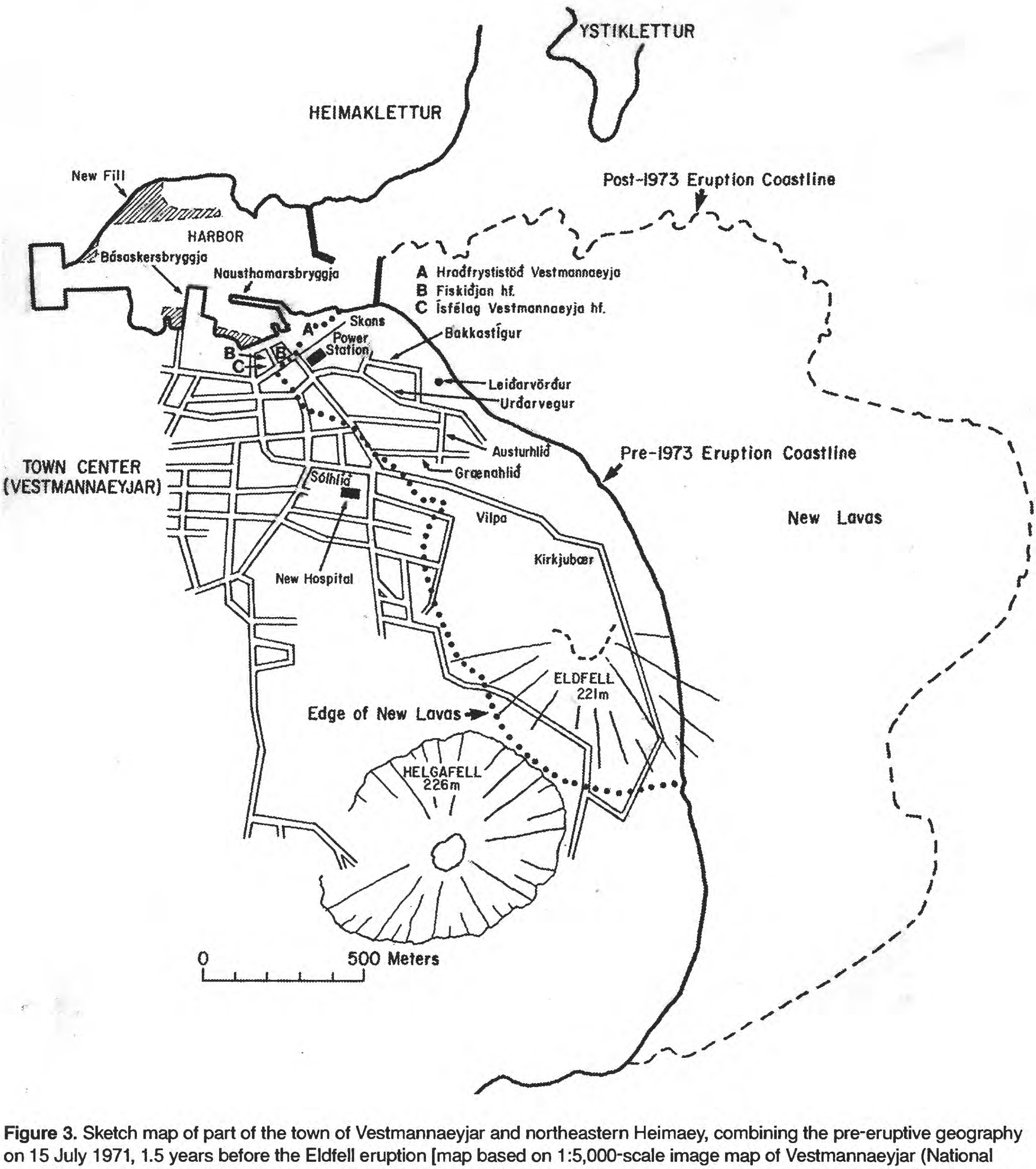

Figure 3. Sketch map of part of the town of Vestmannaeyjar and northeastern Heimaey, combining the pre-eruptive geography on 15 July 1971, 1.5 years before the Eldfell eruption [map based on 1:5,000-scale image map of Vestmannaeyjar (National Land Survey of Iceland, 1973 a) and special 1:100,000-scale line map of Heimaey and Vestmannaeyjar (National Land Survey of Iceland, 1973 b)] with post-eruptive geography on 27 July 1977, four years after the eruption ended [map based on 1:50,000-scale topographic map and 1:10,000-scale orthophotomap of Heimaey and Vestmannaeyjar, respectively (National Land Survey of Iceland, 1979).]

The second report is a technical paper by the engineers, Valdimar Kr. Jonsson and Matthias Matthiasson, that was published in the *Tímarit Verkfræðingafélags Íslands* [Journal of the Icelandic Association of Chartered Engineers] in 1974 (Valdimar Kr. Jónsson and Matthías Matthíasson, 1974). Their paper is the best and most complete description available of the technical aspects of the water-cooling operations on Heimaey, during 1973. At the end of their paper are translations of the editorial comments by Páll Lúðvíksson, Editor of the journal, and brief biographical sketches of the two authors, all of which were included in v. 59, no. 5, of *Tímarit Verkfræðingafélags Íslands* (Appendix No. 1).

The lecture on "Lava Cooling" by Thorbjörn Sigurgeirsson and the companion journal article, "Lava Cooling on Heimaey - Methods and Procedures," by Valdimar Kr. Jónsson and Matthías Matthíasson, aside from their significant contributions to scientific-and-engineering knowledge of the effect of water on the rate and process of cooling of lava flows, have had an important practical application. Knowledge gained from the water-cooling operation during 1973 was directly applied to the construction of a district-heating system for the town of Vestmannaeyjar on Heimaey, in which thermal energy was extracted from the cooling lavas. During the latter part of 1973 and early 1974, scientists and engineers from the University of Iceland, residents of Vestmannaeyjar, and the Icelandic engineering firm, Verkfræðistofa Guðmundar og Kristjáns hf., prepared the conceptual basis for the creation of the district-heating system. Initial experiments were begun in 1974, but it was not until late 1979 that the final engineering design for the system was approved.

By 1983, a 5 megawatt heat-exchanger plant, in which steam produced by spraying water on cooling lava flows at depth in the eastern part of the new lava flows, was circulating hot water to more than 50 percent of the buildings in Vestmannaeyjar. As with the record of the 1973 lava-cooling operations on Heimaey, most of the literature written about the district heating system is only available in Icelandic. A brief, illustrated summary of the system is included in the second edition of the U.S. Geological Survey scientific leaflet, "Man Against Volcano: The Eruption on Heimaey, Vestmannaeyjar, Iceland" (Williams and Moore, 1983), in an article and a paper by Sveinbjörn Björnsson (1980, 1987), in an unpublished mimeographed report (Anonymous, 1982), and in a paper by Þorbjörn Sigurgeirsson (1982).

John McPhee's Account

John McPhee, a well-known natural-history and science writer, took a special interest in the cooling of the lava flows on Heimaey from the viewpoint of interaction of human activities with volcanic processes and from the perspective of the many individuals, scientists and laypersons, whose lives were touched by the Eldfell eruption. McPhee (1988 a, b) wrote a two-part article for *The New Yorker* magazine; the articles were later combined to make a chapter in one of his books (McPhee, 1989).

Movies About the Eldfell Eruption

Several movies about the 1973 volcanic eruption on Heimaey have been made, including two half-hour films by professional cinematographers and several by amateurs (field scientists); only one of the amateur films is included in the synopses of the three half-hour films provided in the following section.

Days of Destruction (27 min.)
Producer: Kvikmyndagerðin Hljóð og mynd, Skúlagötu 61, IS-101 Reykjavík, Iceland; color, sound, English narration.

The film chronicles the eruption on Heimaey in 1973 and the effect it had on the inhabitants of the prosperous fishing village. The footage, depicting the eruption, lava flow, and tephra fall is excellent. A good deal of the film concerns the problems of the citizenry faced throughout the duration of the eruption. These include relocation, salvage of personal property, damage to buildings caused by fire, tephra fall, and advancing lava, and the possible obstruction of the harbor mouth by the advance of the lava. While there is some lack of scientific data, the shock and pain experienced by the islanders is transmitted exceptionally well by the film. The film ends with the unanswered question of what the former inhabitants of Heimaey are to do in the future.

Fire on Heimaey (Eldur í Heimaey) (28 min.)
Producer: VÓK-Film hf., Hellusundi 6A, IS-101 Reykjavík, Iceland; color, sound, English narration; available also in videocassette format.

The film covers the same event as *Days of Destruction,* above, but goes farther chronologically. The major difference between these two films is the extent to which the problems of the inhabitants of Heimaey are covered. This film spends less time on that, concentrating more on the physical phenomena of the eruption. The human element is included but not belabored. The struggle of the Icelanders to halt the advance of the lava and save the town is documented. A great advantage that this film has over the other is that it includes reclamation efforts begun by the Icelanders after the eruption ended. This film ended on a definitely optimistic tone, with the prodigous efforts to reclaim the town proving successful. This film is by far the most complete one covering the 1973 Heimaey eruption. Along with superb photography by the late Ósvaldur Knudsen, is the excellent commentary, written by the late Prof. Sigurður Thórarinsson, the famed Icelandic geomorphologist and tephrochronologist.

The Heimaey Eruption: Iceland 1973 (28 min.)
Producer: Prof. Alan V. Morgan, Department of Earth Sciences,
University of Waterloo, Waterloo, Ontario N2L 3GI Canada;
color, sound, English narration; available also in videocassette format.

The film portrays some of the events following the eruption of the volcano Eldfell in 1973 on the island of Heimaey off the south coast of Iceland. The film was made in three sections; the first depicting the town of Vestmannaeyjar at the end of January shortly after the 5,000 inhabitants had been evacuated. The second section illustrates scenes in mid-April, approximately two weeks after a major lava surge had destroyed a large part of the town. The third part shows the recovery made by the islanders in mid-July. The spacing of the film sections was deliberately set at three-month intervals.

Acknowledgements

The editor would like to acknowledge the technical reviews of and suggested additions to the Introduction and two translations by Sveinbjörn Björnsson, University of Iceland; Henry J. Moore, U.S. Geological Survey; and especially Oddur Sigurðsson, National Energy Authority, who markedly improved the translation of the article by Þorbjörn Sigurgeirsson. Sigrún Rockmaker did her usual superb translation of the technical paper by Valdimar Kr. Jónsson and Matthías Matthíasson.

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Metric Units of Measurement

The metric units used in this publication can be converted to English units by using the approximate conversions given below:

Length
1 kilometer (km) = 0.62 miles (mi)
1 meter (m) = 3.28 feet (ft)

Volume
1 liter (l) = 0.035 cubic feet (ft^3)
1 cubic meter (m^3) = 35.3 cubic feet (ft^3)

Area
1 square kilometer (km^2) = 0.386 square miles (mi^2)
1 square meter (m^2) = 10.76 square feet (ft^2)

Mass
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 2,200 pounds (lb)

Flow
1 liter per second ($l\ s^{-1}$) = 0.035 cubic feet per second ($ft^3\ s^{-1}$)
1 cubic meter per second ($m^3\ s^{-1}$) = 35.3 cubic feet per second ($ft^3\ s^{-1}$)

Temperature
To convert °Celsius to °Fahrenheit, multiply °C by 1.8 and add 32

LAVA COOLING[1]
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Introduction

When lava fields in Iceland are examined, it becomes evident that lava flows can be quite varied, and that the area covered by each is different. Sometimes lava will flow for a distance of 100 km, while at other times it does not extend 1 km beyond its source (fig. 4).

Among the factors that have an important effect upon the areal extent of lava flows are the viscosity of the lava mass, its total volumetric output, the speed of its formation, and the geomorphic character of the terrain. A steep slope permits the lava to flow farthest from its source, but experience has shown that lava can still flow very far on nearly flat ground, as, for example, in Flói [slope gradient of ≤ 1:500; the region between the Ölfusá and Þjórsá (rivers) in southwestern Iceland]. The lava outflow which occurs during a volcanic eruption becomes centered in a given place, and, as is well known, this unavoidably causes changes in the previous landscape. In some cases the lava comes to rest on the terrain as an extensive lava field; in other cases it piles up in the vicinity of the crater.

It is the viscosity of the lava that governs its ultimate movement. Viscosity depends upon the chemical composition of the lava and the temperature of the molten lava; viscosity increases quickly as the lava cools. The mobility of basalt is at a maximum at temperatures of 1,000 to 1,200 °C when it emerges, but when the lava's temperature has decreased to 800 °C it firmly solidifies and does not flow any more. How far the lava reaches before it solidifies depends, therefore, upon the velocity of flow and the rate of cooling. [Editor's note: Volatiles are also an important factor.]

In some cases, cooling begins before the lava erupts from the crater. This happens in submarine eruptions and in subglacial eruptions, where water has access to the eruptive fissure or crater vent. Contact between the water and the viscous magma is dominated by gas bubbles released from the lava that combine with steam and boiling water. Cooling could then be so

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[1]Þorbjörn Sigurgeirsson, 1974, Hraunkæling [Lava cooling]: *Tíminn*, 19 January 1974, p. 8, 9, and 13. Slightly revised version of a lecture given by Prof. Thorbjörn Sigurgeirsson at Norræna húsið [Nordic House], Reykjavík, Iceland, on 4 November 1973. English translation by unknown U.S. Department of State translator. Additional translation and edit by Richard S. Williams, Jr., U.S. Geological Survey, Woods Hole Field Center, Woods Hole, Massachusetts 02543-1598.

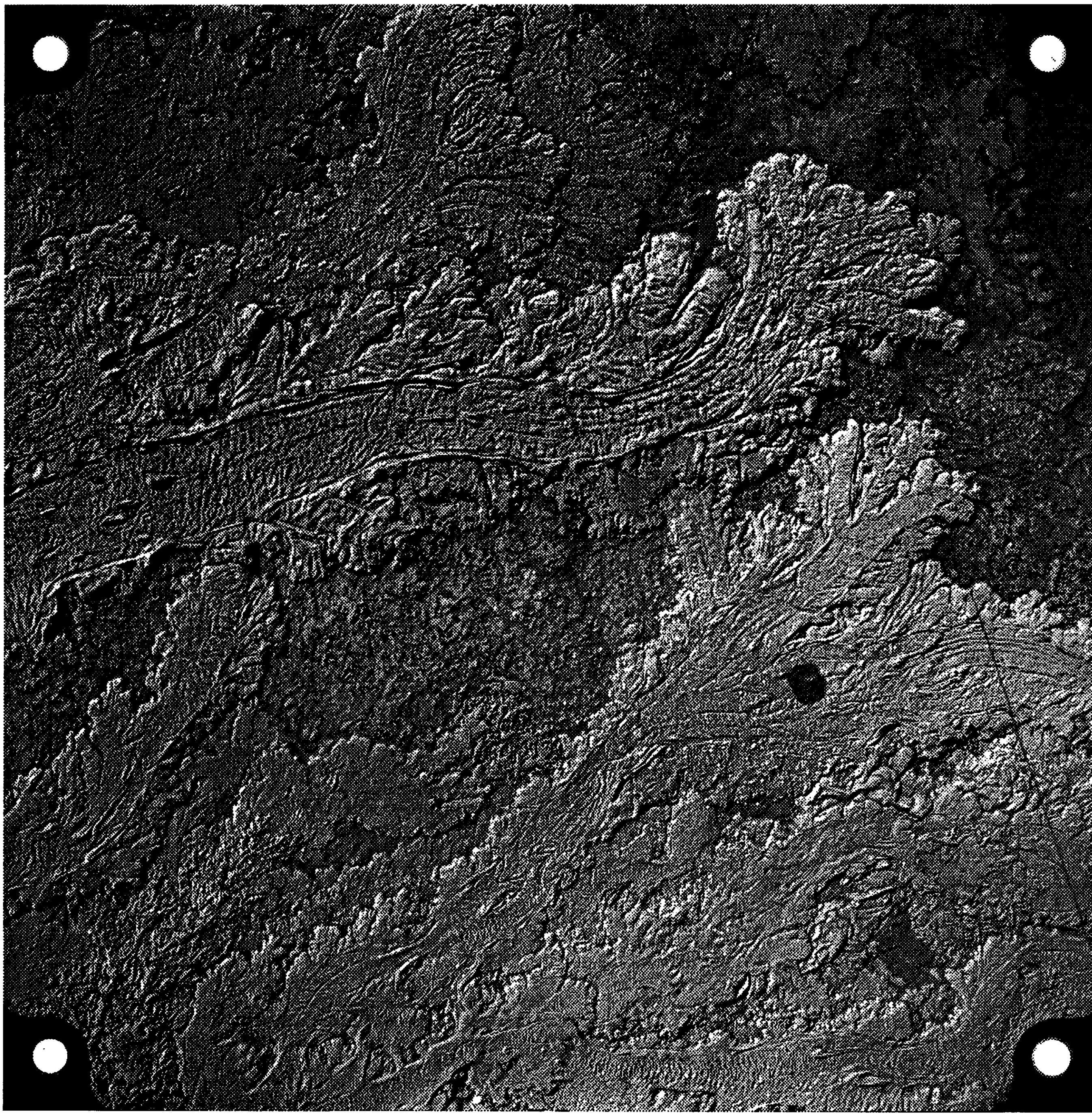

Figure 4. Branching lava flows at Heiðmörk, southeast of Reykjavík in southwestern Iceland. Vertical aerial photograph courtesy of the National Land Survey of Iceland.

rapid that no molten lava manages to flow out from the vent, but, rather, the lava is ejected as scoria or [finer-grained] ash [all airborne ejecta is collectively called tephra] from the eruptive vent of fissure. Examples of this are the eruption of Surtsey, where the sea had direct access to the eruption fissure and crater vent, the eruptions of Katla (a subglacial volcano under the eastern part of the Mýrdalsjökull [ice cap] in southern Iceland) and also the many palagonite (hyaloclastite) ridges that formed from volcanic eruptions during the Pleistocene [and Holocene Epochs, collectively known as the Quaternary Period, a span of 1.6 million years]. Some minor cooling could also take place when fragments of lava are thrown into the air and then fall back into a crater.

After lava has flowed from a crater [or fissure] and expels most of the gas, its agitation diminishes, and cooling slows down. Because of the solid crust that develops on the surface of lava flows, a powerful lava stream flowing forward into the sea can move for a distance along the seafloor just as on land. A slow lava stream, on the other hand, cools when it reaches the sea. A piling up takes place at the coast, and the molten lava is forced to flow on top of the pile-up. Below the surface of the sea, a lava-flow front has the slope angle of scree.

One sort of natural lava cooling is the so-called "pseudo" volcanic eruption that is known from places where lava flows into very shallow water, or over marshy ground (for instance, at Skútustaðagígar on the southern shore of Mývatn in northeastern Iceland, or the area around Kirkjubaejarklaustur in southern Iceland). In such cases it is presumed that water is trapped inside the lava or beneath it, and that steam escapes upward into the molten lava proper, where it is often expelled violently, creating groups of pseudocraters. [There cooling occurs in a similar way as craters that receive water from the upper surface.]

Another type of natural cooling was evident during the volcanic activity on Heimaey. At certain places that had previously been covered by the sea, vapor steamed continuously out of the lava. It was evident that in such areas the cooling of the lava impeded the flow, because the leading edge of the lava became indented, behind which the lava piled up due to the pressure from behind. Information regarding this phenomenon is recorded on vertical aerial photographs.

Efforts to reduce damage caused by the force of the lava flow have been made several times, notably in the form of the construction of dikes or ramparts. The protection measures at Heimaey are undoubtedly the most extensive that have ever been used in a volcanic eruption. The chief reliance was upon cooling by water. This method has been tried previously on a small scale in Hawaii in about 1960, where the spraying was done directly on the lava margin and was considered to have produced results [Editor's Note: Bolt and others, 1977; Blong, 1984; Macdonald and others, 1986]. Perhaps an experiment of this kind was also [said to be] undertaken at Mt. Etna (on Sicily, Italy) a few years ago.

During the volcanic activity on Surtsey, a team was organized to test the effect of pumping water onto the lava flow, but the team was forced to turn back because of unfavorable weather.

Sea-water pumping was later tried on a much smaller scale, but this test yielded no results that could be relied upon. The effect of sea-water cooling upon the lava flow at Surtsey was, nevertheless, evident, because the lava flowed for a long distance along the beach and because the surf cooled the lava front, thereby created a protective wall.

Indeed, the effect of water on molten lava has been noted before the last decade (1960's). The biography of the clergyman Jón Steingrímsson indicates that it was evident to him that water did retard the flow of lava.[2] In his account of the Fire Mass held at Kirkjubæjarklaustur (central part of the south coast of Iceland) on the 5th Sunday after Trinity in 1783, he states *inter alia*: "... then God was invoked earnestly, and His judgment pronounced that the fire should not come the width of a foot farther than it has been before the divine service was celebrated, but it should pile up on top of itself in a mound. Thereby all neighboring waters came down upon it, and suffocated it most decisively." [Pastor Jón Steingrímsson was referring, of course, to the Skaftáreldahraun (or lava flows associated with the famous Laki eruption of 1783)[2]].

Nature of the Lava Cooling

Rock is a poor conductor of heat, so that a lava slab 10 m thick is known to be hot for years, if it is [solidly] intact and not fractured, even if its surface is continually cooled by water. Generally, however, lava is fractured; joints are formed during the abrupt cooling that has taken place.

Water has been found to be the most practical means to achieve lava cooling. Water absorbs heat from the lava; even more so, if it heats up to the boiling point and changes to steam. For most efficient cooling it is important that all of the water should be converted to steam and not flow off, down through, or away from the lava. The experience at Heimaey, where the molten lava was actually covered by a thick layer of tephra and scoria shows that near maximum efficiency is often attainable. Jets of water pouring on the same place in the lava flow at the rate of 100 $l\ s^{-1}$ for several days or weeks, showed scarcely any diminution of steam generation. At first the steam generation was intense in the vicinity of the water jets. After a while, evaporation near the jets dropped, but internal movement of water-generated-steam extended in all directions, so that, eventually, one hectare (ha or 0.01 km^2) of lava surface could be covered with a single stationary stream of water.

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[2]Jón Steingrímsson (Rev.), 1973, Eldritið [Volcano essay]; *in* Æfisagan og önnur rit [Biography and other essays]: Reykjavík, Helgafell, p. 339–390. See also Jón Steingrímsson, 1907, Fullkomið skrif um Síðueld [Complete account of the Síðu eruption]; edited by Þorvaldur Thoroddsen; *in* Safn til Sögu Íslands og Íslenzkra bókmennta (Copenhagen and Reykjavík), v. 4, p. 1–73.

Under these circumstances, it is fairly easy to calculate approximately how large a lava mass will solidify due to water cooling. As the water heats up from 10 °C to a temperature of 100 °C, the steam absorbs 630 kilocalories for each kilogram of water that evaporates. Each kilogram of lava that solidifies and cools from 1,100 °C to 800 °C gives off about 190 kilocalories, and it is safe to estimate that lava that has solidified and cooled all the way down to 100 °C releases a total of about 380 kilocalories. This means that each kilogram of water cools 1.7 kilograms of lava, or that each cubic meter of water cools about 0.7 m^3 of lava. This implies that a mass of lava cooling down to 100 °C as the result of contact with an ample source of water rapidly reaches this temperature on its surface. Furthermore, if water cannot enter [easily through] cracks and joints in the rock, cooling proceeds from the outer to the inner parts of the rock before the temperature has fallen below 100 °C.

From the above considerations and figures, one can calculate, on the basis of a water stream flowing at the rate of 100 l s^{-1} over a 6,000 m^2 area of molten lava, under average cooling conditions and conversion of all water to steam, that a solid layer of lava about 1 m thick will form in 24 hours. This cooling rate has been confirmed by measurements taken in drillholes bored into the lava after the water cooling ended [Valdimar Kr. Jónsson and Matthías Matthíasson, 1974]. In the boreholes, the cooling extended down to depths of 13 to 15 m, after cold [sea] water had been poured on the lava for about two weeks. A hole was bored in an area which had not been cooled by water, and molten lava was encountered directly below the surface.

Although water cooling is a comparatively slow process, it would still require a period of time a hundred times longer in order to cool lava to a sufficient depth, if we relied only on the thermal conductivity of the rock.

Therefore, for water cooling to be effective it is concluded that water must penetrate down into the lava through cracks and joints that form during the [initial] cooling period. This conclusion was confirmed when lava was removed from the terminus of a lava flow that had flowed as far as the fish-cannery plant near the harbor. Fracture planes within the artificially cooled lava showed salt encrustation precipitated in all the joints where steam had been generated. Even adjacent to the lava margin the salt encrustation reached down through the lava, showing that the cooling water had penetrated the lava to the bottom. Wherever the cooling water makes contact, the lava also exhibits many fissures. The same could be seen in the lava at Kirkjubær (east of the new hospital) that experienced significant surface displacement during the cooling operations, resulting in the opening of large fissures well into the interior of the lava flows. Apparently water cooling proceeded quickly at depth when lava was in motion, because its motion opened cracks and fissures before cooling was complete.

Summary of Lava-Cooling Operations

After the inhabitants of Heimaey had been safely transported to the mainland (of Iceland) within a few hours of the beginning of the volcanic eruption on Heimaey, relief activities in the town of Vestmannaeyjar were directed primarily at preventing house fires caused by incandescent lava bombs and at clearing the tephra fall from roofs of buildings because of the imminent danger of collapse from the excess weight. It soon became evident, however, that the chief danger was from the movement of lava, presenting a danger not only to the town, but also to the harbor. The harbor was [absolutely] essential to the economic lifeblood of the town [e.g., fishing].

The first attempt at cooling the lava with water was made 15 days after the onset of the volcanic eruption (23 January 1974), when lava started to approach the harbor entrance. Firemen set to work spraying seawater on the edge of the lava from powerful pumps and fire hoses which had been sent by air to Vestmannaeyjar from the fire station at Keflavík International Airport in southwestern Iceland. It was noted that the water had some effect on the lava flow, and that it exerted some control on the movement of the lava-flow front, where the stream of water was initially directed.

These first attempts resulted in an effort to acquire [many more] pumps, pipes, hoses, and spraying nozzles to achieve maximum effectiveness in pumping water onto the lava. Also, bulldozers were used to make protective ramparts directly in the path of the lava moving toward the town. At the beginning of February, the lava was moving mainly towards the sea, but it slowly began to turn north along the coast in the direction of the harbor entrance. At the same time the lava front was forced laterally upon the coast toward the town. The ramparts were extended along the coast from Skans [south of the outermost breakwater; see fig. 3] near Leiðarvarða, southeast to Vilpa [east of the new hospital (nýja sjúkrahúsið)] onto which sections of water pipe were laid. Attached to the primary water pipe were fire hoses that were tipped with the customary fire nozzle to spray water onto the lava margin. The water jets caused rock pillars to push up out of the viscous lava and become separated, making a mound of rubble at the lava front. When the lava front moved imperceptibly towards the rampart, the rubble strengthened the rampart and formed a strong impediment to the advancing lava front, but they did not prevent the molten lava from welling up behind the margin, gradually causing the lava front to grow in height. Molten lava also oozed from the lava front but never traveled very far before being solidified by water. [As a precaution] the movement of the lava front was monitored day and night.

This long and tenacious struggle was maintained for more than a month. By the end of the month, however, the lava front abutted the rampart along its entire length and, at most places, was somewhat above it. The lava front grew to a height of about 20 m and still posed a hazard. A maximum volume of about 100 l s^{-1} of water were pumped on to the 500 m-long lava front, but, because the water ran off the lava before turning into steam, it was not as effective as expected. Where it was desired that the water should reach over the 20-m high lava-flow front to the active lava margin, the pumps were not powerful enough to do so. Also, it was difficult to move water lines up the face of the lava front, because it was steep, loose, hot, and did not solidify quickly enough for hoses to be placed upon the lava margin. The result was that the solid crust on the lava front was always too thin to sustain the pressure of the lava backed up behind it. Later it turned out that the fight at this frontier had no effect on the result because another lateral lava stream eventually ran along the western margin of the lava front.

In the meantime, the lava moved slowly northward along the shore in the direction of the harbor entrance. At first the lava flow was so fast that it ran along the sea bottom. It soon slowed by itself, and the sea took care of the cooling of the volume of lava that had gone into it. This did not entirely prevent the lava from continuing to flow into the sea. The most dangerous lava flow then headed straight for the outer breakwater and threatened to block the entrance to the harbor. A tactic was adopted to try to pump seawater directly onto the terminus of the lava flow both from the breakwater and from the sea. Use was made of fire trucks, one of the harbor boats, *Lóðsinn*, with its pumps, and the pumping dredge *Sandey* which arrived at Vestmannaeyjar on the first of March [1973] (fig. 5). With this concerted effort the lava front was mostly stopped, but at the same time it started to rise and swell where the backed-up flow of lava continued. *Sandey* had a large-diameter-hose nozzle that was capable of directing a cascade of sea water directly upon the lava and cooling it as far as the water could reach.

The bulk of the water ran back into the sea, however, before reaching the most critical areas. In order to abate the flow of the lava, it was decided to place a water conduit in the lava field about 200 m in back of the lava margin.

This decision involved a highly difficult operation. The pipes that were used in the conduit were of steel, and because *Sandey* was used to pump sand onto land, they were more than 0.5 m in diameter. They could only be moved by using a bulldozer to carry them up over the still mobile lava that was glowing red-hot under its surface. However, tephra that had been deposited on the lava provided an insulating layer. This was probably the first time that a bulldozer was driven onto a still flowing lava. The first experiment was quite successful, because the bulldozer made its way up onto the lava front and was able to clear a road 100 m through the lava field in a few hours. The bulldozer driver had to be very cautious because incandescent lava fragments came to the surface right away. However, the lava showed no sign of subsiding beneath the bulldozer, even if it were in a molten state.

During a period of two days, [additional] roads were cut in two places, but the lava margin grew to such a height that the bulldozer could no longer ascend it. Another suitable spot for making a road was selected that permitted the pipe to be transported by trucks onto the lava flow. Although the workers succeeded in bolting the pipe lengths together from the pumping ship that was standing by in the inlet between the breakwater and the Skans area, it was very difficult to do so. Once the pumping began, the pipes continued to break because of the movement of the lava. It also became increasingly difficult to work because of steam that obscured the worker's vision. Nevertheless, more and more lengths of pipe were put in place until the line extended about 200 m onto the lava, and cooling became possible across the lava

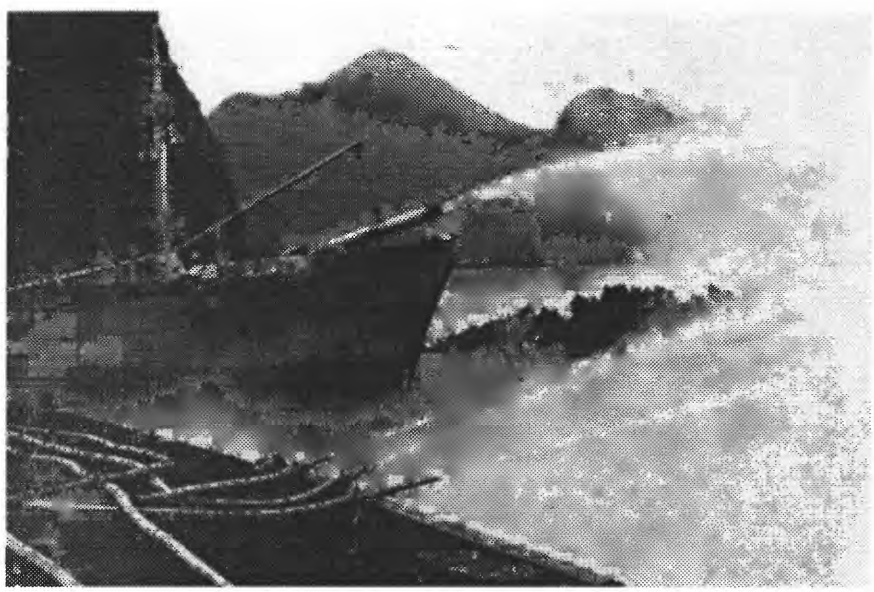

Figure 5. *Sandey* and *Lóðsinn* pumping sea water onto the forward margin of the lava at the breakwater (Photograph courtesy of Sigurgeir Jónasson, March 1973).

tongue that extended towards the breakwater.

After pumping had continued for 15 days, using almost 0.5 million m^3 of seawater, a solid barrier developed across the lava termimus stopping the flow. Many weeks later, there was still some movement in the lava just south of this barrier. The pressure became so great that the surface of the lava buckled, but its cold barrier remained intact. Had it not been for the cooling, the lava tongue could be expected to take on a lower contour, and therefore extend further along its direction of movement. Also, it might have continued to move very slowly for a whole month longer than it actually did. It failed by only about 100 m to block the entrance to the harbor.

It was two months after the start of the volcanic eruption that the lava began to flow into the eastern part of the town so rapidly that no quick measure could be taken before about one-fifth of the town had been covered by lava. The lava stream came directly from the crater along the western border of the molten mass and overran the town from the southeast. The rampart ran from Skans in an arc toward Vilpa. The lava tongue did not move very quickly at first, its terminus lying on the dike for 15 days. Meanwhile, every effort was made to increase the height of the rampart, but the lava tongue grew faster in height and bulged out along its margin. Water-cooling did not succeed there because of insufficient pressure in the available pumps because of the distance from the harbor. The rampart finally reached 12 meters in height, but the lava was two times higher. It was remarkable that the sheer weight of the lava was apparently not able to push the dike material aside, although it was composed of loose material, such as tephra that covered the lava margin.

After the lava flooded into Vestmannaeyjar, a turning point was reached in the water-cooling operations. Essentially, the experience confirmed that more pumps were needed to provide sufficient water volume and pressure. About 50 large pumps were assembled and airlifted to Iceland from the United States in a very short period of time. Up to 1,000 l s^{-1} of water were pumped, with sufficient pressure to be able to raise the height of the water to as much as 100 m. At this time, it was also discovered that plastic tubing produced by Iceland at Reykjalundur could be used for distributing water on the lava. At times the empty tubes melted and burned if they came in contact with hot lava, but, if they were filled with water, they could sustain the heat very well. A pipe with a diameter of 20 cm easily delivered 100 l s^{-1} of water. Plastic pipes were assembled behind bulldozers in 100- to 200-m lengths, and towed out onto the lava. In this way, they were much easier to position than metal pipes. Also they did not break when shifted by the movement of the lava.

The movement of the lava into the town stopped on the morning of 23 March, after it had pushed half way through the town toward the harbor. Where the rapidity of movement rendered the old pumping station useless and the new one not yet installed, there was a halt in the cooling operations. Considerable water-cooling was achieved only at the northeastern corner of the lava flow, at Bakkastígur [east-west street south of Skans], where a 100 to 200 l s^{-1} flow of water was pumped for an entire day, before the movement resumed on 26 March.

When the lava flood again ceased somewhat for the second time on 28 March, pumping from the ships was then at its full strength at the northern edge of the lava, with 300 to 400 l s^{-1} of water being pumped along a lava margin 350 m long. At first, water was directed through nozzles at the lava margin, but, on the third day, hoses were moved onto the lava. The lava edge moved very little after pumping on it began in earnest, and one week later it had become fairly well solidified. However, lava continued to flow into the town along a lava tongue, although it had stopped further upstream. To retard this advance, a road was laid upon the lava tongue beside the new hospital about 0.5 km south of the northern end of the lava tongue. A pipe was put in place, which delivered 400 to 500 l s^{-1} of water upon the lava. Cooling started there on 1 April, or four days later than the cooling at the northern edge, and the water was delivered on the lava by water jets which sprayed out 50 to 100 l s^{-1}. On 4 April, one 100-liter jet was added, 300 m nearer to the crater, where the old Vilpa water-hole was located formerly, now buried under the thick lava (figs. 3 and 6).

When the cooling of the lava east of the hospital had begun, the flow velocity of the lava was only 1–2 m h^{-1}, and the lava flow started to abate very quickly after pumping started. Because of the steam generation, however, it was not easy to absolutely confirm this observation. From this place the water ran about 250 m along the lava flow in a direction towards the harbor, forming a continuous dense cloud of steam. On the other hand, the water did not run off the lava to any extent, because the lava margin was usually higher than its inner parts.

Geodetic engineers from Landmælingar Íslands [National Land Survey of Iceland] and from Orkustofnun [National Energy Authority] kept abreast of the movement of the lava as much as possible and, moreover, changes were measured from vertical aerial photographs. On about 10 April, the movement of the lava into the town was nowhere more than about 1 m during a 24 hour period. Water-spraying operations onto the lava east of the hospital were reduced to 200 l s^{-1}, and the most westerly portion of the lava stream that ran out from the crater's mouth began to be cooled by means of two 100 l s^{-1} water jets. At that time the outflow from the crater was at peak force at the western bank, with a speed of about 2 m h^{-1}. The effect of the cooling was quickly noted, and next day the lava solidified not only where the water jets were located, but also in the direction of water movement which extended 100–200 m along the lava flow-front, cooling it rapidly. The surface of this lava became very rough and very conspicuous. It is on top of the Kirkjubær farm and would aptly be named the Kirkjubæjahraun [Kirkjubær lava].

By the middle of April, continuous cooling was achieved on the lava flow that had flowed into the town all the way from the crater. At the northern edge of the lava tongue that extended towards the harbor, a completely-cooled zone had been created. The water-cooled zone extended 50 m onto the lava, and then the cooling was stopped. There was no risk that the lava flow would move again at the cooled zone, but without water cooling it probably would have continued to flow for many weeks at full force. Then the lava flow within the town would have continued to rise and bulge out, surge forward several times and descend into

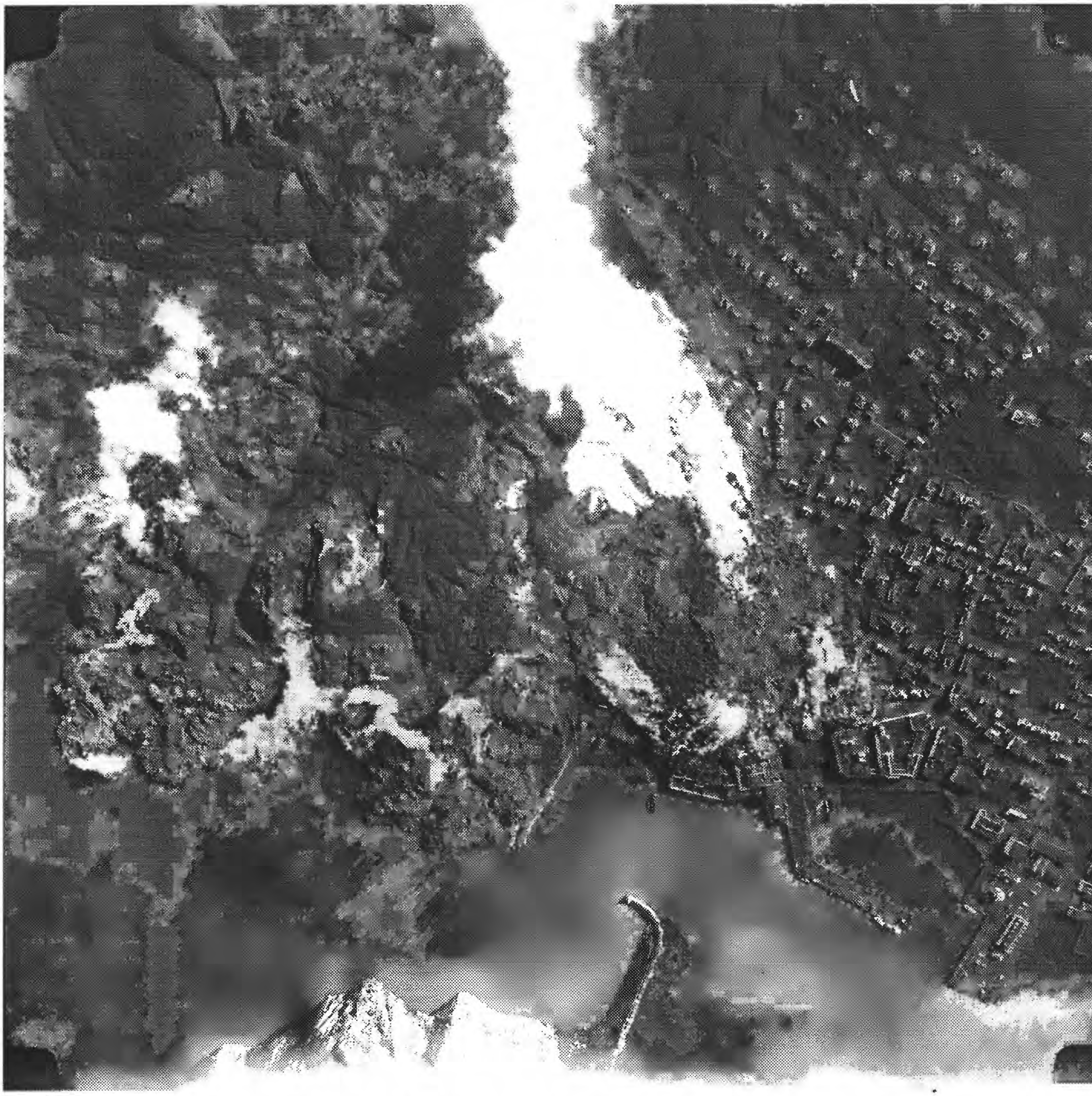

Figure 6. Vertical aerial photograph taken on 6 April 1973, when lava cooling was at its maximum. (See fig. 3 for reference to place-names in the town of Vestmannaeyjar and environs.) In the lower left part of the photograph, the pipe from the *Sandey* cooling operation can be seen extending across the lava flow at the wharf. Water-flow measurements were completed at this location as well as at the *Sandey* operations in the town of Vestmannaeyjar. Most pumps are on the Básaskersbryggа [Básasker Wharf] in the lower right of the photograph, and, from there, the water pipe runs through the town up onto the lava. The primary pipe is located near Sólhíð (a street north of the new hospital), where it extends up onto the lava. This was where the main cooling went on at this time, and from there the water spread over the lava flow near the road to the harbor. The clouds of steam give an idea of the rate of cooling. From the north, the lava flow is situated at the commercial buildings of Hráðfrystistöð Vestmannaeyja, the Fiskiðjan hf., and Ísfélag Vestmannaeyja hf. At the terminus of the lava, fire hoses can be seen in various positions. Farthest to the east, the Vestmannaeyjar barge is pumping water; other pumps are at Nausthamarsbryggja [Nausthamar Wharf], and farthest to the west, the water comes from the pump on Básaskersbryggja. There the generation of steam is beginning to diminish, and water is seen flowing out of the lava or down across it. Close to the center of the photograph, a house is standing at Bakkastígur [Bakka Street] in a narrow valley between the lava flows that overran the town and an older lava flow that was pushed up onto the old shore. South of the house is the high lava margin, where the water was pumped for 24 hours, the creep of the lava flow was somewhat delayed. When the lava flow resumed moving from this area, it did so at a faster rate. North of the house, the new lava was never subjected to cooling, and there the lava margin is low and evenly inclined.

the harbor.

Easter week proved crucial to the progress of the lava flow. The flow westward from the crater stopped gradually, probably from the effect of cooling; at the same time, however, the lava flow from the crater also stopped, and a solid threshold piled up at the crater's edge. Probably, lava started to rise until the pressure became so strong that something had to give way. On 22 April (Easter Day), lava surged from the crater, flowed to the east, as lava poured out of the crater under the rock rim and flowed to the east and south alongside the crater cone, where some of it flowed towards the sea. After that episode, lava flowed only within that confined channel. Lava flowing out of the [Eldfell] crater essentially stopped at the end of May or the beginning of June, 1973.

Apparently, the possibility of the lava breaking out towards the west rather than towards the east seemed to be about equal, but the water cooling might have made the lava more solid on the west side. If the lava flow had come out to the west and freely extended its path directly down into town, the volume of lava that flowed in that direction was certainly sufficient to inundate the entire center of town and fill up the harbor.

By now the lava was cooled in [10] areal segments [fig. 11] by moving the spraying operations east onto the lava, until it had reached a line heading from the western edge of the Eldfell crater north just east of Ystiklettur [hill on the north side of the harbor entrance]. Water was also pumped from two pumps onto the edge of the lava extending to a spot facing Ystiklettur. The lava was forced to stop moving, even though it was still molten in this area and had even entered the harbor mouth especially at Ystiklettur. In the beginning of May the entire 0.5 km^2 area was stationary.

Furthermore, water pipes were put closer to the crater than before or as close as 150 m from the vent. Fire hoses and nozzles were connected to the pipes in case the lava started flowing from the crater along the gorge which had formed on the western edge of the crater mouth. A few lava streams issued from there, but were so small that they stopped by themselves, thus cooling was never really carried out at this location.

This last sign of life from the crater occurred on 26 June. On 2 July I descended into it and found the bottom cold and concealed by rock slides. Water-cooling operations were ended completely on 10 July, and, by then, about 6 million m^3 of seawater had been pumped onto the lava. According to what was said earlier in my lecture, it may be calculated that the water had converted about 4 millon m^3 of molten lava to solid rock. Adding everything together it may be estimated that about 250 millon m^3 of volcanic material were erupted.

Temperature measurements in five boreholes that were bored in the lava in May and June (1973) showed that the cooling had conformed closely to theoretical calculations. In the borehole nearest to the lava margin at Fiskiðjan hf. (fish-packing company), no molten lava was found. In the borehole east of the new hospital there was solid rock down to a depth of 13 m; the same was true of the borehole in the lava over the now buried Vilpa waterhole. In the lava tongue at the harbor entrance, which the *Sandey* had cooled, cooling extended to a depth of 15 m. Only at one site was molten lava found directly under the loose scoria. It was in a hole bored in an uncooled part of the lava tongue where the former intersection of the roads from Austurhlíð and Urðarvegur was located. There, molten lava was encountered at a depth of 5 m, while the boring was continued down to about 17 m. On 13 July, the temperature in this hole was measured at 1,050 °C, whereas the highest temperature of flowing lava during the eruption was measured at about 1,080 °C.

Personal Commentary [By Próf. Þorbjörn Sigurgeirsson]

The water-cooling of lava was a strongly debated subject while the operation was in progress. It was a very costly operation, but no one could have predicted what the outcome would be. Nevertheless, I suppose that now nobody will regret the cost.

The true value of the lava-cooling operations on Heimaey will probably never be known or about how conditions would be different if people had not turned out to battle against impending destruction. The inference that I have drawn is an educated guess and will only be judged by persons familiar with the local setting and with the behavior of the lava. It was not easy to estimate the effect water-cooling will have on lava movement on the first day after water-spraying operations began because of many uncertainties associated with gradual cooling of the lava. Several technical problems remain unsolved, but it would worthwhile to find satisfactory answers for them. One problem that requires a solution is to find a method for measuring the amount of steam that rises from the lava. Borehole measurements conclusively showed that the great force of the lava was contained by the effect of the water-cooling, but borehole measurements are a slow method that cannot be undertaken before the lava flow has stopped.

On Heimaey, much damage was avoided by preventing fires or safeguarding houses from being crushed by the weight of tephra upon them. I cannot cite any numerical figures in this connection, but undoubtedly the cost can be calculated. As for the defense against flowing lava, the threat of total destruction of the town of Vestmannaeyjar and its harbor required an innovative approach using virtually untested methods. By the end of the volcanic eruption, however, it was clear that the increased thickness of the lava contributed to a smaller area of inundation than would have been anticipated, based on prior experience with unconstrained lava flows. It is also obvious that the lava came very close to destroying some very valuable fish-processing factories. The lava lies adjacent to the harbor, more than 1 km along the harbor entrance. If the lava were to have flowed 100 m more at some points, the harbor would have been blocked [fig. 7].

Figure 7. Heimaey at the end of the volcanic eruption. The light tone in the center of the lava between Eldfell and Ystiklettur is the result of marine salts that were deposited on the lava from the water spraying operations. (8 September 1973 aerial photograph courtesy of the National Land Survey of Iceland) [Editor's note: The aerial photograph shows the new land to the northeast and east, an addition of approximately 2.5 km² to the island of Heimaey, and the encroachment of lava flows on the eastern one-third of the town of Vestmannaeyjar (Iceland Geodetic Survey, 1973a and b). Tephra blankets the remainder of the town, except where cleanup operations have already removed the tephra. Some of the tephra removed has been used to build a new NNE-SSW airstrip.]

I have described here the lava-cooling [history] on Heimaey, without going into individual specifics of the operation. There will be accounts of specific aspects of the water-cooling operations by others [Valdimar Kr. Jónsson and Matthías Matthíasson, 1974]. It was an unusual and difficult operation, relying entirely on all those who worked in a disciplined manner and with selfless zeal demonstrated their energy and their ability to adapt to unique conditions. There is no question that a memorable heritage of pioneering spirit was displayed.

A volcanic eruption has long been considered to be a most awesome and destructive event upon certain districts, and on the whole there was very little that could be done to prevent it. No procedures have ever been perfected to safeguard against a volcanic eruption or against the destructive force of advancing lava such as occurred on Heimaey. In this case, however, the threatening catastrophe proved to be not so terrible and uncontrollable as had been initially feared.

The experience at Heimaey gives reason to suppose that we may be able to exert an effective influence upon the movement of lava if the conditions are favorable, if sufficient water is available, and provided that local material can be used to construct a protective rampart or dike of sufficient height on the flowing lava. In this way, and if both the time and the morphology of the landscape permits, lava may be forced to circumvent valuable land and be guided to where it can do the least damage. Similarly, efforts could be directed at having the lava pile up into a thick mound and, in this way, hinder it from spreading (fig. 7).

Iceland was created by volcanic eruptions in the past, and to these we gratefully owe our existence. For the Icelander, therefore, it is not fair to look upon a volcanic eruption first and foremost as an agent of terror and destruction. In the Heimaey eruption, there was certainly a severe loss, but we are already seeking different ways to increase the fertility of our soil and to improve our harbor. There is much work to do along these lines, and to reshape our land as it was at the time of first settlement (874 A.D.).

LAVA COOLING ON HEIMAEY - METHODS AND PROCEDURES[3]

by

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Introduction

On 23 January 1973, a volcanic eruption, which will not be easily forgotten, began on Heimaey in the Vestmannaeyjar archipelago. In a few hours most of the inhabitants had been evacuated to the mainland on ships and aircraft, and efforts were already underway to save their personal belongings. The purpose of this technical article is to report on the measures taken to prevent the lava from flowing over the town and into the harbor, namely the lava-cooling operations.

It should be noted that the two authors had very little to do with the lava-cooling operations until March 22. At that time the Viðlagasjóður [State Disaster Relief Fund] asked Valdimar Kr. Jónsson to supervise the installation and management of pumping equipment to be used for the lava cooling, that was expected soon from the United States. Up to that time, various groups had been working on the problem of cooling lava flows; for example, Prófessor Þorbjörn Sigurgeirsson [a physicist with the Science Institute at the University of Iceland in Reykjavík] and Sveinn Eiríksson, Fire Chief at the Keflavík International Airport.

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[3] Valdimar Kr. Jónsson and Matthías Matthíasson, 1974, Hraunkæling á Heimaey - Verklegarframkvæmdir [Lava cooling on Heimaey - Methods and Procedures]: *TímaritVerkfræðingafélags Íslands*, v. 59, no. 5, p. 70-81 and p. 83.
English translation by Sigrún Rockmaker, Foreign Service Institute, U.S. Department of State. Additional translation and edit by Richard S. Williams, Jr., U.S. Geological Survey, Woods Hole Field Center, Woods Hole, Massachusetts 02543-1598.

The start of lava-cooling operations

The first attempt to prevent the advance of the lava by water cooling was made two weeks [7 Feb 73] after the eruption began [23 Jan 73], but by then the lava was dangerously close to the entrance to the harbor. Firemen from the fire department in Vestmannaeyjar started to spray seawater on the headwall of creeping lava, and it soon appeared to have some effect on the lava flow. Soon thereafter, more powerful pumps were ordered from the [Icelandic] mainland and from other countries. Gradually the number of pumps was increased, but at this stage the capacity never was very significant (about 100 $l\ s^{-1}$).

Fire hoses were used to spray water along about a 500-m-long stretch of the lava edge from Skans to Grænahlíð [east-west street about 0.4 km south of Skans; see fig. 3 in the Introduction for map of the town of Vestmannaeyjar and environs on Heimaey]. The lava along this stretch started to pile up, and the lava edge reached about 20 m in height and appeared rather unstable. The water did not seem to be utilized to its utmost, because every so often it flowed down along the lava edge. The pumping equipment on hand was not powerful enough to pump water to the top of the lava edge, and it was entirely out of the question to lay hoses up onto the lava edge, because it was both steep and hot and constantly moving.

By the latter part of February, the lava field had piled up on the [outer] breakwater. The dredging boat *Sandey* was used to strengthen the lava edge [by spraying seawater onto it], having arrived in Vestmannaeyjar on 1 March. About the same time, a section of the [new] mountain [northern part of the Eldfell crater wall] became loose [and began to be carried north by the lava flows]; it was given the name Flakkarann ["The Wanderer"]. It crept over the existing lava field aiming directly for the harbor entrance. The *Sandey* was given the task of preventing its advance.

The *Sandey* brought water pipes that were made of steel 22 inches (56 cm) in diameter. Each pipe section was joined together with more than 40 bolts, which was a very slow process. The lava, where the pipes were laid, was still moving and that increased the difficulty, because joints split and the pipes broke. In spite of all that, it was possible to lay a pipeline about 200 meters eastwards on the lava at Skans.

An attempt was made to compute how much seawater the *Sandey* sprayed on the lava, but that was quite difficult, because it was hard to get to the pipe ends to measure the flow. Also, pumps were often stopped because of malfunctions in the pipes or because the ship had to be moved. According to the most reliable sources, it is estimated that the *Sandey* pumped about 400 $l\ s^{-1}$, when the water was pumped up on the lava tongue 30 meters high, or a total of about 0.4 million metric tonnes of seawater.

The result of this cooling was quite visible. The lava tongue that was cooled did not move from that time on, in spite of a great pressure later caused by Flakkarann and additional lava that piled up to the south and west of the Flakkarann.

About that time people realized that, if the lava flow was to be stopped, far more powerful pumping equipment was needed. The equipment needed should be able to pump the water up to two or three times higher than the existing equipment was able to do.

On 11 March, a report was prepared and signed in Vestmannaeyjar by six men: Þorbjörn Sigurgeirsson, Sveinn Eiríksson, Þórhallur Jónsson, Pálmi R. Pálmason, Páll Zóphóníasson and Guðmundur Karlsson. In the report, three types of pumping equipment were mentioned (according to preference), that might be considered capable of preventing the lava from flowing into the harbor and/or the town. It was requested that the capacity be increased to about 800 l s^{-1} and the delivery head be increased up to 60 meters. Those, signing the report, estimated that this equipment had to be on hand within one week, if it was to be possible to save the harbor and town in Vestmannaeyjar. A little over two weeks later, on 26 March, the first delivery of pumping equipment came by air from the United States.

It has been seriously discussed, whether it would have been possible to stop the lava flow that started 8 weeks after the eruption and flowed in one week over one fifth of the houses in town. That lava flow covered the shortest distance from the crater, ran along the western edge of the older lava, and flowed into the town south and east of Grænahlíð. The lava tongue travelled slowly in the beginning. Its end lay on an artificial dike [rampart] that had been constructed from scoria; in two weeks, it was build to a height of 25 meters. By that time the lava tongue had become twice as high as the dike and overtopped it.

What would have happened if the pumping equipment had arrived one week before as the group of six had requested? In answer to that, even if the pumps had arrived in the country on 18 March, and the pumping started 23-24 March, taking into consideration that it would have taken 5 to 6 days to transport them to Vestmannaeyjar and install the first phase, it would have been impossible to stop the lava flow, which by then had [already] started to flow with great force.

Pumping capacity increased

After lava had covered one fifth of the town by the end of March, there was a change in the operation. At that time 32 pumps, fully equipped, were received from the United States. Their capacity was 800-1000 l s^{-1}, the delivery head was approximately 100 meters in 1,000-m-long pipe sections. After they were put into use, the lava edge facing the town moved only a little, then came to a standstill.

All of these pumps arrived by airplanes at Keflavík on 26-30 March (on three U.S. Air Force C-141's and one C-5 transport aircraft), and they were transported by ship to Vestmannaeyjar immediately.

Originally it was planned to place all of the newly arrived pumping equipment on Nausthamarsbryggja [Nausthamars Wharf], where loading and unloading is rather easy in emergencies and access to seawater were good. But, when the lava flow started to cover the town, and headed directly towards the pier, it was decided, therefore, to move all of the pumping equipment to Básaskersbryggja [Básaskers Wharf] to cool the north side of the lava edge. A few pumps were also put on a barge from the State Lighthouse and Port Authority and on the dredging boat *Vestmannaey*; it pumped for awhile on the lava edge directly from the seaside.

When the pumps were installed, they were divided into four independent units in order to increase reliability. Each unit consisted of two low-pressure suction pumps that pumped into a reservoir vessel. Five to seven high-pressure pumps were used to transfer the water from the reservoir to a high-pressure tank. The water was transferred in 8 in - 12 in (20 cm - 30 cm) diameter pipes from the high-pressure tank onto the lava.

The pumps were assembled without any problems, and the work continued day and night. The first unit was put into use on 30 March, the second unit on 1 April, the third unit on 2 April, and the fourth unit on 4 April. The quantity of water these 4 units pumped was about 1,000 $l\ s^{-1}$, and it was aimed at the westerly lava edge from the processing plant up to Vilpa and across the lava flow above Sólhlíð. In addition, about 200 $l\ s^{1}$ was pumped on the northern edge from Nausthamarsbryggja.

Pumps and engines

Table 1 is a summary of the [types of] pumps used in the lava cooling from the beginning of April until cooling operations were terminated on 10 July 1973. It should be mentioned that the suction pumps were only used to supply the high-pressure pumps. It should also be noted that the quantity of water-pump discharge under a certain pressure does not indicate the actual quantity pumped each time, because it was dependent upon distance, delivery head, and pipe diameter.

The total number of pumps [deployed] was 43. Of those, 23, or more than half, were operated by gasoline engines, the others by diesel engines. The power of the gasoline engines was more than two-thirds of the total power of all the engines. They were considerably more inconvenient to use than the diesel engines, because of greater maintenance requirements and noise. The pumps that were connected to the gasoline engines were, in addition, designed to pump oil and gasoline, not water, and certainly not seawater. The pumps in question are the so-called "invasion pumps," that originally were supposed to pump oil-and-gasoline supplies ashore for the U.S. Navy. These pumps were manufactured before 1953 and had become obsolete. However, because of their great delivery head, it was possible to pump seawater far onto the lava and close to the crater.

Table 1. - Summary of pumps [deployed for lava cooling]

	Number	Capacity	
		Quantity (l s^{-1})	Capacity (m)
Suction pumps	10	1,700	10-12
Suction/pressure pumps	7	575	30
Pressure pumps, single-stage	7	224	100
High-pressure pumps, double-stage	19	608	150
Total:	43		

Horsepower total: 3,600 hp (2,700 kw)

23 gasoline engines: 68 percent of total power

20 diesel engines: 32 percent of total power

When the pumps had been operating for several weeks, the impeller shafts started to break (approximately 50 percent of them). The pumps were kept operating by constantly building new and improved shafts of stronger steel in Reykjavík.

The reasons for the shafts breaking were without a doubt manyfold; as was mentioned before, some of the pumps were not designed for pumping water, but for pumping oil and, therefore, the shafts were too weak. It was also noticed that the impellers eroded non-uniformly because of cavitation, especially on the suction pumps, and that caused the shafts to break from metal fatigue.

Other difficulties were caused because packing between the pumphousing and the shaft tended to deteriorate. The pumps then had to be taken out of service and the packing changed. Close to the end of the operation the valves began to wear out. However, this can be considered normal wear and tear, because, by then, the pumps had been operating almost continuously for three months.

Quantity of water

Figure 8 shows the quantity of water, which was pumped on the lava. It is given in liters per second (l s^{-1})as a function of the number of days from the start of the eruption [23 January 1973].

As the figure shows, the pumping began on 7 February, or 14 days after the beginning of

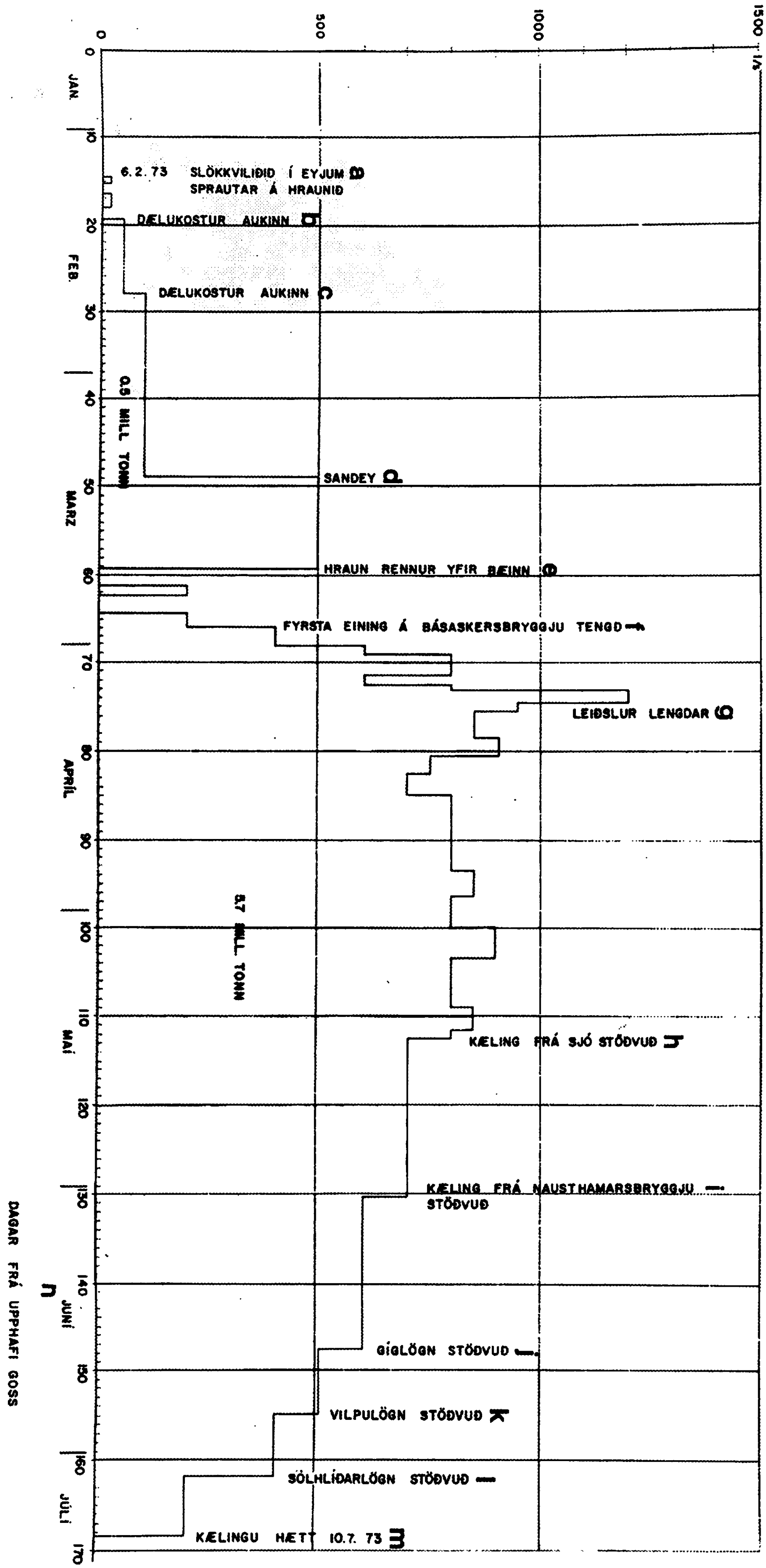


Figure 8. Quantity of sea water (in l s^{-1}) used to cool the lava between 6 February and 10 July 1973

- a - 6 February; the Vestmannaeyjar fire department starts spraying [water on] the lava.
- b - Amount of pumping equipment is increased.
- c - Amount of pumping equipment is increased.
- d - The dredge *Sandey* begins operation.
- e - Lava flows over the town.
- f - The first [pumping] unit at Básaskers Wharf is connected.
- g - Pipes are connected.
- h - Cooling from the sea is stopped.
- i - Cooling from Nausthamars Wharf is stopped.
- j - [Cooling from] crater pipeline is stopped.
- k - [Cooling from] pipeline at Vilpa is stopped.
- l - [Cooling from] pipeline at Sólhlíð is stopped.
- m - [All] cooling is terminated on 10 July 1973.
- n - Days from beginning of eruption [from 23 January 1973].

the volcanic eruption, but on a very small scale. The quantity is considerably increased when the dredge *Sandey* started to pump (fig. 9). To be sure, the pumping was not continuous as the diagram shows, but it is estimated that it [*Sandey*] pumped [at a rate] equivalent to 400 $l\ s^{-1}$ uninterrupted for more than 10 days. Actually the pumping lasted more than three weeks. It is estimated that the *Sandey* pumped about 0.4 million metric tonnes of seawater onto the lava up to 23 March, and other pumping equipment [contributed] about 0.1 million metric tonnes.

When the lava flow advanced on 23 March, there was a two-day interruption in the pumping, while the pipes had to be repositioned, but 200 $l\ s^{-1}$ were then pumped for 24 hours in between advances of the lava.

On 28 March, pumping was started again and from then on it was continuous until the 168th day of the eruption [10 July 1973], when the pumping was terminated. It is estimated that during this time a total of 5.7 million metric tonnes of seawater was pumped after lava started to flow over the town. A total of 6.2 million metric tonnes of seawater was pumped in all.

As may be seen from the diagram, the pumping reached its peak on 4 April, when all of the pumping equipment received from the United States had been connected (fig. 10). This quantity gradually decreased. The reason for that is basically that the pipes had to be constantly moved further onto the lava, closer to the crater, so that the pressure drop in the pipes, as well as increased height, caused less efficiency [loss of head due to friction]. Cooling with seawater was stopped around the middle of May, and the quantity decreased about 100 $l\ s^{-1}$.

After the middle of June, it was decided to stop the cooling in stages, so that each week one pumping unit was disconnected, and the engines and pumps were cleaned. The first units disconnected pumped comparatively farther onto the lava and, therefore, relatively less quantity than those closer to the town that were stopped later.

Figure 11 shows how much seawater was pumped onto the lava at [10] different locations [on the lava flows]. [Area K was not cooled.] These locations [10 areas: A-J] represent, so to speak, a continuous area measuring about 0.45 square kilometers that corresponds to about a nine-meter-thick layer of lava that has been cooled down to 100^0 C. on the average. However, this does not give a wholly accurate picture, because some places were cooled more than others. The area above the [fish-]processing plants and a lava field just north of the crater were cooled most markedly. Considerable amounts of seawater was also pumped around Flakkarann ["The Wanderer"], that was for a long time moving slightly. On the south side of Flakkarann, there was a large amount of steam rising as a result of convective currents.

Additionally, it may be mentioned that salt accumulated on the lava from the pumping. This can be easily seen where there are great patches of white on the lava. It is estimated that 220 thousand metric tonnes of salt were deposited on the lava.

Figure 9. Seawater being pumped directly on the lava-flow front from the dredge *Sandey.* Photograph by Matthías Matthíasson.

Figure 10. Array of gasoline and diesel engines deployed on Básaskers Wharf (Heimaklettur in the background) to power pumps used to cool the lava flows. Photograph by Valdimar K. Jónsson.

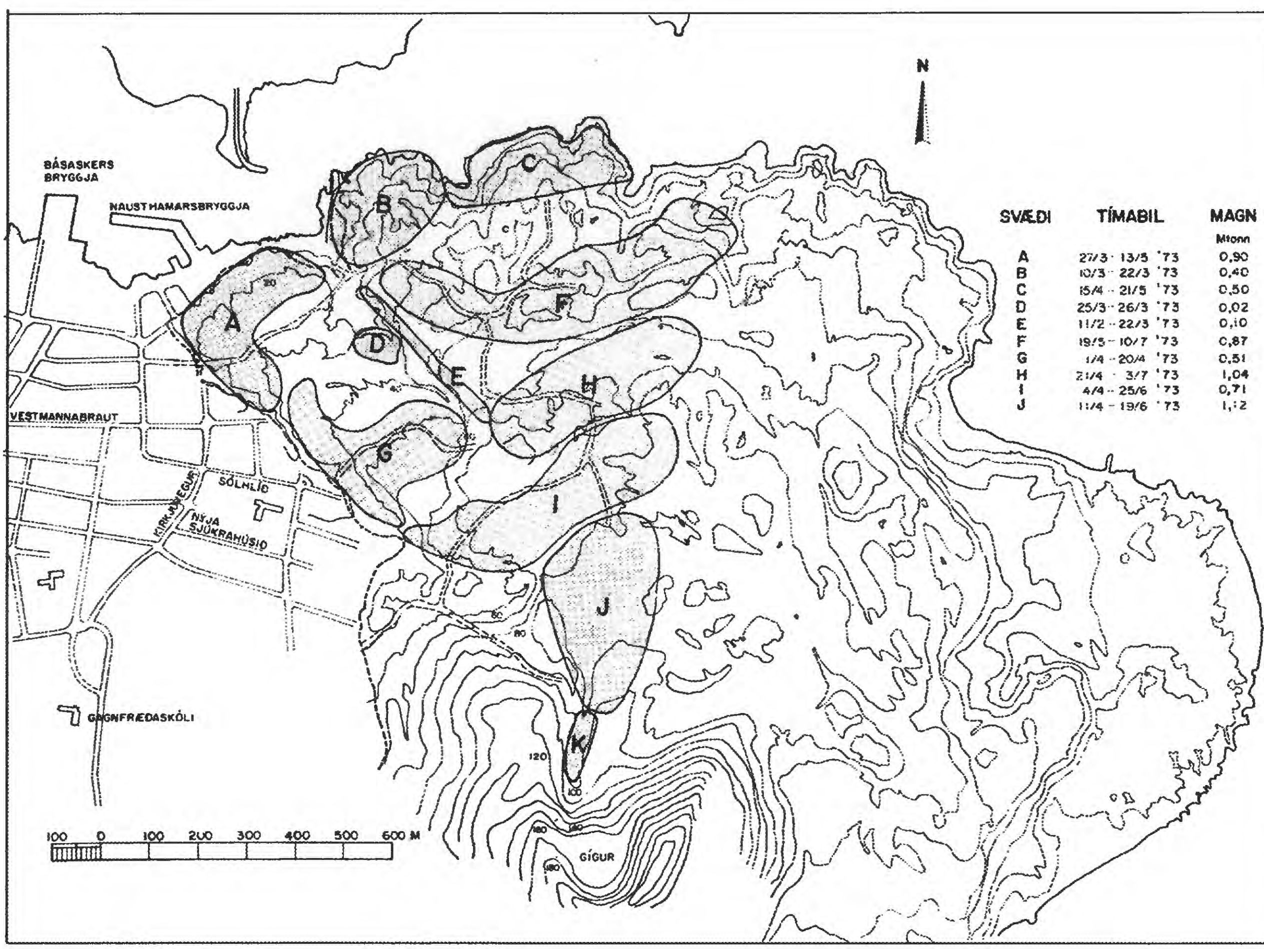


Figure 11. Map showing area (svæði), dates indicating duration of lava-cooling operations (tímabil), and quantity (magn) in tonnes (metric tons) of seawater delivered. Nýjasjúkrahúsið = new hospital; Gígur = crater of Eldfell; Gagnfræðaskóli = high school; Básaskersbryggja and Nausthamarsbryggja = Básaskers Wharf and Nausthamars Wharf, respectively. Vestmannabraut, Kirkjuvegur, and Sólhlíð are names of three streets in Vestmannaeyjar.

Pipes and Distribution System

When the cooling first started, 6-inch [15-cm] aluminum pipes, that were easily connected, were used along the lava margin. Nozzles were made for some of the pipes, and fire hoses were connected to them.

When the dredge *Sandey* arrived in the beginning of March, pipes were laid onto the red-hot lava, and water was pumped out of the pipe ends. In addition, water was allowed to drip at the joints. These pipes were very heavy and inflexible and tended to break as the lava moved.

After the middle of March, plastic pipes from Reykjalundur[-Vinnuheimill SÍBS of Reykjavík] started to arrive. Those pipes were 225 mm [9 in] in diameter and were at first used from *Sandey* up along the northeast margin of the lava that flowed on 23 March. A successful attempt was made to pump 200 $l\ s^{-1}$ of seawater there for about 24 hours, before the lava advanced again on 25 March. The area that had been cooled remained firm. It is quite evident from an aerial photograph how the lava flow curved around it.

Figure 12 is a summary of the types and quantities of pipe used in the cooling that [eventually] totaled more than 12 km. A little more than three-quarters of the pipes were the plastic pipes from Reykjalundur[-Vinnuheimill SÍBS]. They served extremely well, and it is doubtful what the outcome would have been if they had not been available.

The plastic pipes (140, 225, and 315 mm) [6 in, 9 in, and 12 in] arrived in 15-m-long sections that were welded together into 100–200-m-long sections at the Básaskers Wharf. These [lengthy] sections were then hauled to their respective places and welded together on the spot or joined by connectors. It took from one to two days to lay a 1-km-long pipeline, because only one welding machine was available in Iceland.

In the beginning, it was extremely difficult to transport the plastic pipes up onto the lava, because the lava was moving 1-2 meters every hour, and there was also the danger of the plastic melting. However, because of the flexibility of the plastic pipes, this was successful beyond all hopes, because the water running through them cooled them enough to withstand the heat.

Wooden supports (fig. 13) were placed under the pipes, but where it was hottest the wood burned without exception. Aluminum and asbestos supports were then used; the [fact that] the aluminum supports melted clearly shows how resistant the plastic pipes were [to the high temperatures].

Figure 14 A , B, C, and D show the positions of the pipelines at four different times. [Figure 15 shows two sets of pipelines laid on top of a tephra-filled street.] On 5 April, after all of the pumps had been installed, they were mostly concentrated on cooling the lava edge on the northern and western sides.

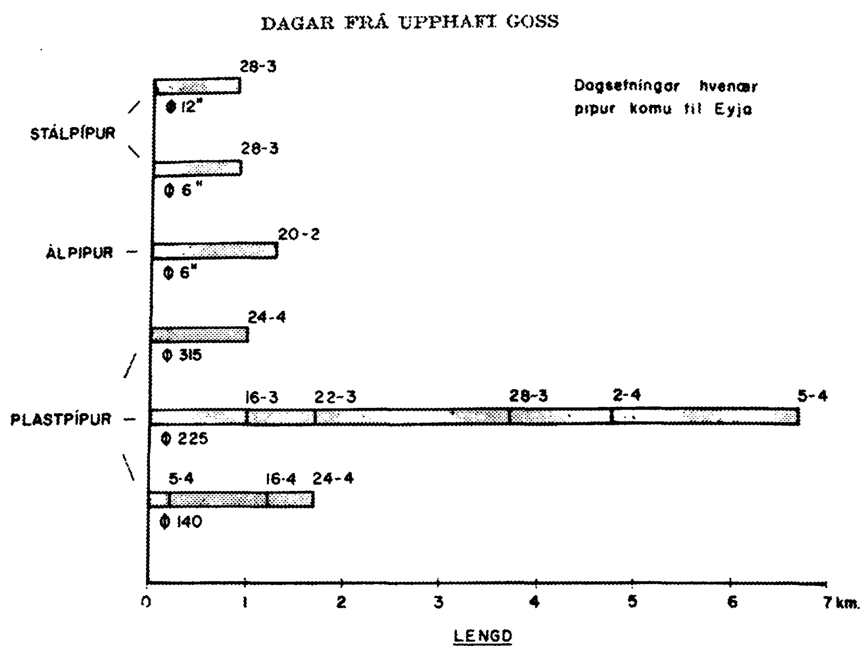


Figure 12. Graph showing type of pipe (stálpípur = steel pipe; álpípur = aluminum pipe; plastpípur = plastic pipe) used in the lava-cooling operations. Lengd = length; Dagsetningar hvenær pípur komu til Eyja = Dates of arrival of pipes in Vestmannaeyjar.

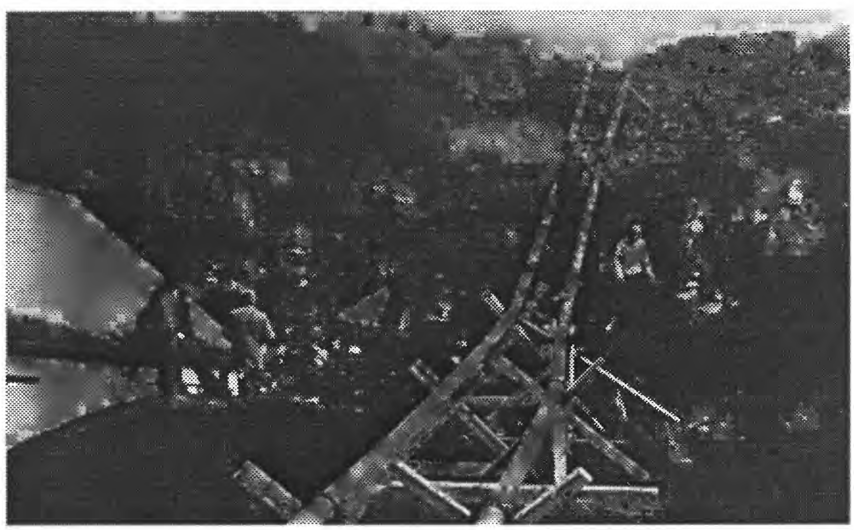


Figure 13. View of two sections of plastic pipe, mounted on wooden cribbing on the tephra (note depth of tephra with respect to the building on the left), extending up the lava- flow front onto the lavas. Photograph by Matthías Matthíasson.

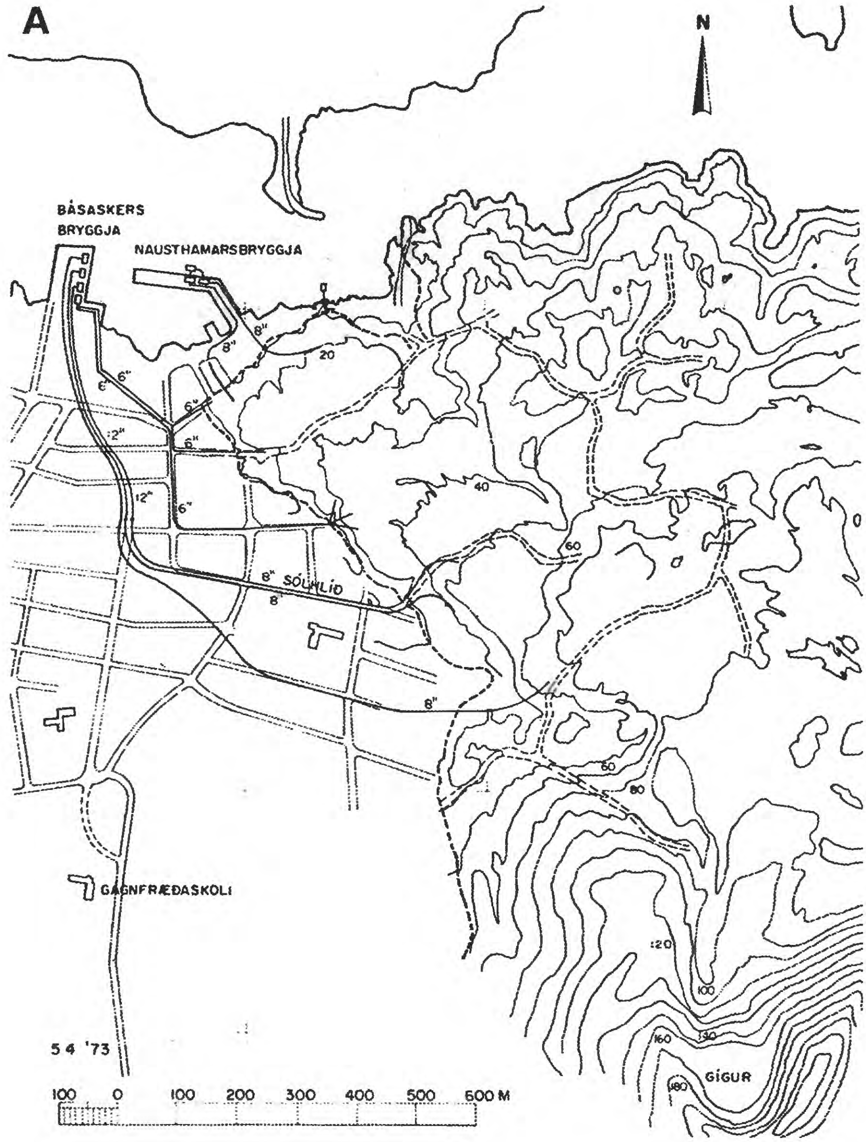
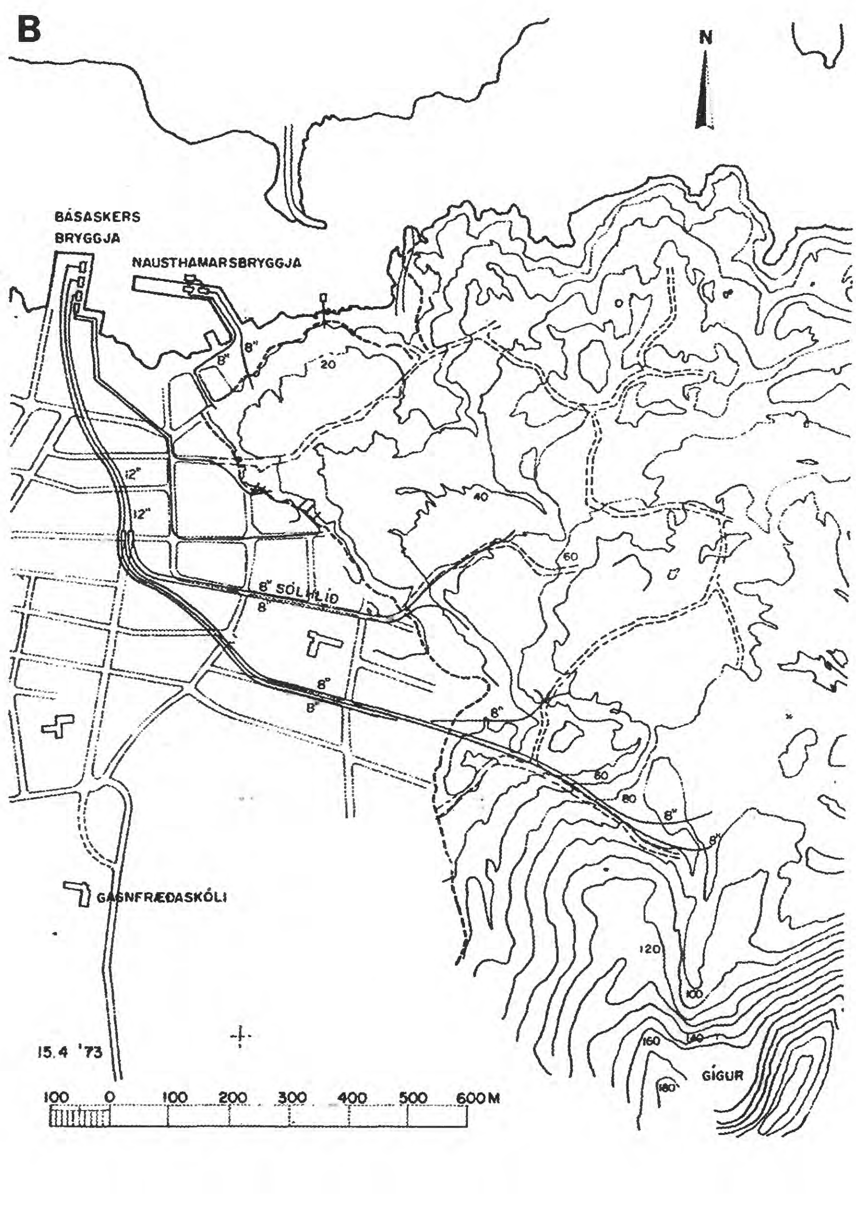


Figure 14. Map showing location of pipelines in the water-distribution system used for lava cooling on four different dates: A, 5 April 1973; B, 15 April 1973; C, 30 April 1973; D, 30 May 1973.


B
N
BÁSASKERS
BRYGGJA
NAUSTHAMARSBRYGGJA
8"
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12"
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15.4 '73
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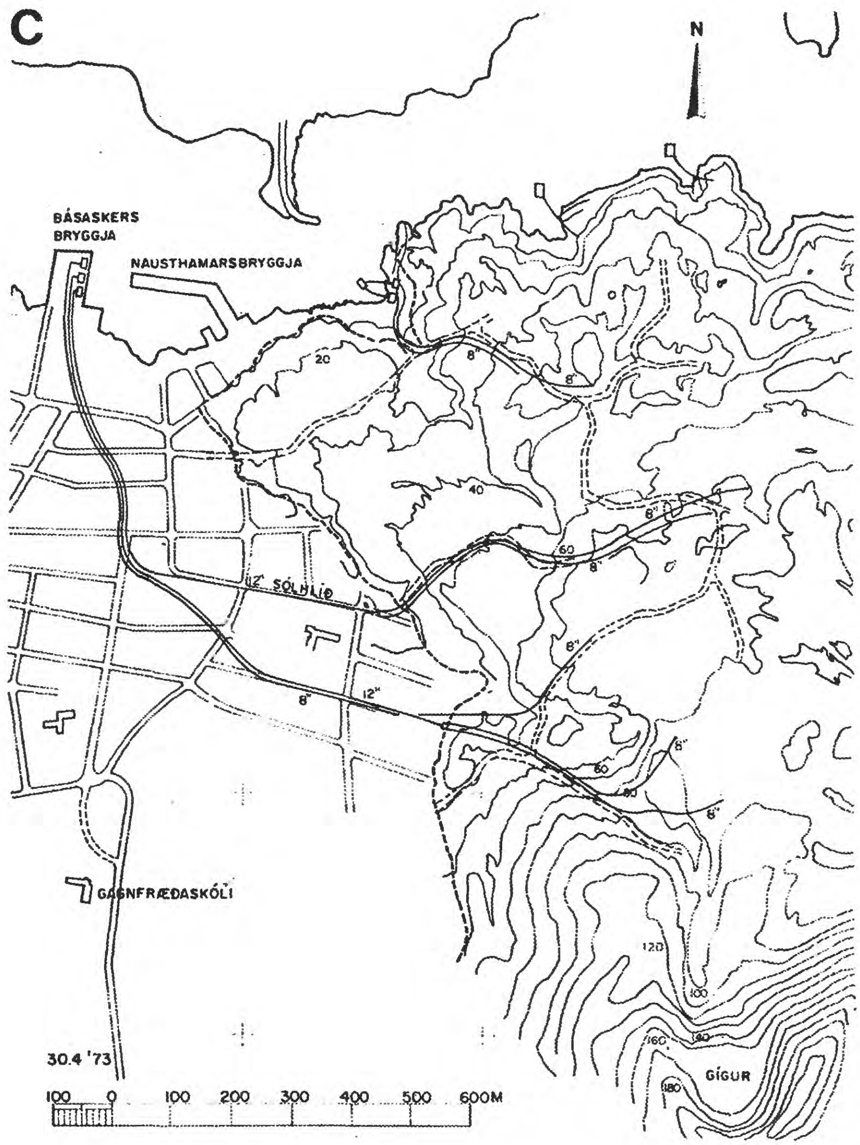
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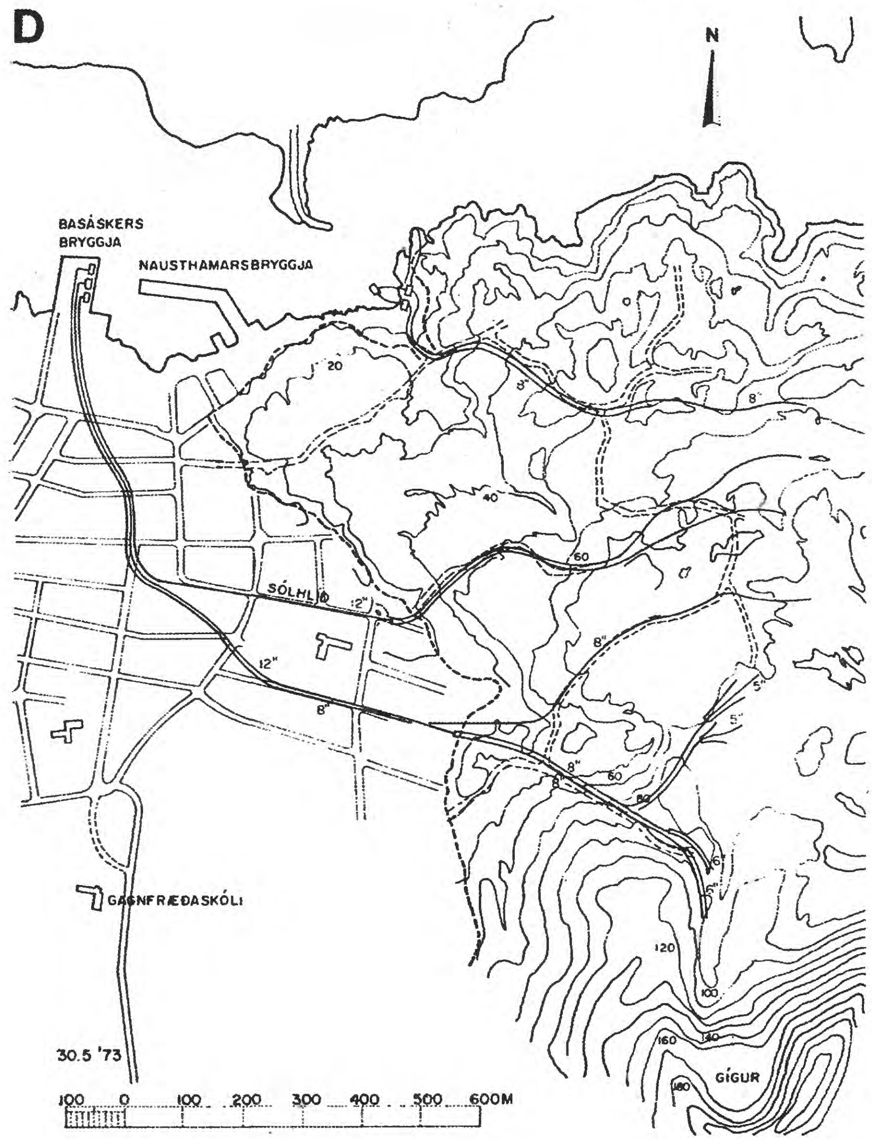
GÍGUR
30.4 '73
100 0 100 200 300 400 500 600M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140
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GÍGUR
30.5 '73
100 0 100 200 300 400 500 600M

Figure 15. View of two sets of 8-inch pipelines laid on the surface of a tephra-filled street (Sólhlíð) that extended from Básaskers Wharf on the north to the lava flows on the east. Photograph by Matthías Matthíasson.

On 15 April, the pipelines extended further onto the lava field near Sólhlíð and two new pipelines, each about 1,600 m long, lay on the lava field north of the crater, 90 meters above sea level. On 30 April, pipelines had been laid further onto the lava field, especially around the center of the area that was being cooled. On 30 May, the pipelines reached their final planned distribution. By that time, the objective of cooling the lava flows west of an imaginary line extending [north] from the [Eldfell] crater to the [west] side of Yztiklettur was achieved. The pipelines were not significantly moved from then on, from 19 June until 10 July, when cooling was gradually decreased.

It should be mentioned that Prófessor Þorbjörn Sigurgeirsson's advice was [closely] followed in deciding which areas to cool. The professor also followed the movement of the lava and suggested the areas of [greatest] danger.

Manpower

In the beginning of April, when the lava-cooling reached its peak, about 75 men were working on the cooling operation. In May, the number of workers had decreased to 40-50, and by the beginning of June only about 30 were involved. Most often the method used was to have the men work for 13 consecutive days from 8 a.m. to 10 p.m. and then give them 2 days off with full pay. Machine tending and crater watch was done in shifts. Engineers, supervising the operations, worked one week in Vestmannaeyjar and spent the next week on the mainland. This method was used to avoid fatigue and also because they had other duties [e.g., their regular jobs]. Table 2 indicates how the manpower was divided during this time; the figures show the number of workers for each month.

The item in the table called crater watch may draw special attention. The reason for this watch was that, on 26 April, lava flowed from the crater along a gorge, which had formed on the western edge of the lava flows. No one noticed the lava flow until it had stopped by itself. It was then decided to lay pipes connected to fire hoses along the edge of the gorge to spray water over the lava, in case it started to move again. This pipe reached closer to the crater than any of the others, or approximately a 150-m distance from the edge of the crater.

The crater watch was conducted day and night from then on in order to avoid a recurrence [of a missed lava flow]. The men responsible for the crater watch catalogued the behavior of the eruption, until the crater watch was eliminated on 3 July.

Table 2.—Types of jobs and number employed in lava-cooling operations between April and June 1973

	April	May	First part of June	Second part of June
Engineers/technical engineers	3	2	1	off and on
Machinists	22	15	13	5
Mechanics, welders, and maintenance people for pumps and pipes	24	10	4	2
Crater watch	0	4	4	4
Supply	1	1	1	1
Movers and supervisors of pipes	25	13	7	3
Total:	75	45	30	15

It is hard to describe the difficulties involved in placing the pipeline network on the red-hot lava, and the risk the men took who did the work. A small example will have to suffice.

The first step in bringing piping up from Sólhlíð, close to the new hospital, was to build a new road up onto the lava edge. This was done by pushing together tephra which was abundant. The first day the road was built on a 25–30-m-high edge and [extended] 5–6 m onto the lava. The following day, this whole stretch [of road] had been transported 10 m to the north, so the work had to be started all over again on that part. When that was completed, plastic pipes, 225 mm [9 in] in diameter, were hauled up onto the lava and laid approximately 20 meters inward. Pumping was started, as soon as possible, so that the pipes would not melt. This caused a great column of steam to form, which soon spread about 50 meters onto the lava and north along the lava flow. Because of the heat and poor visibility, it became impossible to maneuver in the area. [However,] because of perseverance by the men laying the pipelines, it became possible to travel through the steam with a bulldozer and the use of a walkie-talkie. Another pipeline was laid about 130 meters inward on the lava, directly across the lava advance. During this work, a few men were burned on their hands and feet.

When the cooling had continued for a few days, the lava had become widely cracked and rough with a strong sulphur smell. This made all operations exceedingly more difficult. Other difficulties were that the lava edge rose and became much hotter. In some cases, where cooling operations were intense, rifts formed that were 5-6 m deep and 5 m wide. Lava piled up above the cooled areas and fissures which had formed and, in some places, had cracked open the lava crust.

The men adjusted to these difficulties amazingly well, and some of them became extremely agile in finding their way over the [rough and irregular] lava surface through the steam and smoke. Thus came into existence a group of hardy men that was called "The Suicide Squad". No serious accidents happened during the cooling, in spite of such extremely dangerous work.

Influence of Cooling on Lava Temperature

Five boreholes were drilled in the new lava, four in areas that had been cooled non-uniformly and one in an area which had not been cooled. The positions of the boreholes are shown in figure 16, and the results of the temperature measurements in figures 17 and 18. Figure 16 also shows the position of trenches that were dug all along Helgafellsbraut in order to avoid having vapor [e.g., steam, carbon dioxide, and other gases] spread any farther [to the west] along the former surface [contact between the old land surface and new overlying tephra].

On 12 May, a drill was sent to Vestmannaeyjar from Orkustofnun [National Energy Authority]. The drilling proceeded well, and a total of five 10-25-m-deep holes were drilled into the lava and three into the area west of the lava edge (fig. 16); one of the holes [borehole V] was 35 m deep. People from the State Drilling Contractors had the unique opportunity into drill in red-hot lava. It is only known to have been done once before in Hawaii [e.g., Alae lava lake, Kilhauea caldera, Hawaii. See Peck, D.L., 1978, Cooling and vesiculation of Alae lava lake, Hawaii: U.S. Geological Survey Professional Paper 935-B, 59 p.].

The drilling was started where the lava had been cooled the most [borehole I], for example, [just up onto the lavas south of] Fiskiðan hf. [fish-processing company]. The next borehole [borehole II] was in an area that had been cooled a little less and the 3rd one [borehole III] in an area where no cooling had been tried at all (fig. 16). Borehole IV, which was close to Vilpa [see fig. 3 in the Introduction] showed very similar results as from borehole II, and, therefore, its temperature profile is not shown.

Borehole V, VI and VII were drilled in the area where lava had not flowed, [but was covered by a layer of tephra]. These three boreholes were drilled because of the intense heat that formed in the soil west of the lava edge. The houses had started to deteriorate from the heat. [Also, the new hospital was situated just to the west (fig. 16).] In boreholes V and VI (fig. 18), the temperature of the soil was 100 °C. at 10-m depth, but dropped to a near-surface

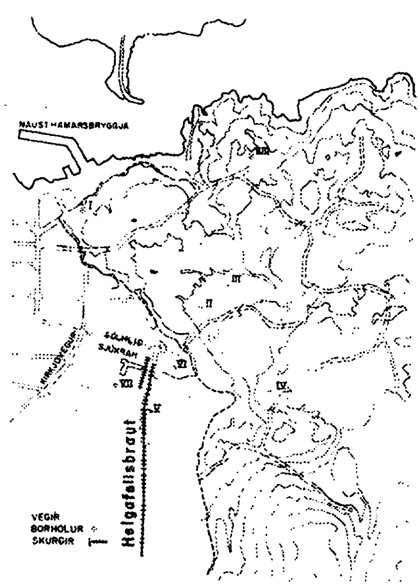

Figure 16. Map showing the locations of eight boreholes [three in the tephra, five in the new lava flows], old and new [on top of the lava flows] roads, and two trenches. Vegir = roads; borholur = borehole; skurðir = trenches.

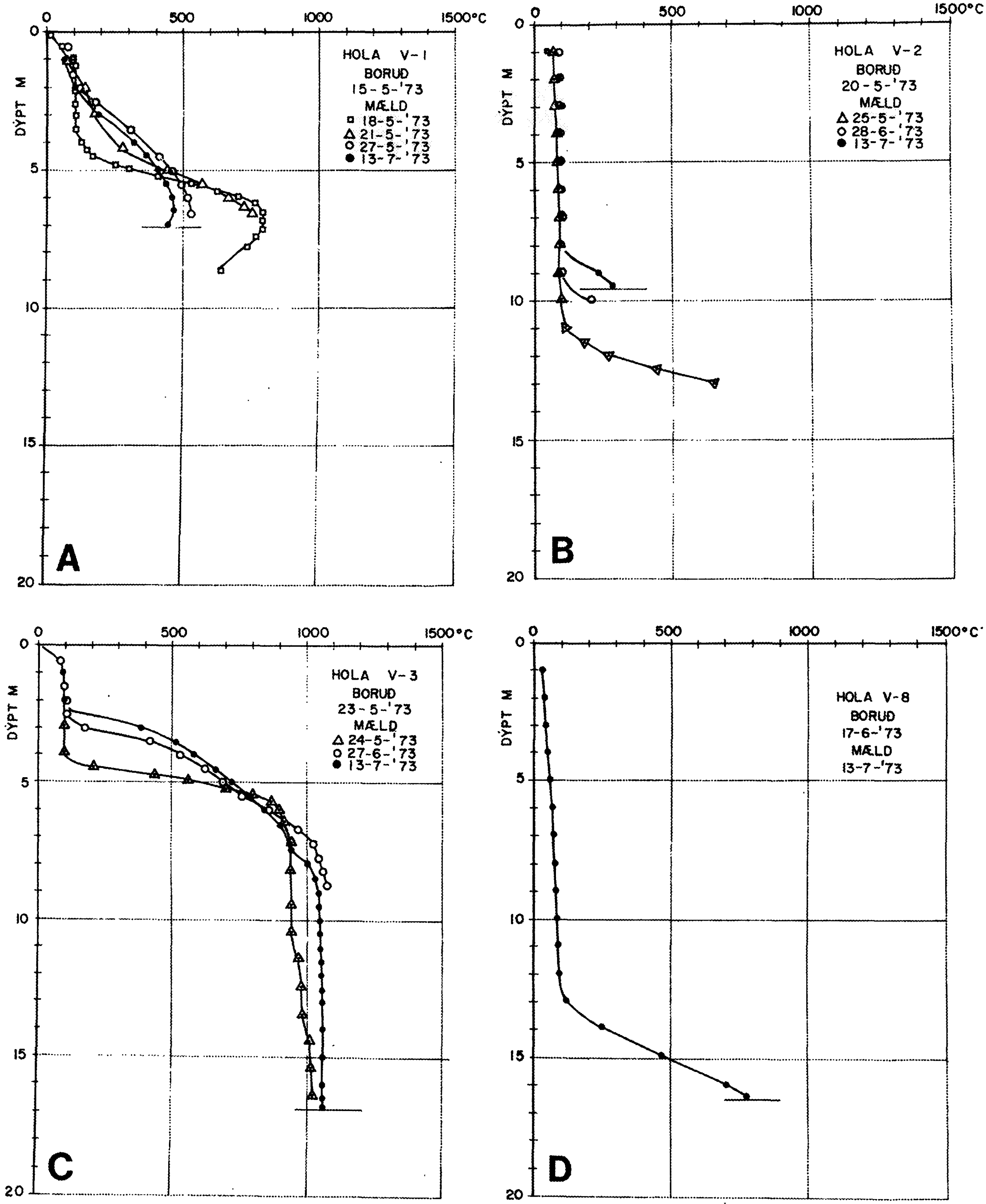

Figure 17. Temperature measurements in borehole I, II, III, and VIII [see fig. 16 for locations of boreholes] drilled on different dates; temperature measurements made on one to four dates in each borehole. Hola V-1 = borehole I; Boruð = drilled; 15-5-'73 = 15 May 1973; Mæld = measured; dates of temperature measurement; dýpt = depth in m.

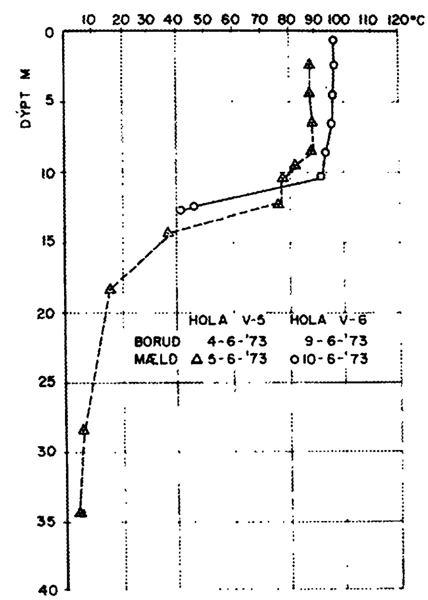

Figure 18. Temperature measurements in boreholes V and VI [see fig. 16 for locations of boreholes and fig. 17 for translation of Icelandic captions.]

[ambient] temperature in the next 5 to 10 meters. Borehole VII, which was south of the new hospital, showed on the other hand, a temperature of 4 °C. from the surface to the bottom.

The last borehole, borehole VIII, was drilled into the lava east of Skans [see fig. 3 in the Introduction], but that was the only one drilled beyond [northeast of] the former coastline of the island. Much cooling had been carried out there, within a relatively small area, when *Sandey* was pumping [seawater onto the lavas] there; the temperature of the lava was 100 °C. from the surface to a depth of 13 m.

If a theoretical cooling of a lava field, based on air cooling only, is studied in order to realize how rapid the cooling is, one may look at a simple model of a smooth and thick lava field that originally was a lava flow. In the beginning, the temperature is the same all through the lava flow; i.e., 1050 °C. Temperature measurements performed [by us] support this [theoretical calculation].

The heat-transfer-equation of solidifying rock is:

$$\partial^2 T/\partial x^2 = 1/\alpha_1 \, \partial T/\partial t$$

where T is temperature, x is depth measured from the surface, t is the time during the process of solidification, and α is the heat-transfer-constant. [Figure 19 is a diagram showing the depth-temperature profile and lava-solidification front at depth.]

Boundary conditions are: t equals O; T equals T_o equals 1050 ^{0}C. everywhere.

Depth conditions (t > 0) are:

$$x = 0, T = T_1$$

$$x = x_1, k_1 \, \partial T/\partial x \Big|_{x = x_1} = h_1 \rho_1 \, \partial x_1/\partial t$$

where h_1 is the solidifying temperature of the rock, ρ_1 is the specific gravity of solidified rock, and k_1 is the heat-transfer-constant of solidified rock.

The common solution is:

$$T - T_0 = T_1 - T_0 + A \cdot \text{erf}\,(x/2\sqrt{\alpha},t)$$

The approximate solution of this equation is:

$$T - T_1/T_0 - T_1 = \text{erf}\,(x/2\sqrt{\alpha},t)/\ \text{erf}([c_p(T_0 - T_1]^{1/2})$$

where C_p is the specific heat of lava and T_1 is the average ambient temperature.

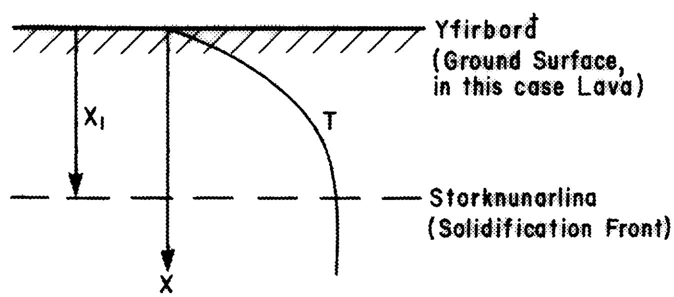

Figure 19. Diagram showing the lava surface, temperature (T) profile, original thickness of molten lava (X), lava-solidification front (dashed line) migrating downwards over time, and thickness of solid lava.

If the following value for specific heat at constant pressure for solidifying rock is used:[4]

$C_p = 0.25$ Kcal kg^{-1} ^{0}C.

$h_1 = 100$ Kcal kg^{-1}

$\alpha_1 = 0.8 \text{ X } 10^{-6}\text{m}^2 \text{ s}^{-1} = 24.6 \text{ m}^2 \text{ a}^{-1}$

$T_o - T_1 \approx 1050$ ^{0}C.

one arrives at an answer that is shown in figure 20, where the depth of the lava in meters is a function of the time in years.

The two plus signs on figure 20 show the temperature in borehole III, where the lava was not cooled. Theoretical cooling of the lava is slightly faster than this result of measurements indicates, because the effect of rainfall was not taken into consideration. Average rainfall in the Vestmannaeyjar is about 1.5 m a year, which corresponds to the cooling of one meter of lava down to 100 °C. a year, if all rainwater vaporizes. If the effect of the seawater cooling from the holes drilled is studied, it will be noticed that the cooling was 50-100 times faster in those areas compared with self-cooled lava.

Effect of Cooling on Lava Movement

As has been stated, the lava flows were constantly moving in varying degrees during the cooling operations. The movement decreased progressively, especially where the cooling took place.

Figure 21 shows the lava movement within the center of Vestmannaeyjar on 25-31 March. The movement is at its peak during the night of 26 March, because very little cooling was done due to the salvage of pipe sections before the advancing lava-flood [overran them]. On 28 March, cooling was started again, and on 29 March the water discharge was 400 l s^{-1}. All pumping was concentrated on this lava edge. On 31 March, the lava has just entered the street

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[4]Pálmason, Guðmundur, 1973, Kinematics and heat flow in a volcanic rift zone with application to Iceland: *Geophysics Journal of the Royal Astronomical Society*, v. 33, p. 451–481.

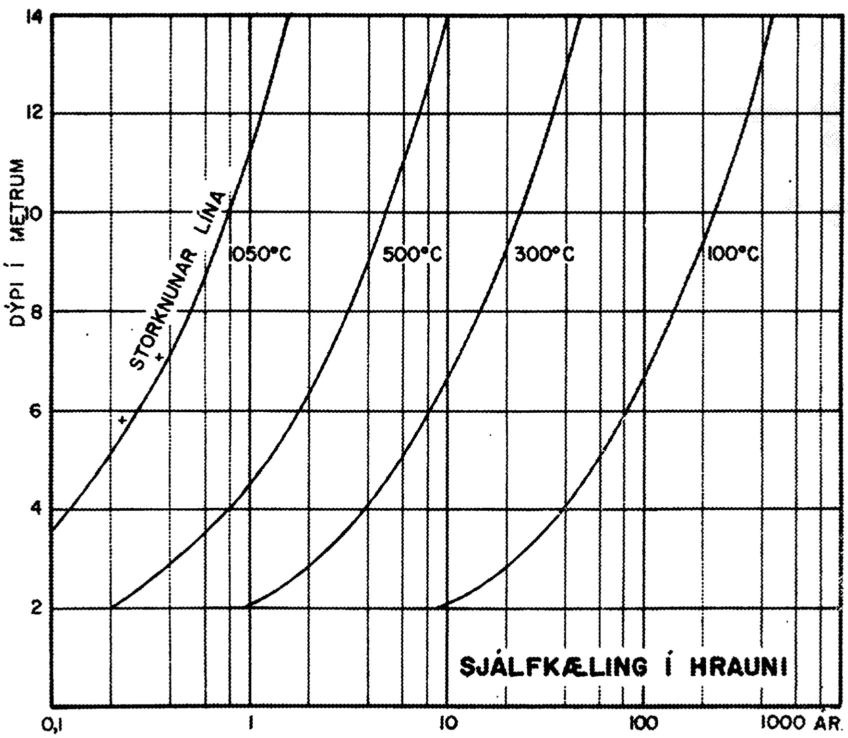

Figure 20. Graph showing normal rate of cooling of lava over time with depth from the surface. dýpt í metrum = depth in meters; storkunar lína = solidification front; sjálfkæling í hrauni = self-cooling in lava; ár = years.

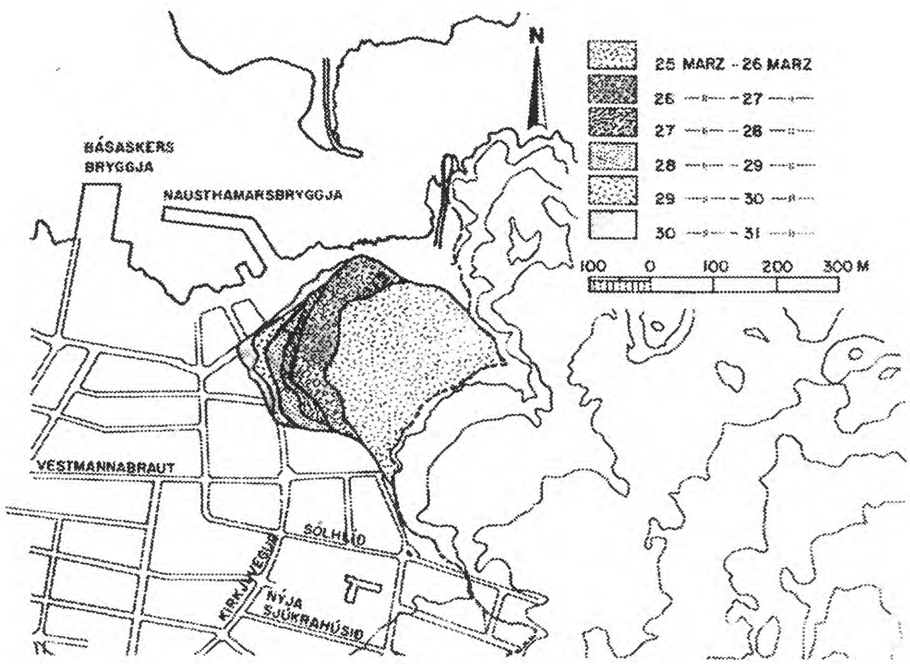

Figure 21. Map showing the surge of successive lava flows into the center of Vestmannaeyjar in late March 1973.

between the fish-processing plants [Fiskiðjan hf. and Ísfélag Vestmannaeyja hf.; see fig. 3 and fig. 22], and after that, the movement of the lava edge is minimal.[5]

Figure 23 shows the movement of the lavas for a period of about five weeks, or from 25 March to 30 April. It should be mentioned that it was extremely hard to measure the lava flow during this period, because it became difficult to place markers because of steam that formed as a result of the cooling. Even though moveable markers are few, it is possible to obtain a fairly clear picture of the lava flows. In determining the movement of these markers, a theodolite was depended upon as well as vertical aerial photographs. Figure 24 shows lava-cooling operations closest to the Eldfell crater.

If the most westerly marker (A) is analyzed, it can be seen that the lavas moved extensively between 27 and 31 March, or about 150 m. During the next four days, the movement was 76 m, or 19 meters each day on the average. This speed was maintained until 6 April, but then the effect of the cooling of the lava [from pipes along] Sólhlíð starts to be felt, and by 9 April there is no further movement of this marker.

The next marker (B) is on the lava flows east of Skans, that was cooled in the beginning of March. There was no more movement there.

The next two markers (C) and (D), show clearly the effect of the cooling on the direction the lava took. Marker (C) was emplaced on 27 March and observed until 31 March. On 1 April, extensive cooling was started along the road (dashed lines) north of marker (C), so it was not possible to measure the movement of that marker after that because of [obscuration by] steam. On 25 March, another marker (D) was placed approximately 300 meters southeast of marker (C). In the beginning, the lava seemed to flow in the same direction at those two markers. On 6 April, marker (D) has arrived where marker (C) was on 27 March, but then it changes direction to the north, most probably because of the cooling, and maintains that direction until 30 April, when it stopped [moving].

Marker (E) shows that there is still a slight movement of the lava field south of Flakkarann, and that it is pressing on it. Fissures formed on the lava crust in an area approximately 50-m wide; their length was about 5 m with a height of 2-3 m from the bottom of the fissure to the top.

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[5]See also the two photographs taken by Richard S. Williams, Jr., U.S. Geological Survey, of the street between Fiskiðan hf. and Ísfélag Vestmannaeyja hf. (two fish-processing companies) [Williams and Moore, 1983, p. 10 (23 July 1973) (also reproduced here as fig. 22) and 11 (7 July 1974)]. The photographs were taken from under the elevated passageway between the two buildings.

Figure 22. View looking south-southeast of the late March surge of lava into the town of Vestmannaeyjar that stopped at the back of and in the street between the two fish- processing plants, Fiskiðan hf. (left) and Ísfélag Vestmannaeyja hf.(right), in late March 1973. Water-cooling operations were concentrated along the advancing edge of the lavas until the forward motion of the lavas was halted. Photograph taken by Richard S. Williams, Jr., U.S. Geological Survey, on 23 July 1973. A photograph taken a year later (July 1974) would show the lava flow completely removed and the street restored to use.

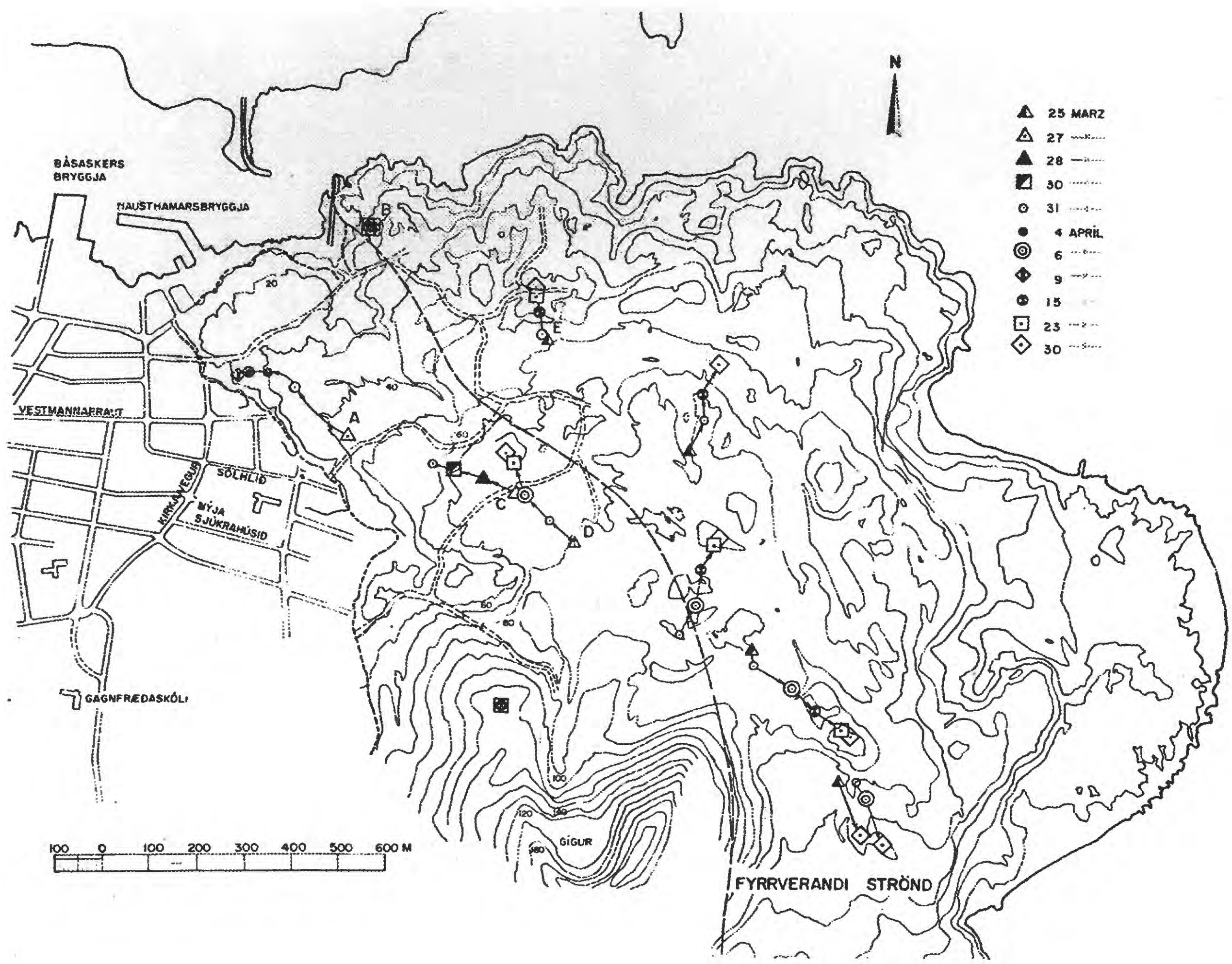

Figure 23. Map showing movement of the new lavas during a five-week period, from 25 March to 30 April. Movement was determined by ground photogrammetry (tracking fixed markers with a theodelite) or aerial photogrammetry (measuring the movement of fixed markers on successive, stereoscopic vertical aerial photographs). fyrrverandi strönd = former coastline.

Figure 24. Installation of pipeline to cool lava flows closest to the Eldfell crater. Photograph by Matthías Matthíasson

Other markers are in an area which was not cooled, and they seem to indicate that the lava speed was considerably more there than in the cooled lavas. In preparing this article, data was used from Landmælingar Íslands [National Land Survey of Iceland], Orkustofnun [National Energy Authority], and Forverk hf. [private company].

Lava-Cooling Costs

It is not an easy task to calculate exactly the cost of the cooling, because it is very hard to distinguish between the various tasks. As an example, the cost of building a rampart of tephra at the beginning of the eruption is not considered a cost related to the cooling. On the other hand, the retaining wall near Vilpa, which still exists, is included in the cost.

In the beginning it was difficult to separate salaries of people working on the lava cooling and others doing salvage and rescue work, because some people worked on both projects and consequently these figures can only be estimated. By March, this [mixing of tasks] has become less of a problem.

Table 3 is a summary of costs. It is divided into five sections: contracted services; salaries; materials; gasoline and oil; and pumping equipment. **Contracted services** amounts to 24 million Icelandic kronur or 17.8 percent of the total cost. The biggest item included is to Björgun hf. for the dredge *Sandey* or 7.55 million Icelandic kronur. Next is Vita- og Hafnamáskfrifstofan [State Lighthouse and Port Authority] with an amount of 2.26 million Icelandic kronur paid for barges and machinists, and Orkustofnun [National Energy Authority] with an amount of 1.13 million Icelandic kronur [expended] for drilling [operations] and workers [salaries, travel costs, and per diem].

The engineering services were mainly divided between a few firms, and the engineering-service costs covers both work in Vestmannaeyjar and on the mainland. The firms mostly used were: Hönnun hf. Verkfræðistofa FRV, Vermir hf., and the firm of Þórhallur Jónsson. Vélsmiðjan Héðinn hf. undertook the fabrication of various new items, especially connectors, as well as making replacement shafts for the ones that broke.

Miscellaneous services includes payments of less than 1 million Icelandic kronur to various parties. The majority of those were machine shops that offered their services for a limited time during the installation of the [high-capacity pumping] equipment from the United States.

Salaries totaled about 34 million kronur, or a little more than 1/4 of the total cost. These are salaries to all people registered with Viðlagasjóður [State Disaster Relief Fund].

Materials, mostly in connection with pipes and valves, amounted to 16.5 million Icelandic kronur, which is a little less than 1/8 of the total cost. **Gasoline and oil** for the engines that were connected to the pumps amounted to 1/8 of the total cost.

The last item and the largest totaled 44 million Icelandic kronur, which is a little less than 1/3 of the total cost. Included in this amount is the estimated value of **pumps and pumping equipment**, some of which were borrowed. About half of the pumps were borrowed; all of these were diesel pumps. They were returned in December 1973.

At the time that this article was written, the cost of the transactions with the United States has not been finally settled. It is estimated that the cost of the pumps that were not returned, because the United States declared that they do not need to be returned, is about 25 million Icelandic kronur. The Viðlagasjóður [State Disaster Relief Fund] put up this amount as a security deposit when the shipment [of pumps] arrived.

The total cost of the lava cooling amounted to 135 million Icelandic kronur, or a little less than 22 Icelandic kronur per metric tonnes of seawater pumped. If it is estimated that the average distance was about 1 kilometer, then this is not much compared with other means of transportation, especially when unfavorable circumstances are taken into account.

Table 3.—Summary of cost[6] of lava cooling [operations]

[Category]		Icelandic kronur (X1000)	Percentage
CONTRACTED SERVICES			
Björgun hf.		7,550	
Vita- og Hafnamálaskrifstofan [State Lighthouse and Port Authority]		2,255	
Orkustofnun [National Energy Authority]		1,125	
Engineering services		4,630	
Vélsmiðjan Héðinn hf.		2,090	
Miscellaneous services		6,405	
	Subtotal:	24,055	17.8
SALARIES	Subtotal:	33,960	25.2

[6]The monetary exchange rate at the time of preparation of this table is estimated to be 93 Icelandic kronur = $1 U.S.; e.g., 134,640,000 Icelandic kronur = $1,447,742 U.S.

MATERIALS		
Plastic Pipes from Reykjalundur-	1,560	
Vinnuheimill SÍBS		
Valves from Innkaup hf.	3,195	
Miscellaneous materials	1,370	
Subtotal:	16,125	12.0
GASOLINE AND OIL Subtotal:	16,500	12.3
ESTIMATED COST OF PUMPING EQUIPMENT LOANED/PURCHASED Subtotal:	44,000	32.7
TOTALS:	134,640	100.0

Source

Þorbjörn Sigurgeirsson, 1974, Hraunkæling [Lava cooling]: *Tíminn*, 19 January 1974.

Appendix No. 1

PUBLICATION OF SOURCE MATERIAL

The volcanic eruption on Heimaey is still fresh in people's minds. During the eruption many scientists and engineers worked on various research projects on Heimaey, and many of them were also active in the salvage operations and in the implementation of preventive measures taken to diminish the destruction caused by the eruption.

All of these undertakings were performed in an orderly manner and under the supervision of people who kept records of this work, including the results and outcome, so that conclusions can be drawn from their findings. Therefore, the people who were involved are in possession of important facts, few of which have been published so far.

During the eruption, the Association of Chartered Engineers in Iceland [Verkfræðingafélag Íslands] held two meetings in which the natural disaster was on the agenda. After the eruption, the Association held one more meeting and discussed the eruption and its consequences from the technical point of view. Five lectures about various phases of the eruption and the measures used were given by men who had spent long periods of time on Heimaey during the eruption and followed all undertakings closely. These lectures and discussions at meetings on the subject to be introduced have been mentioned in previous issues of the journal.

During discussions at a meeting after the eruption occurred, the people who had been working on Heimaey were challenged to publish articles about their experiences, because much of what happened there is extraordinary and has no comparison in the world under the circumstances in which it occurred. It was also pointed out that there exist various source materials that provide definitive information about the history of the eruption and functions performed and, therefore, were facts to be preserved for later information and references.

Tímarit Verkfræðingafélags Íslands [the Journal of the Association of Chartered Engineers in Iceland] immediately made arrangements to publish some of the source material that was discussed at the aforementioned meeting and now publishes the first article about the subject that was on the agenda at the meeting. The journal [editor] has received assurance that more material on the subject will be published in [future issues of] the journal. The journal has, in previous issues, encouraged publication of such articles and would like to do so again.

In view of that, those who are in possession of source material about the eruption and measures taken during it, are encouraged to prepare them for publication, and at the journal offers its services to [all] those interested. We want to thank all the people who have already made the source material more accessible to the people who were unable to follow the eruption at such close quarters.

PL
[Páll Lúðvíksson, Editor]
[1974]

[Note: The table-of-contents page of the journal includes a photograph of Próf. Þorbjörn Sigurgeirsson, with the eruption in the background. The photograph was also used as the cover of this issue of *Tímarit Verkfræðingafélags Íslands* but is not included in this open-file report.]

BIOGRAPHICAL SKETCHES OF THE AUTHORS

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Prófessor Valdimar Kr. Jónsson was born on 20 August 1934. He finished the first half of his undergraduate studies in engineering at the University of Iceland in 1957 and received his degree in mechanical engineering from the DTH [Danske Technische Hochschule], Copenhagen, Denmark, in 1960, and his Ph.D. from the University of Minnesota in 1965, after five years of study and research there. He worked as an engineer for the "Regncentralen" in Copenhagen and for Orkustofnun [National Energy Authority] in Iceland in 1960. He taught at the Imperial College of Science and Technology in London from 1965 to 1969. He was professor at Pennsylvania State University in the United States [State College, Pennsylvania] from 1969 to 1972. He has published many scientific articles in English and U.S. technical journals.

Matthías Matthíasson:

Matthías Matthíasson, technical engineer, was born on 14 October 1937. He graduated from the DTH, Copenhagen, Denmark, in 1962. He did graduate work at the University of Kansas during the years 1962-1963 and 1964-1965. He worked for Hjá Íslenzkum Aðalverktökum [The Icelandic Prime Contractors] during the summer of 1962 and 1963 and for Vermir sf. engineering firm (now Vermir hf.) from 1963 to the present. In 1969, he became executive manager of the firm.

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