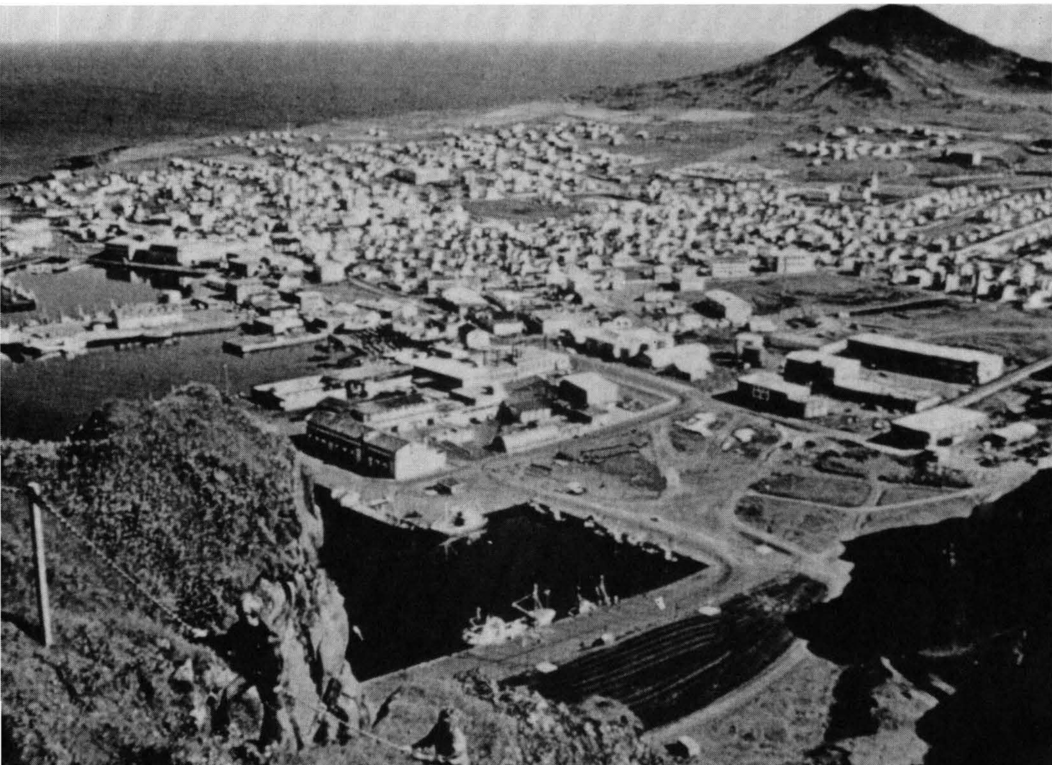
U.S. Department of the Interior/Geological Survey

Man Against Volcano:
The Eruption on Heimaey, Vestmannaeyjar, Iceland

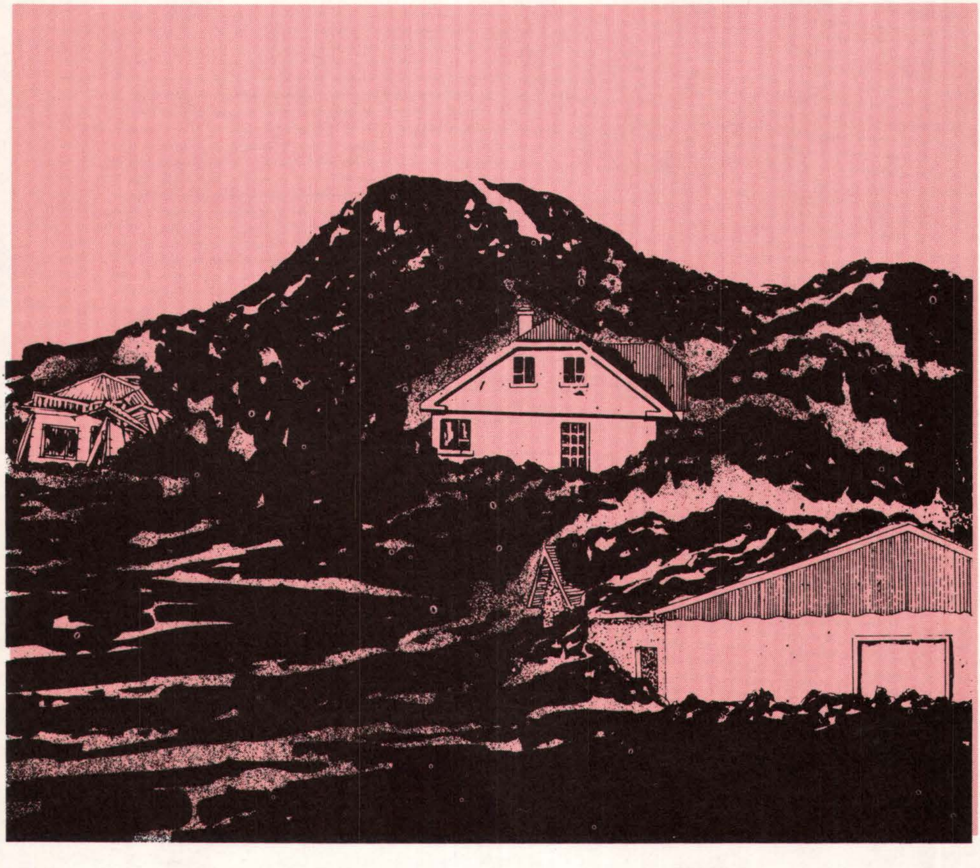
Cover photograph: View looking southeast along streets covered by tephra (volcanic ash) in Vestmannaeyjar: Eldfell volcano (in background) is erupting tephra and fountaining lava.



View of Heimaey before the eruption: Town of Vestmannaeyjar with Helgafell in the right background *(photo courtesy of Sólarfilma)*.

Man Against Volcano: The Eruption on Heimaey, Vestmannaeyjar, Iceland

by Richard S. Williams, Jr., and James G. Moore



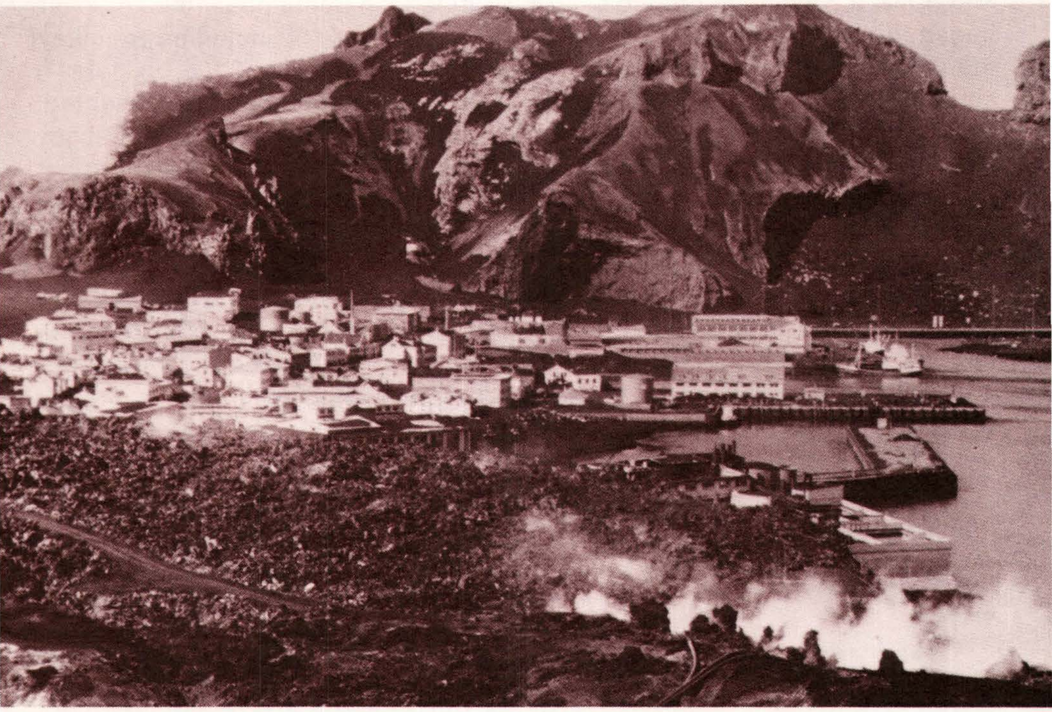
Preface

The U.S. Geological Survey carries out scientific studies in the geological, hydrological, and cartographic sciences generally within the 50 States and its territories or trusteeships, but also in cooperation with scientific organizations in many foreign countries for the investigation of unusual earth sciences phenomena throughout the world. In 1983, the U.S. Geological Survey had 57 active scientific exchange agreements with 24 foreign countries, and 47 scientific exchange agreements were pending with 30 foreign countries.

The following material discusses the impact of the 1973 volcanic eruption of Eldfell on the fishing port of Vestmannaeyjar on the island of Heimaey, Vestmannaeyjar, Iceland. Before the eruption was over, approximately one-third of the town of Vestmannaeyjer had been obliterated, but, more importantly, the potential damage probably was reduced by the spraying of seawater onto the advancing lava flows, causing them to be slowed, stopped, or diverted from the undamaged portion of the town.

The Survey was interested in the course of the Heimaey eruption because of the possibility that the procedures used to control flowing lava and to reduce the damage to a modern town may some day be useful in Hawaii and possibly even in the continental United States.

This publication is based on observations by the authors, both with the U.S. Geological Survey, as well as on information from the Icelandic Ministry for Foreign Affairs, Icelandic scientists' reports through the Center for Short-Lived Phenomena, other published scientific reports, and articles in popular publications. A number of Icelandic scientists studied the scientific aspects of the eruption. The engineering aspects of the control of lava flows were studied particularly by Prófessors Thorbjörn Sigurgeirsson and Thorleifur Einarsson of the University of Iceland's Science Institute. Also, during 1973, and in subsequent years, Icelandic officials provided support to the authors for this and other volcanological studies. In 1982, the U.S. Geological Survey and the National Research Council of Iceland signed a formal agreement (MOU-IC-1) for the exchange of scientific information in the geosciences, to facilitate exchange of scientific personnel, and to provide a mechanism for cooperation on scientific subjects of mutual interest, such as volcanology, seismology, geothermal studies, glaciology, and remote sensing.



Introduction

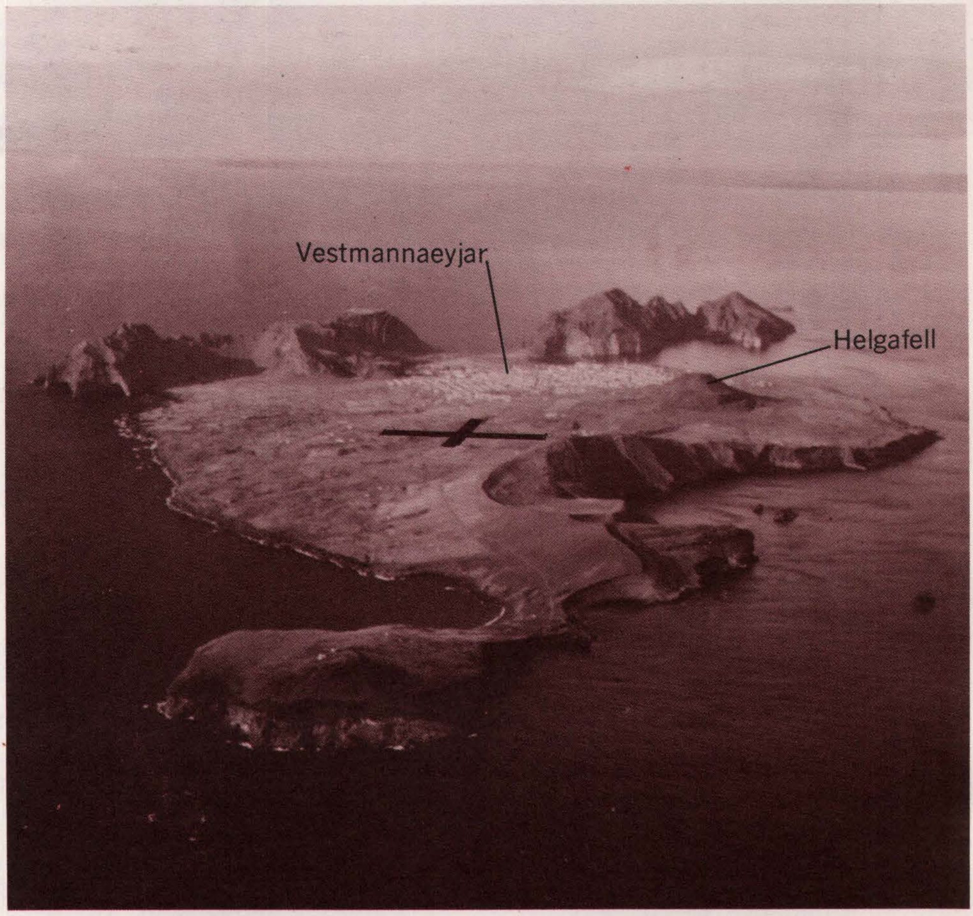
One of the most destructive volcanic eruptions in the history of Iceland began in the early morning of January 23, 1973, near the Nation's premier fishing port, the town of Vestmannaeyjar (Vést-mun-ayar), on Heimaey (Háme-a-ay), the only inhabited isle in the Vestmannaeyjar volcanic archipelago.

Both the fishing port and the group of volcanic islands have the same name—Vestmannaeyjar. In English, Vestmannaeyjar means Westmans' Islands. In Viking times, the Nordic peoples referred to the Irish and other Celtic men as "West" men. Tradition says that the group of volcanic islands, which includes Heimaey and Surtsey, got their name Vestmannaeyjar from escaped Irish (or Celtic) thralls who fled there after killing Hjörleifur Hródmarsson, sworn brother of Ingólfur Arnarson, the first person to permanently settle in Iceland.

The effusive January 23, 1973, eruption was the fifth in a sequence of 16 volcanic eruptions which have occurred in Iceland during the past 36 years. Between 1973 and mid-1983, for example, there have been 11 additional eruptions in Iceland, including 4 in 1980, 3 in 1981, and 1 in 1983. Two eruptions have occurred at Hekla in 1980 and 1981; 8 eruptions have taken place in the Krafla area of northern Iceland, where an active rifting episode (active spreading apart of the Earth's crust along the mid-ocean boundary between two crustal plates) began in late 1975 and still continues; and, in late

May 1983, a subglacial eruption began in the southwestern part of the Grímsvötn caldera which is situated in the western part of Vatnajökull, Iceland's largest glacier. The 1973 eruption on Heimaey was also the second major eruption (the other being Surtsey) definitely known to have occurred in Vestmannaeyjar since the settlement of Iceland in the ninth century, although there is evidence of a submarine eruption in the archipelago in September 1896. At least 13 offshore (14 including Heimaey) and approximately 125 onshore eruptions have been documented since Iceland's settlement in about A.D. 874. Ten of the 13 offshore eruptions occurred along the submarine Reykjanes Ridge, an extension of the Reykjanes peninsula. This Ridge lies along a parallel fracture system approximately 110 miles west of the northeast-southwest-trending Vestmannaeyjar.

Oblique aerial view looking north-northwestwards of the island of Heimaey, Vestmannaeyjar, Iceland, in August 1966, showing the fishing town of Vestmannaeyjar, the east-west-trending harbor in the background, and the extinct volcano Helgafell rising to 741 ft in the right center of the island. On January 23, 1973, lava began to pour from a 0.9-mi north-northwest-trending fissure to the east (right) of Helgafell. Eldfell eventually grew to be similar in height to Helgafell, 0.6 mi to the northeast.



Volcanic Eruptions in Iceland During the 36-Year Period: 1947-1983

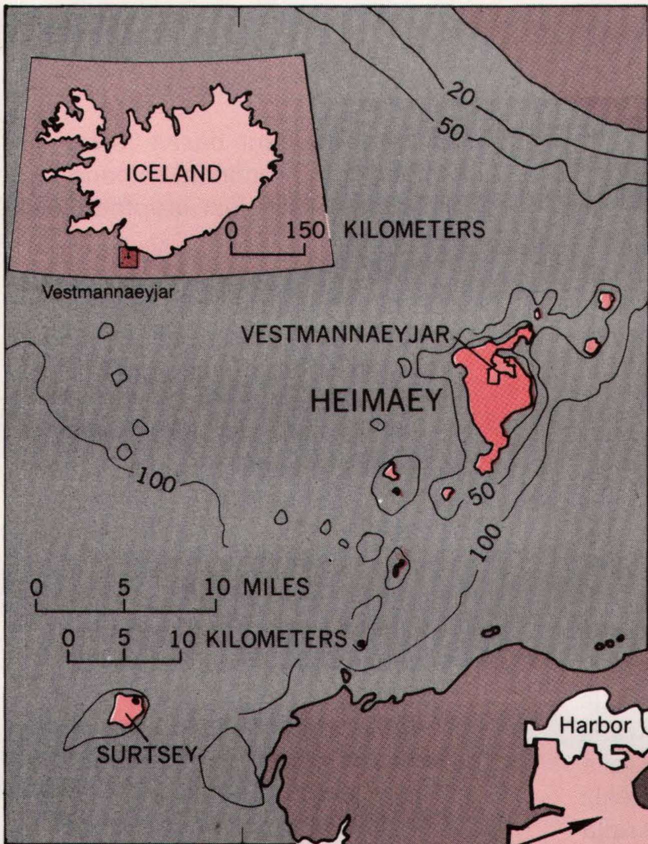
Date of Start of Eruption	Geographic Location
March 29, 1947	Hekla
October 26, 1961	Askja
November 14, 1963	Surtsey (Vestmannaeyjar)
May 5, 1970	Hekla
January 23, 1973	Heimaey (Vestmannaeyjar)
December 20, 1975	Krafla
April 27, 1977	Krafla
September 8, 1977	Krafla
March 16, 1980	Krafla
July 10, 1980	Krafla
August 17, 1980	Hekla
October 25, 1980	Krafla
January 30, 1981	Krafla
April 9, 1981	Hekla
November 18, 1981	Krafla
May 19, 1983	Grímsvötn (Vatnajökull)

Except for the main island of Heimaey, all the islets in the archipelago are composed of Holocene (geologically recent; that is, less than 10,000 years old) basalts, and, except for Surtsey, the islets are bounded by high sea cliffs and extend out of the sea as a series of stacks. Surtsey has a sandy point to the north and a narrow boulder and cobble beach fringing the rest of the island, including the steep lava cliffs on its windward side and *indurated* (hard and compacted) tuff on the west. Rocks of Pleistocene age (the span of geologic time from about 3 million to 10,000 years ago) crop out on the north and south parts of the island of Heimaey. These are overlain by younger Holocene basalt flows capped by a prominent volcano, Helgafell, which last erupted 5,000 years ago.

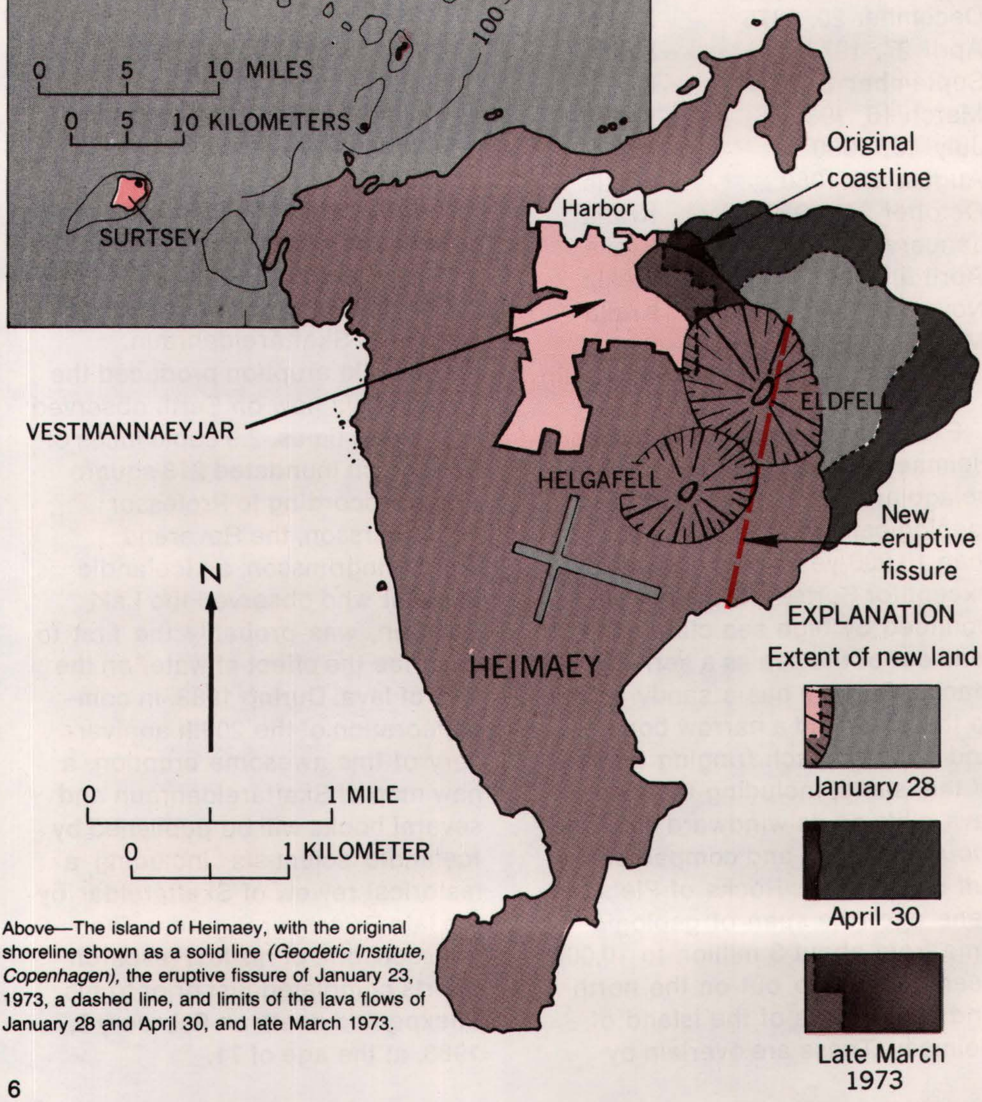
The Vestmannaeyjar islands parallel the structural trend of tectonic fissures (gjár), grabens, and crater rows on the mainland to the north in the eastern volcanic zone. This is a zone of historically active volcanoes, including Hekla, Katla, and the famous Laki fissure eruption of 1783.

The Laki eruption derives its name from a mountain (Laki) which was split by a fissure from which a large volume of lava and gas emanated. In Iceland, the eruption is referred to as Skaftáreldar; the crater row which formed along the fissure is called Lakagígar, and the multiple lava flows are collectively known as Skaftáreldahraun.

The Laki eruption produced the largest lava flow on Earth observed in historic times, 2.9 cubic miles of lava which inundated 218 square miles. According to Prófessor Sigurgeirsson, the Reverend Jón Steingrímsson, an Icelandic minister who observed the Laki eruption, was probably the first to describe the effect of water on the flow of lava. During 1983, in commemoration of the 200th anniversary of this awesome eruption, a new map of Skaftáreldahraun and several books will be published by Icelandic scientists, including a historical review of Skaftáreldar by the late Prófessor Sigurdur Thorarinsson, one of his last research efforts completed just prior to his unexpected death on February 9, 1983, at the age of 71.



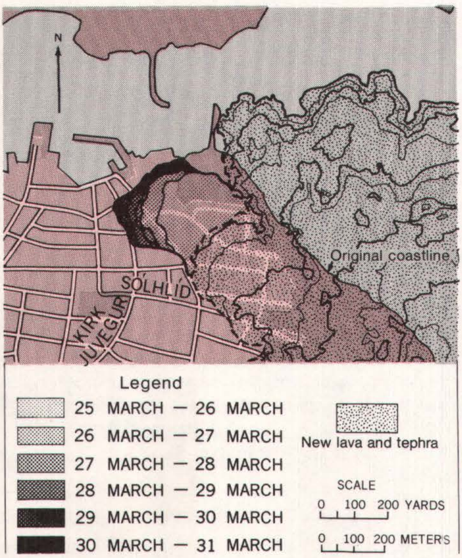
Left—Index map of Vestmannaeyjar *(modified from Thorarinsson, 1964, and Iceland Geodetic Survey).*



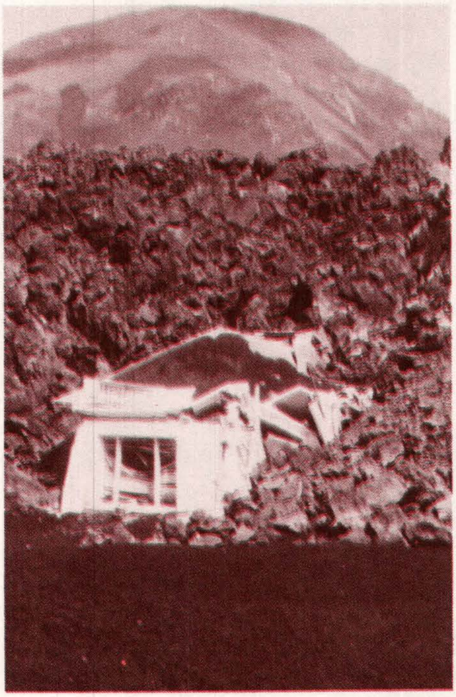
Above—The island of Heimaey, with the original shoreline shown as a solid line *(Geodetic Institute, Copenhagen)*, the eruptive fissure of January 23, 1973, a dashed line, and limits of the lava flows of January 28 and April 30, and late March 1973.

Course of the Eruption

The 1973 eruption began just before 2 a.m., January 23, on the eastern side of Heimaey, approximately 1,100 yards from the center of town. A north-northeast-trending fissure rapidly opened to a length of about 1¼ miles, traversing the island from one shore to the other. Spectacular continuous lava fountains (curtain of fire) played in the initial phase of the eruption, but the activity soon consolidated to a small area along the fissure about one-half mile northeast of Helgafell. Also during the first 3 days, submarine volcanic activity occurred just offshore at the north and south ends of the fissure vent. Within 2 days a cinder-spatter cone rose more than 110 yards above sea level and was later named Eldfell or "fire mountain" by the official Icelandic place name committee. The output of lava and *tephra* (a collective term for fragmental volcanic materials initially airborne, such as ash and bombs) was estimated to be about 130 cubic yards per second. Within a few days after the eruption, strong easterly winds resulted in a major fall of tephra on the town of Vestmannaeyjar, completely burying homes close to Eldfell. By early February the tephra fall slackened markedly, but a massive lava flow approached the eastern edge of the town and threatened to fill in the harbor of Iceland's most important fishing port. Also in early February submarine activity just



Daily movement of lava into Vestmannaeyjar in late March 1973. Cooling operations finally halted the flow against the fish-processing plants shown on pages 12 and 13. Light lines show former roads of the town under the lava field *(modified from Jónsson and Matthíasson, 1974).*



View on July 23, 1973, looking north toward a house engulfed by the March lava flow on the eastern part of Vestmannaeyjar.

north of the fissure severed an electric power cable and a water pipeline which supplied electrical power and water from the Icelandic mainland.

Icelandic geologists and geophysicists monitored the volcano continuously, both from the air and the ground. Frequent aerial photographs were taken by the Iceland Geodetic Survey. Foreign scientists also made short-term observations. Satellite studies and imagery of the eruption were acquired by both the NOAA-2 and the Landsat-1 satellites. Posteruption aerial photographic and thermographic surveys were carried out under a cooperative study by the U.S. Geological Survey and the University of Iceland Science Institute in association with the Icelandic National Research Council.

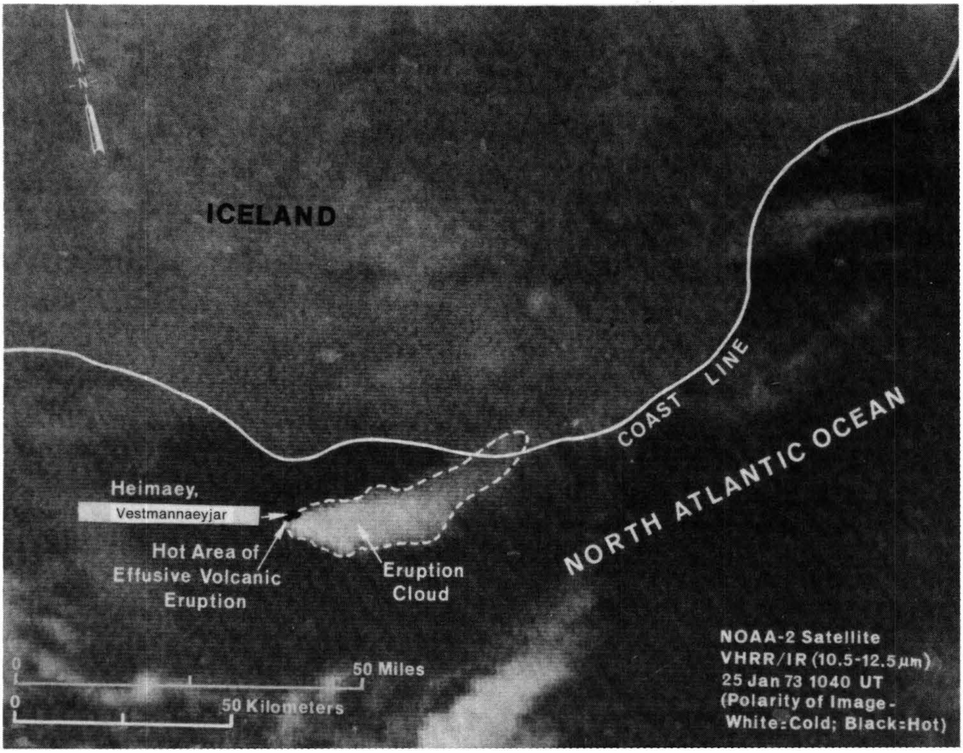
By the end of February the cinder-spatter cone was more than 200 yards high. The central crater of Eldfell fed a massive blocky (aa lava) flow which moved slowly but relentlessly toward the north, northeast, and east. By early May this flow was 10 to 23 yards high at its front, averaged more than 40 yards thick, and was as much as 110 yards thick in places. Its upper surface was littered with *scoria* (cinderlike fragments of dark cellular lava) and volcanic bombs, as well as large blocks from the main cone which broke off and were carried along with the flow. The largest block soon was dubbed "Flakkarinn" (The Wanderer). Some of these blocks of welded scoria were about 200 yards square and stood 20 yards above the general lava surface and were rafted more than 1,000 yards. Measurements made from a series of aerial photographs taken from the end of March to the end of April indicated that the lava was flowing as a unit about 1,000 yards long by 1,000 yards wide with an average speed of 3 to 9 yards per day.

As the flow advanced to the north and east, large blocks slumped from the cone on February 19 and 20 and moved toward the southeastern part of town. Also, in late March a second large lava flow moved northwest on the west side of the main flow and covered many houses and the town powerplant.

By February 8, lava ejection dropped from about 130 cubic yards per second to 80 cubic yards per second; by the middle of March to 13 cubic yards per second; and by the middle of April to about 7 cubic yards per second. As noted before, easterly winds blew tephra over the town during the early stages of the eruption. By January 29, the thickness of tephra varied from less than 1 yard in the

(Top right.)
Eruption of Eldfell volcano as viewed from the NOAA-2 weather satellite, 33 hours after the eruption began. The plume extends 37 mi downwind to the east, away from the town of Vestmannaeyjar. This thermal infrared image also shows the "hot" area of lava flows at the base of the plume *(National Environmental Satellite Data and Information Service, NOAA)*.

(Bottom right.)
View on July 23, 1973, southeast across homes partially buried by tephra. Vapor-shrouded Eldfell looms in the distance. Pipes which conveyed seawater to the lava flows cross the tephra in the middle ground. Gases rise from the tephra behind the telephone pole.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ICELAND
COAST LINE
NORTH ATLANTIC OCEAN
Heimaey,
Vestmannaeyjar
Hot Area of
Effusive Volcanic
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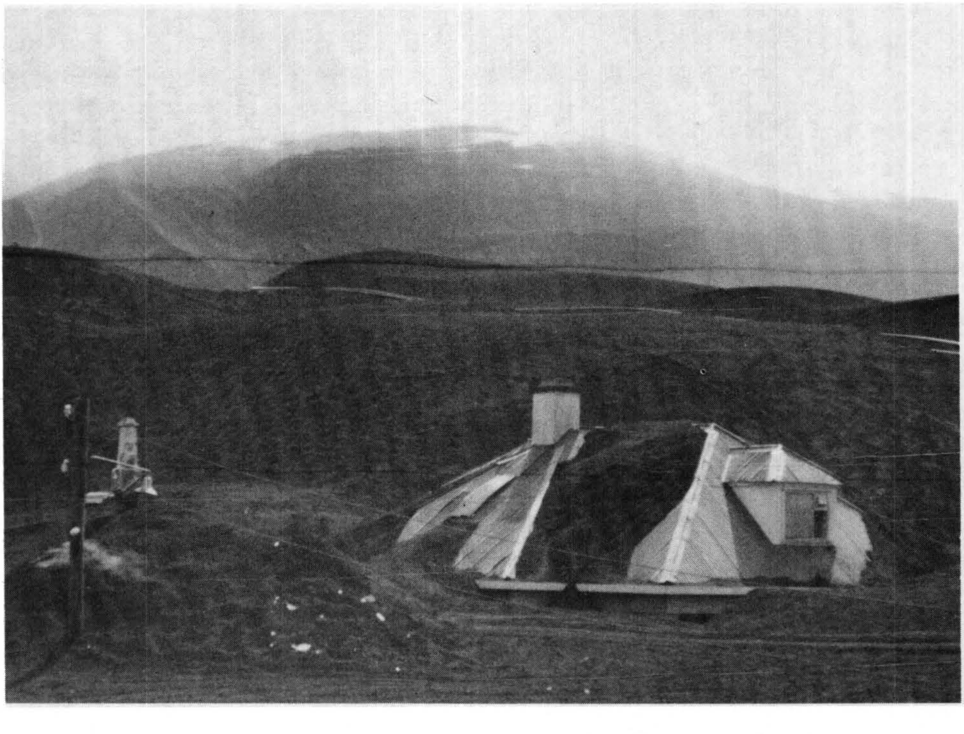
White=Cold; Black=Hot)

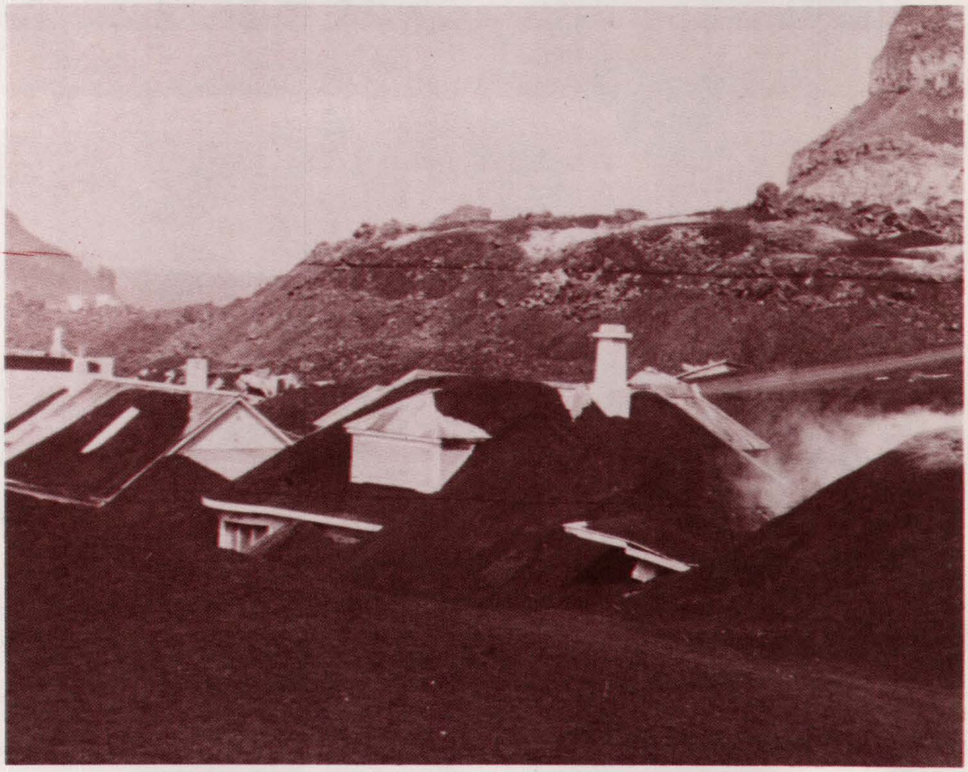


northwest part of town to more than 5 yards in the southeast part.

The eruption stopped in early July 1973; flowing lava was no longer visible, although hidden subsurface flow may have continued for awhile. Earlier, on May 26, for example, short-lived submarine activity was discovered by a fishing boat captain about 4 miles northeast of Heimaey only 1 mile from the Icelandic mainland. According to preliminary estimates about 300 million cubic yards of lava and 26 million cubic yards of tephra were deposited on and adjacent to Heimaey.

Studies of the volcano's eruptive products by a number of Icelandic scientists have shown that, as the eruption progressed, the composition of the material changed until it became similar in composition to the lava making up the island of Surtsey. This compositional change implies that the lava probably came from a zoned magma chamber enriched in alkalies and silica in its upper part. The chemical changes in the lava were accompanied by mineralogic changes as well as temperature changes. The temperature of the lava also varied from 1,885° to 1,930°F (1,030°-1,055°C) during the first week of the eruption and increased later to as much as 1,975°F (1,080°C).

View on July 23, 1973, north across homes partially buried by tephra in the eastern part of Vestmannaeyjar. The lava flows loom in the background. Gases that are moving through the tephra rise from the house on the right. The houses were eventually exhumed and restored.



Volcanic gases of widely varying composition were collected from several locations, showing that processes of gas fractionation operate effectively over short distances. Gases collected at sea along the submerged part of the active eruptive fissure were dominantly carbon dioxide. Gases collected at sea bubbling up from cooling submerged lava flows were found to be about 70 percent hydrogen.

Poisonous gas accumulated in low areas within the eastern part of Vestmannaeyjar and particularly was concentrated in houses partially buried by tephra. The gas contained 98 percent carbon dioxide and some carbon monoxide and methane. The gas had a subtle, somewhat sour odor. One fatality resulted from breathing gas within a building, and several other people were partially overcome by the gas.

The origin of the carbon dioxide is a matter of some conjecture among geologists familiar with its occurrence on Heimaey. Perhaps it separated from the other volcanic gases (chiefly water and sulfur dioxide) at the volcano's vent, flowed downhill to the town, and collected in low areas. Carbon dioxide concentrations also have been associated with eruptions from Iceland's best known volcano, Hekla; sheep have been found asphyxiated in small dales.

Another more likely possibility is that the volcanic gas moved up and outward from deeper within the volcanic conduit through older volcanic rocks directly into the town. Other gases were removed through condensation or reaction, and the travel path was such that carbon dioxide remained the dominant residual gas. A sizable tephra wall was constructed by bulldozers between the vent and town to divert the gas; a long trench was also excavated to permit the escape of steam. Neither barrier was completely effective.

Destruction Caused by the Eruption

The prolonged destruction related to the course of the eruption was twofold: the highly visible destruction of homes, public buildings and installations, commercial properties, and partial infilling of the harbor by tephra falls and lava flows; and the economic and social impact on the residents of Vestmannaeyjar, local commerce, and the national and international economy of Iceland.

Within 6 hours after the eruption began, nearly all of Heimaey's 5,300 residents had been evacuated safely to the mainland. This rapid evacuation was accomplished through the foresight of the Icelandic State Civil Defense Organization, which had a contingency evacuation plan ready for just such a disaster. The fishing fleet in port expedited the evacuation.

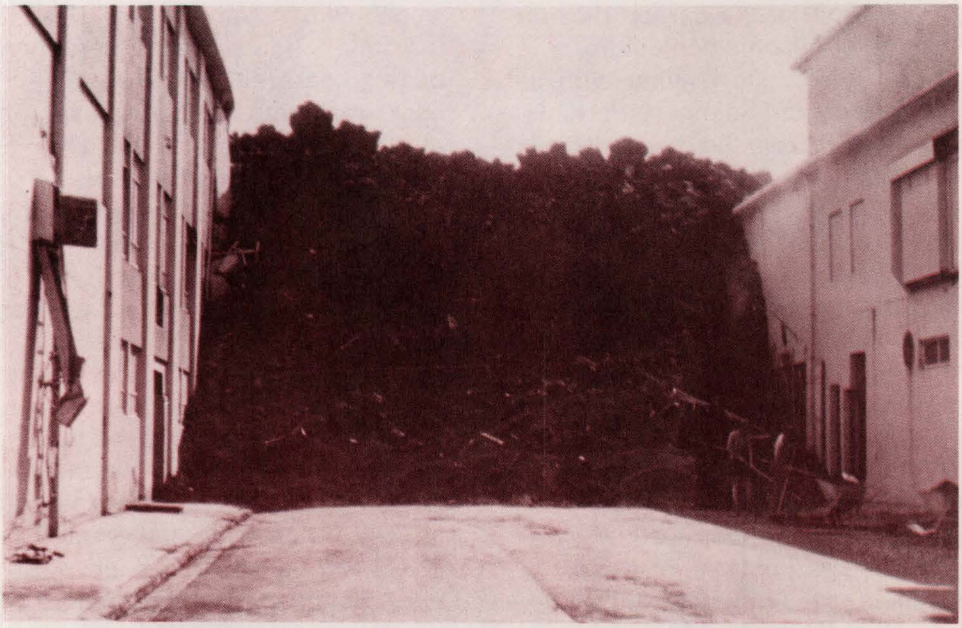
Homes and farmsteads close to the rift were soon destroyed by tephra burial or by fire from lava bombs and flows. The heavy tephra fall caused severe property damage a few days after the onset of the eruption. Numerous homes were completely buried by tephra, set afire by glowing lava bombs, or overridden by the advancing front of lava flows. Although many structures collapsed from the weight of the tephra, dozens were saved by crews of volunteers who cleared the roofs of accumulated tephra and tacked corrugated iron "shutters" over the windows.

By early February the lava had begun to narrow the harbor entrance, a situation which threatened the future use of Vestmannaeyjar as Iceland's prime fishing port. The harbor on Heimaey is the best along the entire south coast of Iceland and is located in the midst of some of the richest fishing grounds in the North Atlantic.

In late March, a new surge of lava into the eastern edge of the town destroyed a large fish-freezing plant, damaged two others, and destroyed the local power-generating facility and a great number of homes. By early May, some 300 buildings had been engulfed by lava flows or gutted by fire, and another 60 to 70 homes had been buried completely by tephra.

The economic and social consequences of the eruption will be felt for many years. The initial social impact was in the total upheaval of a 1,000-year-old island community. A proud and industrious people, with many close bonds of family and friendship, had been uprooted involuntarily, and their livelihoods altered in most cases. Short-term and long-term costs totaled many tens of millions of dollars, a very

View on July 23, 1973, southeast from dock area in the northern part of Vestmannaeyjar toward edge of lava flow where it stopped against and between two fish-factory buildings. Two boys can be seen in the right background sweeping up the tephra. By July 1974 the lava had been completely removed and restoration of the factories had begun.



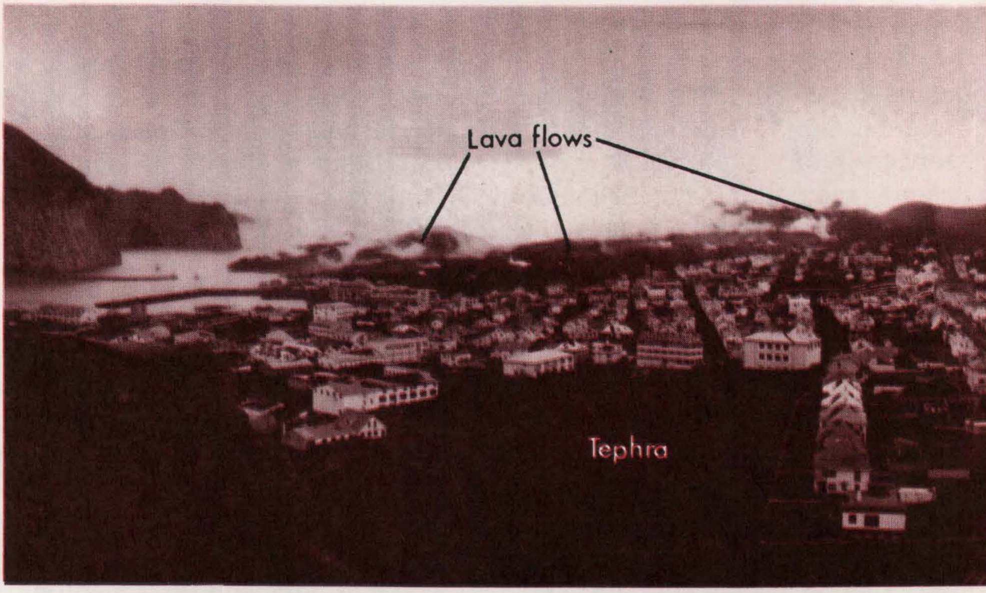
large amount when compared with Iceland's 1971 gross national product (GNP) of $500 million. The location and housing and other services for 5,300 people, for example, was equivalent in national impact to finding emergency housing with overnight notice for 5.3 million Americans.

Control of the Lava Flows

Icelanders, from the time of settlement to the present day, have had to contend with the consequences of natural disasters: volcanic eruptions, glacier outburst floods (jökulhlaups), earthquakes, advances of outlet glaciers, and periods of climatic change (usually caused by the presence of sea ice off the north and east coasts). All Iceland, either directly or indirectly, pitched in to lessen the burden on the residents of Heimaey.

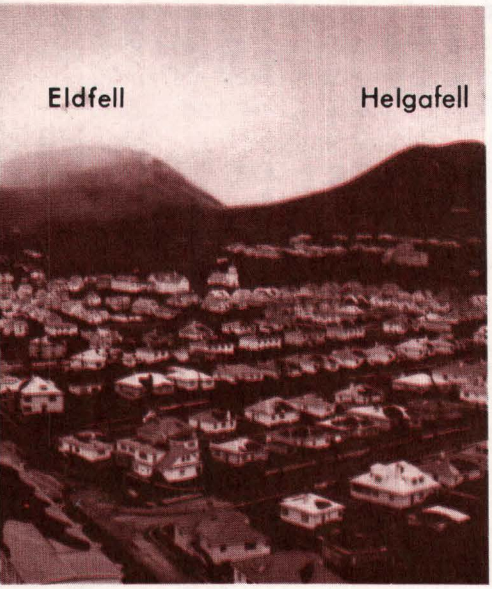
Of great interest was the decision by officials, on the advice of Icelandic geologists and geophysicists, to "fight" the lava flows. Drawing on field observations made on Surtsey, together with theoretical calculations on the cooling effect of water on molten lava, and on small experiments conducted on Surtsey and later on Heimaey at the beginning of the eruption, several Icelandic scientists recommended that cooling and hardening of lava by spraying of seawater be used to try to impede or stop the flow of lava on Heimaey. This effort ultimately became the most ambitious program ever attempted by man to control volcanic activity and to minimize the damage caused by a volcanic eruption. Consequently, it was an experiment of importance to other

View on July 7, 1974, southeast from dock area in the northern part of Vestmannaeyjar after removal of lava flow which had stopped against and between two fish-factory buildings.



A panoramic view east-southeast across the fishing port of Vestmannaeyjar on May 5, 1973. Dark, tephra-covered ground is apparent, with lava flows into the town and harbor in the left background.

View to the south from Vestmannaeyjar's outer harbor on May 4, 1975. Seawater is being sprayed directly onto the lava flow front to arrest infilling of the harbor entrance.



communities threatened by damage from volcanoes.

Advance of the main lava flow to the north initially threatened to close the entrance to Vestmannaeyjar harbor. Likewise, advance of the flow to the northwest threatened the town proper and the many fish-processing factories. Accordingly, a twofold program was begun in late February: lava cooling by spraying to increase the lava's viscosity and cause it to slow and thicken, and construction of a lava barrier on the flow's northwest margin to prevent its advance into the town.

A limited cooling operation was first begun on February 6, just 15 days after the eruption began. This use of the city water supply indicated that spraying water on the flow slowed its advance and caused the flow front to thicken and solidify. In early March a pump ship that could deliver a large volume of water was brought into the harbor. In late March and early April, large-capacity pumps were leased from the United States and were used to deliver water to the flow front and to selected sites on the surface of the flow.

In early April, pumps situated in the harbor were delivering seawater up to 1.3 cubic yards per second to various parts of the flow. Practically all this water was turned into steam. It cooled about 70 percent of its volume of lava to 212°F (100°C), substantially below the solidification point of basalt. The basalt is quite fluid at 1,800° to 2,200° (1,000°-1,200°C) and essentially ceases to flow by the time it cools to 1,500°F (800°C).

Water was pumped directly on the flow front at sea level and also was pumped through a number of primary plastic pipes. Each main pipe branched into a series of smaller pipes. In addition, a large steel pipe was used. More than 19 miles of pipe (75 percent plastic) and 43 pumps were eventually employed in the cooling program.

The most difficult aspect of the cooling program was to deliver large volumes of seawater to the surface of the flow far behind the flow front. The water effectively increased the viscosity, thereby producing internal lava barriers and causing the flow to thicken and ride up over itself.

First, the margin and surface of the flow were cooled with a battery of firehoses. Then a bulldozer track was made up the side of the slow moving flow. The water produced large volumes of steam which markedly reduced visibility and made road building difficult. Then

Part of northeastern Heimaey and the eastern part of Vestmannaeyjar showing deployment of pipes along northwestern edge of new lava flows on April 15, 1973, and access roads (dashed lines) bulldozed onto and through the lava field. Intake pumps are positioned along two harbor piers *(modified from Jónsson and Matthíasson, 1974).*

the larger plastic pipes were snaked up onto the flow; they did not melt from the heat as long as water flowed through them. Small holes in the pipes also helped to cool hot spots.

The discharge pipes were mostly 8 inches or 10 inches in diameter, delivering 13 or 26 gallons of water per second in one spot on the lava surface. From there the steaming water would gradually spread out. At the higher flowrate up to 3 acres of lava were engulged in dense steam. At each point water was poured on for about 2 weeks, until steaming near the point of discharge had decreased markedly. By then the lava flow had cooled to the boiling point of water to a depth of 10-15 yards.

Cooling of the flow margin was used in conjunction with bulldozed diversion barriers of scoria adjacent to the flow margin. The marginally cooled flow tended to pile up against the barrier rather than to burrow under it as would be the case if the flow were more fluid.

The water-cooling program produced a noticeable effect on the main lava flow. The lava was distinctively changed where water had been poured on it. Before watering, the flow surface was blocky and covered with partly welded scoria and volcanic bombs and had a distinct reddish, oxidized color. The general surface had a local relief of 1 yard or less, which was the general dimension of many of the blocks. Large masses of welded scoria which had broken off from the main cone, however, stood 10 to 20 yards above the flow surface. After watering, the general flow surface became much more jagged and had a local relief of up to 5 yards and was much more difficult to walk on. Cooling had apparently caused the more plastic interior of the flow to break upward and ride over itself.

The flow surface turned black to gray. In places closely spaced joints perpendicular to larger joints and shears were similar to the joints in pillow basalts. Elsewhere, white incrustations of salt coated fractures that were formerly deeper in the flows, where the cooling

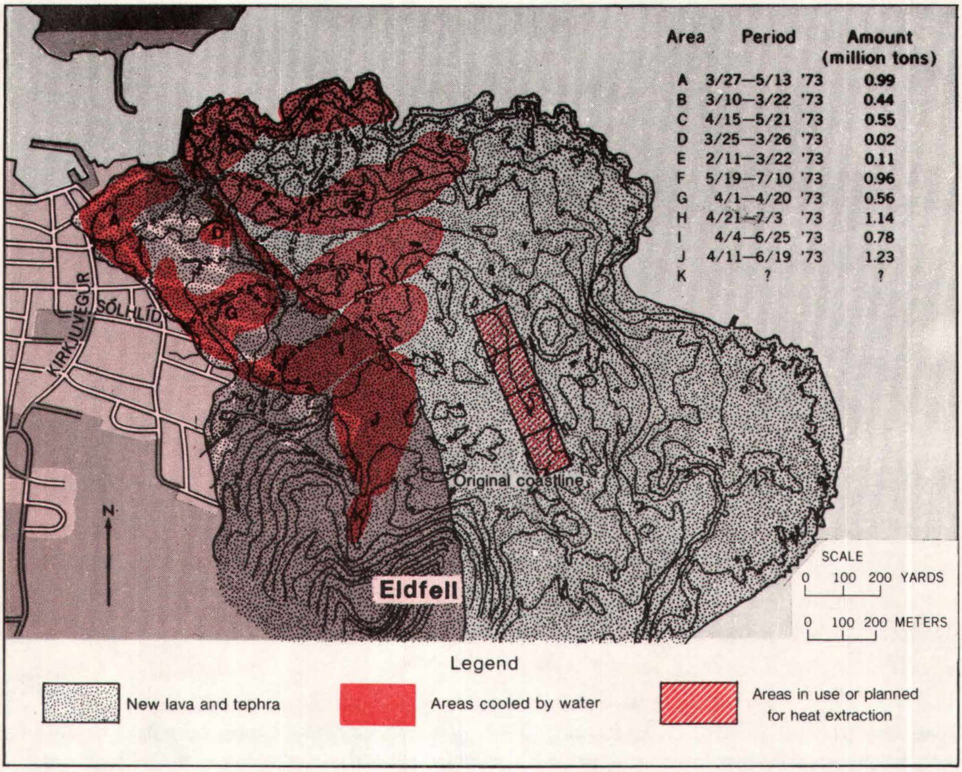
On May 4, 1973, workmen laid additional pipes to carry seawater up onto the lava flow front and tephra bulwark to cool and harden the still-flowing lava behind the chilled lava margin.

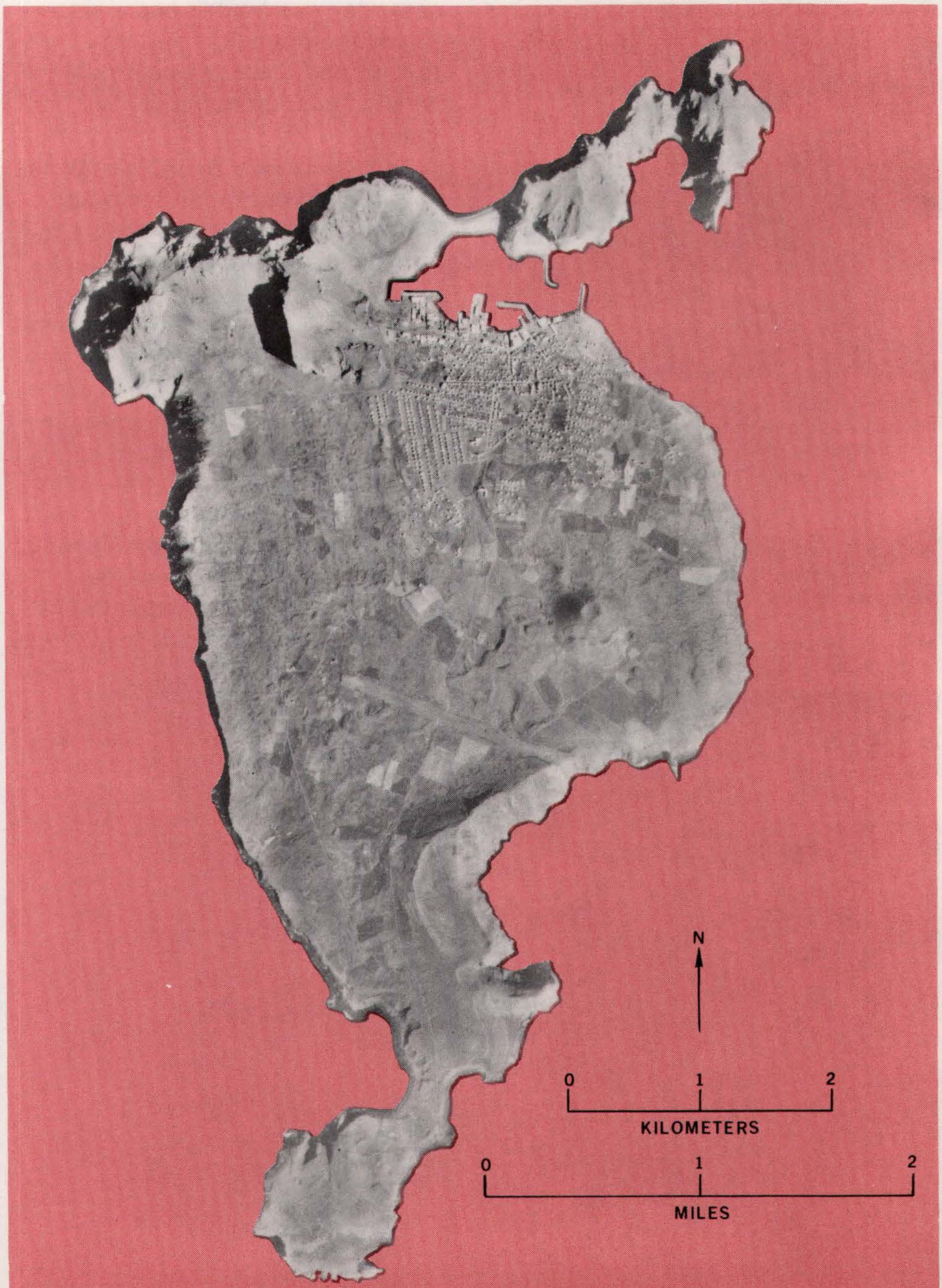
Area around eastern Vestmannaeyjar showing the parts of the new lava field that were cooled over different periods of time and the amount of seawater pumped. Heat extraction areas also shown *(modified from Jónsson and Matthíasson, 1974).*

seawater was heated and evaporated. The change in surface texture and color can be noted readily on color aerial photographs.

From February 6, 1973, until the lava cooling operation ended on July 10, 1973, approximately 8 million cubic yards of seawater were pumped onto the lava flows, converting about 5 million cubic yards of molten lava into solid rock. At the peak of the lava cooling, in early April 1973, 75 men were employed around the clock.

Like all volcanic eruptions, the Heimaey eruption was a special case, and the methods employed to control the lava flows were especially suited to local conditions. First, the initial eruptive fissure was





Vertical aerial photograph taken on August 4, 1960, of the island of Heimaey, Vestmannaeyjar, Iceland, showing the fishing port of Vestmannaeyjar, the crater of Helgafell volcano, and the single airstrip. *(photo by U.S. Air Force).*

Vertical aerial photograph taken on September 8, 1973, of the island of Heimaey, Vestmannaeyjar, Iceland, showing the fishing port of Vestmannaeyjar, the craters of Helgafell and Eldfell volcanoes, the double airstrip, and the new land on the east *(Iceland Geodetic Survey).*

only 1,100 yards from the center of a large town with an adjacent and economically important harbor, and consequently it was in the national interest to attempt to minimize damage. Secondly, the main lava flow was viscous and slow moving, allowing time to plan and carry out the control programs. Thirdly, seawater was readily available in the nearby harbor. And fourthly, transport by sea as well as by a local road system was good, and it was relatively easy to move in pumps, pipe, and heavy construction equipment. Nevertheless, it is likely that some of the lessons learned from the Heimaey experience can be adapted to eruptions in other places.

Scientists and planning authorities also had the benefit at Heimaey of detailed topographic maps rapidly produced from vertical aerial photographs. These maps, in connection with geodetic surveys, permitted measurement of the rate of movement of the main lava flow and an assessment of the best places to build lava diversion barriers. They also were critical in planning for administrative, engineering, and scientific purposes.

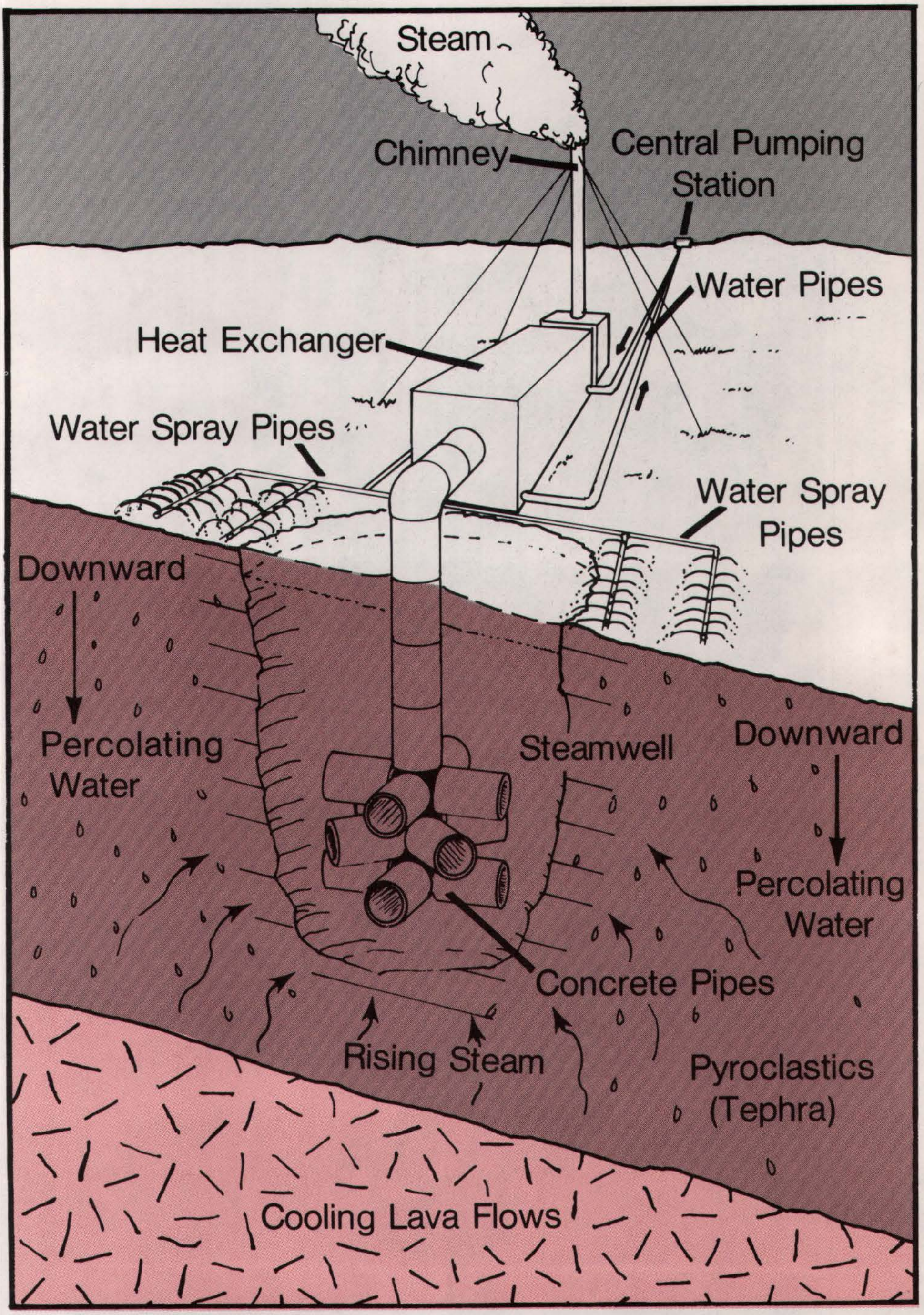
The water cooling and construction of lava barriers definitely have had a marked effect on the character and course of the lava flows on Heimaey. From boreholes drilled into various parts of the lava field north of Eldfell, temperature measurements indicated that the lava cooled 50 to 100 times more rapidly in areas sprayed with seawater than in areas of self-cooling. The placement and measurement of movement of markers (from ground surveys and aerial photographs) on the lava field substantiate the effect of cooling on the speed of lava flow. It has been established clearly that the work on Heimaey represented the greatest effort ever attempted to control lava flows during the course of an eruption; the total estimated cost for the lava cooling operations (labor, equipment, transportation, fuel, and others) was $1.5 million.

Extraction of Heat From Cooling Lava Flows

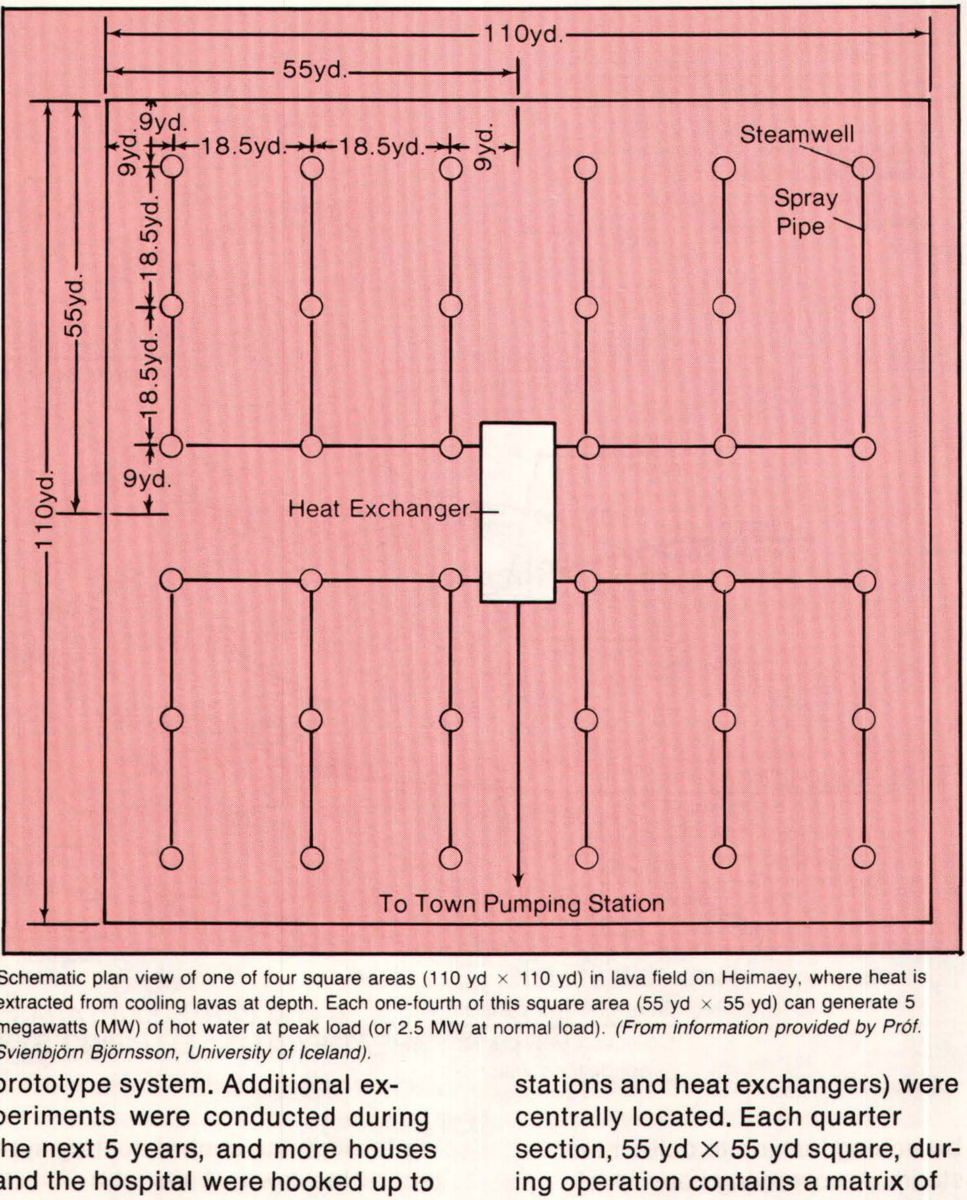
Scientists and engineers from the University of Iceland, residents of Heimaey, and an Icelandic engineering firm, Verkfraedistofa Gudmundar og Kristjáns, teamed up to create a district-heating system for the town of Vestmannaeyjar using the thermal energy from the cooling lava flows. Initial feasibility studies on the eastern part of the new lavas indicated that about 5 yards of scoria (tephra) lay on top of about 100 yards of new lava, all of which was resting on the former sea bottom. It was also determined that molten lava was slowly cooling inward from the top and bottom of new lavas, but that the thermal energy from this molten lava could be used to provide space heating to the town of Vestmannaeyjar.

By early 1974, heating experiments had proven successful, and the first house was connected to a

Vertical aerial thermograph taken on August 20, 1973, at 2233 hrs UT of the island of Heimaey, Vestmannaeyjar, Iceland, showing the thermal emission from joints and fissures in the cooling lava flows (compare with the September 8, 1973, aerial photograph on p. 19) *(courtesy of NASA).*



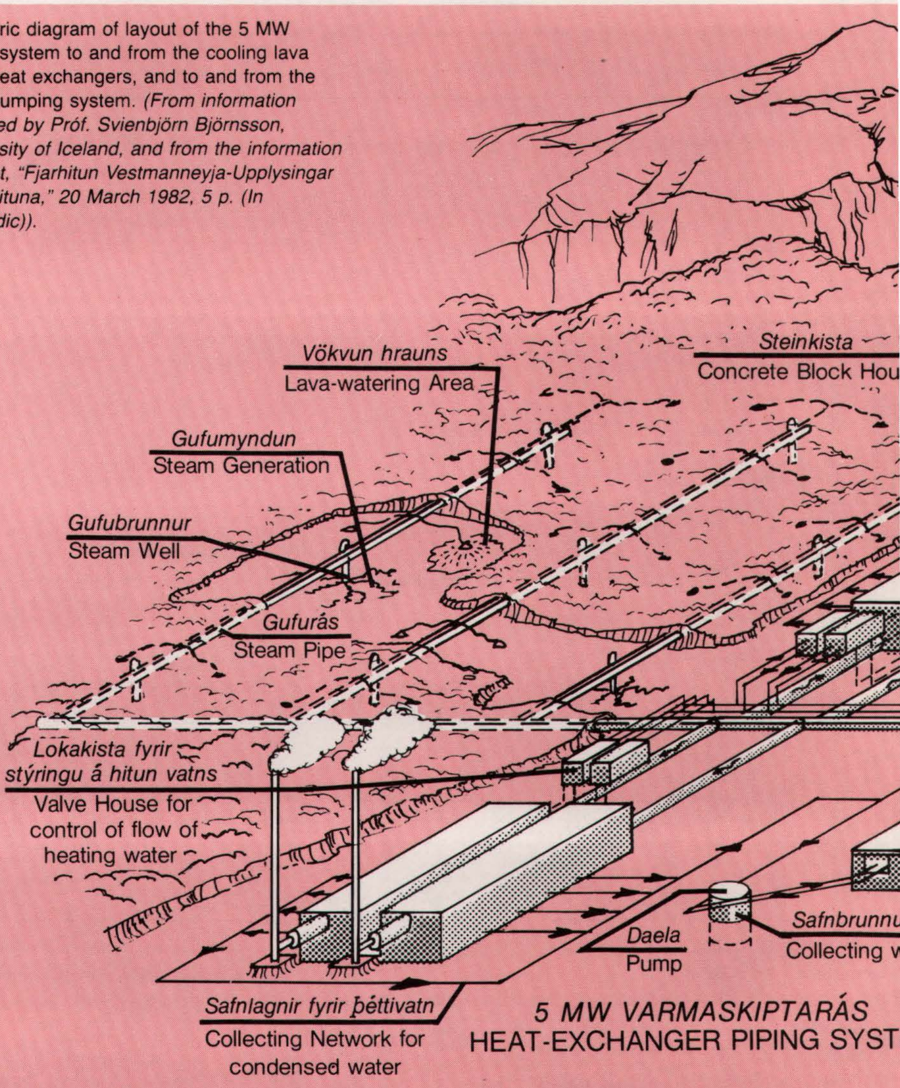
Cutaway schematic diagram of the subsurface emplacement of concrete pipes above the cooling lava and connection to the heat exchanger on the surface to provide a source of heat for a district-heating system for the town of Vestmannaeyjar. *(Modified from Björnsson, 1980, by permission of the author and the publisher, Atlantica and Iceland Review).*



Schematic plan view of one of four square areas (110 yd × 110 yd) in lava field on Heimaey, where heat is extracted from cooling lavas at depth. Each one-fourth of this square area (55 yd × 55 yd) can generate 5 megawatts (MW) of hot water at peak load (or 2.5 MW at normal load). *(From information provided by Próf. Svienbjörn Björnsson, University of Iceland).*

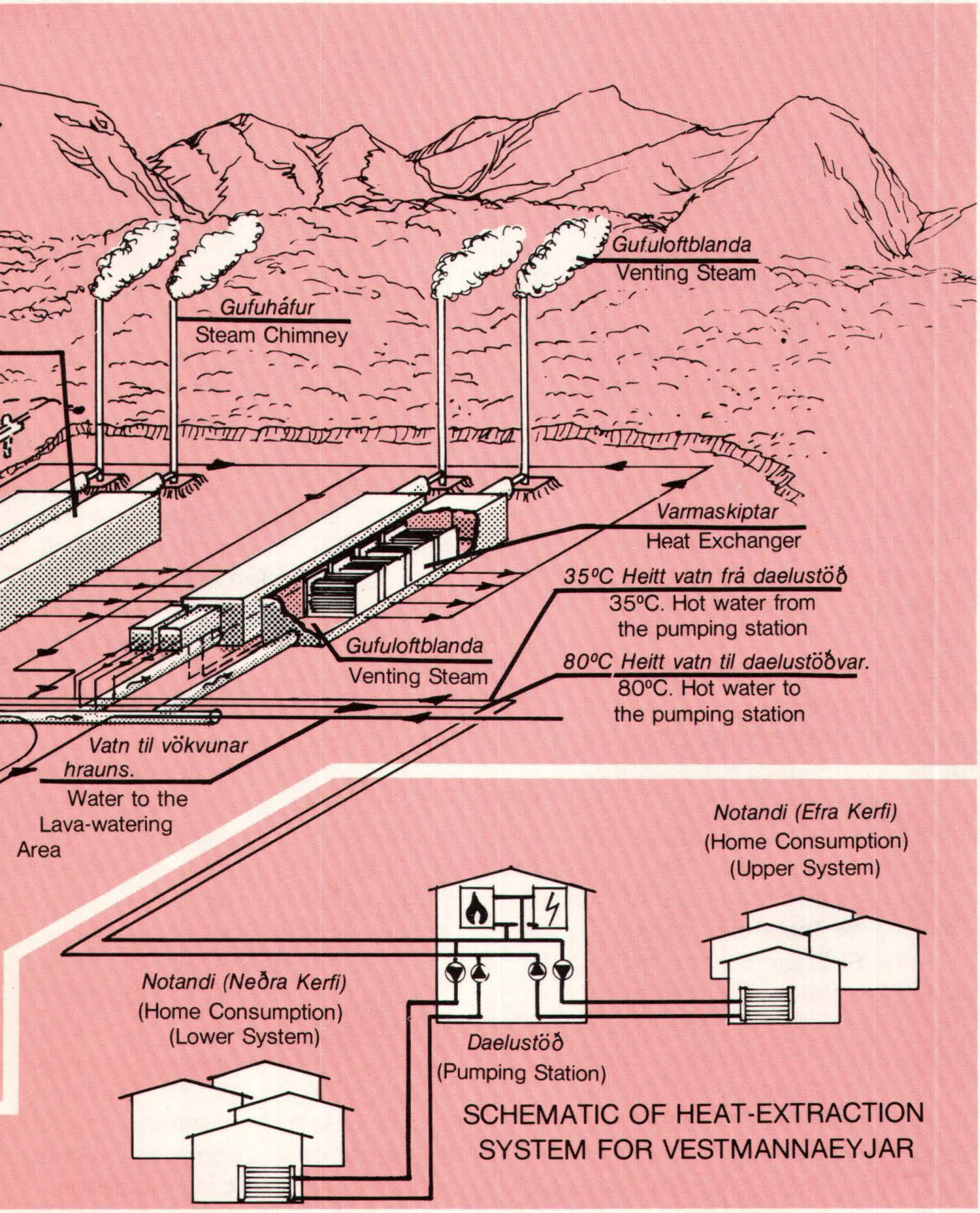
prototype system. Additional experiments were conducted during the next 5 years, and more houses and the hospital were hooked up to the heating system. By late 1979, with the design for a heating system based on cooling lava experimentally proven, a major engineering effort got underway to develop 4 areas, each 110 yd × 110 yd square, in the eastern part of the new lavas. Each area was designed so that the fixed facilities (pumping stations and heat exchangers) were centrally located. Each quarter section, 55 yd × 55 yd square, during operation contains a matrix of nine steamwells spaced at 18.5 yd intervals and is capable of producing 5 megawatts (MW) of peak power or 2.5 MW at normal operation. The steamwells are constructed in the unconsolidated tephra deposits, and a series of short concrete pipes are laid horizontally, one on top of the other, in a

Isometric diagram of layout of the 5 MW piping system to and from the cooling lava field, heat exchangers, and to and from the town pumping system. *(From information provided by Próf. Svienbjörn Björnsson, University of Iceland, and from the information booklet, "Fjarhitun Vestmanneyja-Upplysingar um Veituna," 20 March 1982, 5 p. (In Icelandic)).*



branching fashion to collect the steam. An overlying network of pipes sprays water onto the area surrounding the steamwells. The water percolates downward until it encounters the cooling lava where it is converted to steam. The steam rises vertically where it is collected by the steamwells and moves through pipes to the heat exchangers, which heat up water circulating through the central heating system of the town. Water at a temperature of 176°F is supplied to the town pumping station; 95°F water is returned from the town pumping station.

By early 1982, the district heating system had been connected to nearly every home on Heimaey. According to Dr. Sveinbjörn Björnsson, Professor of Geophysics



SCHEMATIC OF HEAT-EXTRACTION SYSTEM FOR VESTMANNAEYJAR

at the University of Iceland, the volcanic heat is projected to last about 10 years (an estimated 2½ years for each of the four 110 yd × 110 yd areas), after which a return to other energy sources will be necessary. Of practical importance to the United States and to other countries, however, is that the lessons learned by the Icelanders, in directly tapping heat from cooling lava, can be applied to other areas of active volcanism.

Conclusion

Even after all the devastation and disruption of lives and livelihood, the volcanic eruption had some peripheral benefits. On the plus side, the lava and tephra added nearly a square mile to the preeruption area of Heimaey, increasing the island's size by about 20 percent. About 2 million cubic yards of tephra have been cleared away from the town and have been used to extend the runways on the island's only airfield and as landfill for the siting of 200 new homes. Even the remaining heat of the volcano has been tapped, an effort first begun in January 1974, only 1 year after the eruption began. The tongue of lava that almost blocked the harbor entrance has also been turned into an asset and is now acting as a breakwater, helping to protect the harbor from storms.

Another aspect of the recovery effort was the enormous cleanup and restoration effort funded by all Icelanders through a special surtax and by Iceland's foreign friends. Substantial economic help was provided by the government and private groups and organizations of the other Nordic countries. The Danish Government was the biggest benefactor, providing direct assistance of $1,488,000. The U.S. Government provided $339,000 in direct and indirect assistance. Even the tiny Faeroe Islands contributed $97,600. The value of assistance from all nations was about $2,100,000, with an additional $380,000 provided by international organizations and private groups, such as the American-Scandinavian Foundation. By the summer of 1974, about 2,600 residents, or about one-half of the population, had returned and plans had been developed for the construction of an additional 450 new homes. By March 1975 the population had grown to 4,300 people, or 80 percent of the preeruption population. By December 1, 1982, the population of Vestmannaeyjar had reached 4,657. Vestmannaeyjar once again has become a vigorous fishing community, a laboratory for geologists, a major tourist attraction, and a testimony to the perseverance and courage of the islanders to turn, with the help of other Icelanders and foreign friends, a seemingly hopeless situation into a bright future.

The success of the islanders in their battle with the volcano has prompted other communities faced with volcanic hazards to look to the lessons learned on Heimaey. The worldwide interest has contributed to making Eldfell one of the best known volcanic eruptions in the world. Scientists in Iceland and around the world will be studying the photographs, aerial thermographs, and rock samples for years to come, looking for clues that will contribute to an understanding of the nature of volcanoes, as well as for methods to mitigate the destructive effects of future eruptions whether they be in Iceland, in the United States, or in any other inhabited volcanic region of the world.

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The measurements used in this publication can be converted to metric equivalents by using the appropriate entries from the following table:

Approximate Conversions

	To convert	to	Multiply by
Length	inch (in)	centimeter (cm)	2.5
	foot (ft)	cm	30.0
	yard (yd)	meter (m)	0.91
	rod	m	5.0
	statute mile (mi)	kilometer (km)	1.61
	nautical mile	km	1.85
Area	square inch (in^2)	cm^2	6.45
	square foot (ft^2)	m^2	0.093
	acre (43,560 ft^2)	hectare (ha)	0.405
	square mile	km^2	2.6
Volume	US:		
	quart (qt)	liter (L)	0.95
	gallon (gal)	L	3.8
	barrel (42 gal)	L	160.0
	cubic foot	m^3	0.028
	cubic yard	m^3	0.76
Mass	ounce (oz)	gram (g)	28.0
	pound (lb av)	kilogram (kg)	0.454
	short ton (2,000 lb)	metric ton (t)	0.907

The approximate conversions are derived from the following factors:

1 inch = 2.54 (exact) centimeters

1 pound = 0.4 535 924 kilograms

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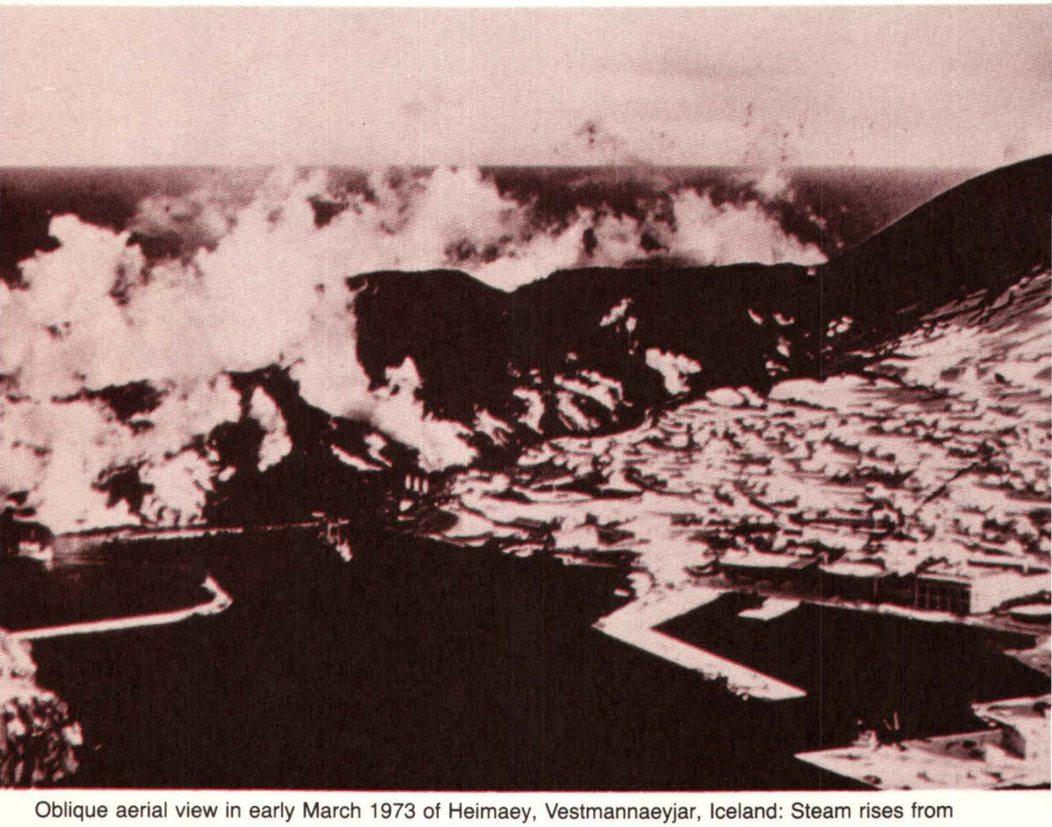

Oblique aerial view in early March 1973 of Heimaey, Vestmannaeyjar, Iceland: Steam rises from lava-cooling operations on land and from lava entering the sea *(photo by Gudmundur Sigfússon. Courtesy of Sólarfilma).*

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