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RESEARCH ARTICLE

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Constraints on the dynamics of subglacial basalt eruptions from geological and geochemical observations at Kverkfjöll, NE-Iceland

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Abstract The Kverkfjöll area, NE Iceland is characterised by subglacial basalt pillow lavas erupted under thick ice during the last major glaciation in Iceland. The water contents of slightly vesiculated glassy rims of pillows in six localities range from 0.85±0.03 to 1.04±0.03 wt %. The water content measurements allow the ice thickness to be estimated at between 1.2 and 1.6 km, with the range reflecting the uncertainty in the CO_2 and water contents of the melt. The upper estimates agree with other observations and models that the ice thickness in the centre of Iceland was 1.5–2.0 km at the time of the last glacial maximum. Many of the pillows in the Kverkfjöll area are characterised by vesiculated cores (40–60% vesicles) surrounded by a thick outer zone of moderately vesicular basalt (15–20% vesicles). The core contains ~1 mm diameter spherical vesicles distributed uniformly. This observation suggests a sudden decompression and vesiculation of the still molten core followed by rapid cooling. The cores are attributed to a jökulhlaup in which melt water created by the eruption is suddenly released reducing the environmental pressure. Mass balance and solubility relationships for water allow a pressure decrease to be calculated from the observed change of vesicularity of between 4.4 and 4.7 MPa depressurization equivalent to a drop in the water level in the range 440–470 m. Consideration of the thickness of solid crust around the molten cores at the time of the jökulhlaup indicates an interval of 1–3 days between pillow emplacement and the jökulhlaup. Upper limits for ice melting rates of order 10^{-3} m/s are indicated. This interpretation suggests that jökulhlaups can reactivate eruptions.

Keywords Pillow lavas · Subglacial volcanism · Iceland · Ice thickness estimates · Jökulhlaups

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Introduction

Pillow basalt formations are common in Iceland (Jones 1968; Furnes and Fridleifsson 1978; Fridleifsson et al. 1982; Walker 1992) and most examples were formed by subglacial eruptions during the last major glaciation. These formations are concentrated within Iceland's volcanic zone. In this paper we present an investigation of basalt pillow lava formations from the Kverkfjöll area, NE-Iceland. The area is close to the centre of Iceland, where the ice sheet during the last major glaciation of Iceland should have been thickest. We describe the geological features of the pillows in order to constrain the eruptive and environmental conditions. We focus particularly on the origin of vesicular cores to many of the pillows, which we relate to a depressurization event during eruption caused by jökulhlaup generation. We also measure the water contents of the glassy pillow margins using FTIR analysis. We use solubility relationships to estimate the thickness of the ice at the time of the eruption and the pressure drop associated with the vesiculation event. We also estimate time scales involved in these events and processes from consideration of cooling of individual pillows and the pillow pile.

General background

Pillows occur in three main types of settings in Iceland: (1) ridges and hillocks entirely made up of pillows, such formations only being found within the centre of Iceland; (2) the lower-most part of hyaloclastite formations in tuya-mountains (e.g., Herdubreid and Hrútfell in Iceland; Jones 1968) and hyaloclastite ridges, these formations being observed in the centre of Iceland as well as towards the coastal areas; and (3) as products of initially subaerial lava flows that have subsequently flowed into water. The sharp division between pillows and hyaloclastites that is observed in many sub-glacial volcanic formations is thought to reflect eruptive pressure conditions. McBirney (1963) and Sigvaldason (1968) suggested that pillows formed when the confining pressure was sufficient to inhibit significant exsolution of dissolved magmatic gas.

Morphological studies of pillows, viscosity considerations, analogue experiments, and numerical calculations suggest that pillow size and shape variations are primarily controlled by eruption rate and viscosity (Jones 1968; Moore 1975; Fridleifsson et al. 1982; Fink and Griffiths 1990; Walker 1992; Klingelhöfer et al. 1999). The cooling history of a pillow pile can be divided into two main stages. In the first stage the pillow is erupted into water and immediately exchanges heat with its surroundings. In the second stage the pillow is buried beneath later pillows and becomes part of the pillow pile. Any individual pillow is then surrounded by other, still-hot pillows and cooling is now by circulation of either water or steam through the pillow pile. After burial the cooling rate is expected to slow down. Another aspect of subglacial eruptions is that heat loss from the pillow basalt results in rapid melting of the surrounding ice (Hoskuldsson and Sparks 1997). The resulting large bodies of water are unstable and can escape from the ice in catastrophic outbursts or jökulhlaups. The sudden change of environmental pressure can feedback into the eruptive activity, causing vesiculation of the magma and a switch to explosive activity.

Confining pressure influences magma degassing and the amount of degassing is further limited by the pre-eruptive volatile content of the magma. At low pressures the most abundant magmatic volatile is H_2O, since the much less-soluble CO_2 starts degassing at much greater depths. The rapidly quenched glassy rims of pillows can provide information on the pre-eruptive volatile content of the magma. Since water solubility in magmas is pressure-dependent it can be used to estimate erupting pressures, provided that the magma can be shown to be volatile saturated. In turn the pressures can be used to estimate the thickness of either water or ice above the lava.

Methods

We measured pillow sizes, shapes, and other morphological characteristics in 6 different stratigraphically distinct pillow ridge formations in the Kverkfjöll area (Fig. 1). The Mount Virkisfell location was extensively studied with measurements on 101 pillows. We measured up to 10 pillows in each of the other five locations, measuring maximum width (horizontal length, H), and maximum depth (vertical length, V, perpendicular to H), to characterized each pillow cross-section. Pillows were further classified in the field as being ellipsoidal, spherical, sagged, or elongated according to there cross section. Pillow jointing was noted and the longest joints were measured. If vesicular bands were present they were counted and the distance between them measured. We also measured the width and height of vesiculated cores observed in many of the pillows of Mount Virkisfell. Samples were taken from selected pillows from the glassy rim through to the vesiculated core for further study. Pristine glassy rims of pillows were sampled for FTIR measurements of glass OH^- content, which was then calculated to H_2O content. Doubly polished glass chips (80–170 μm thick) were prepared from the glassy pillow rims for FTIR analysis. Analyses followed methods and procedures described in Danyushevsky et al. (1993) and Carroll and Blank (1997). Photographs of thin sections of 14 samples from Virkisfell were scanned into digital format and then analyzed by graphical software to measure accurately the form of vesicles and porosity of the samples. Bubble size distribution was analyzed by the method of Higgins (2000, 2002). For size distribution bubbles where treated as being spherical with a roundness of 0.8 and massive fabric as described in the CSD correction program version 1.32 (Higgins 2003).

Study area

The Kverkfjöll volcanic system, partly buried under the Vatnajökull ice sheet, forms the easternmost segment of the North Iceland Volcanic Zone, extending from Vatnajökull in the south to Melrakkaslétta 150 km to the north (Fig. 1). In Kverkfjöll pillow lava formations commonly form ridges elongated along the strike of the rift. The ridges are abundant close to the Kverkfjöll volcanic centre, where they commonly overlap each other. However, to the north along the rift system the abundance decreases and individual ridges are separated from one another. Near Kverkfjöll the ridges are largely composed of pillow lavas. The proportion of hyaloclastite in the ridges generally increases to the north along the rift zone.

The pillow ridges at Kverkfjöll rise from the central plateau at about 600 m up to about 900 m altitude. The ridges are up to 2 km wide at the base and stretch NE–SW for up to 5 km (Fig. 1). All the pillow ridges are feldspar-phyric quartz-tholeiite pillow lava, except for the ridge Karlsrani, which is aphyric. Typically the lavas contain 10–15% plagioclase phenocysts, although phenocryst abundance is very variable on a small scale due to segregation within individual pillows. All ridges are made of pillows from top to bottom (Fig. 2). Table 1 provides data on the dimensions and volume of each of the six ridges.

Kverkfjöll was close to the centre of the Quaternary ice sheet during the last major glaciation in Iceland (Einarsson 1995). Estimates from field observations on the height of Table Mountains in Iceland suggest that the maximum thickness of the Quaternary ice sheet in the Kverkfjöll area was around 1.5–2.0 km (Walker 1965). Model simulations based on early Holocene coastlines, mantle viscosity and ice plasticity further support these inferences (Sigmundsson and Einarsson 1992).

The composition of the glass rims of the pillows range from about 50.10 wt % SiO_2 at Virkisfell to about 48.09 wt

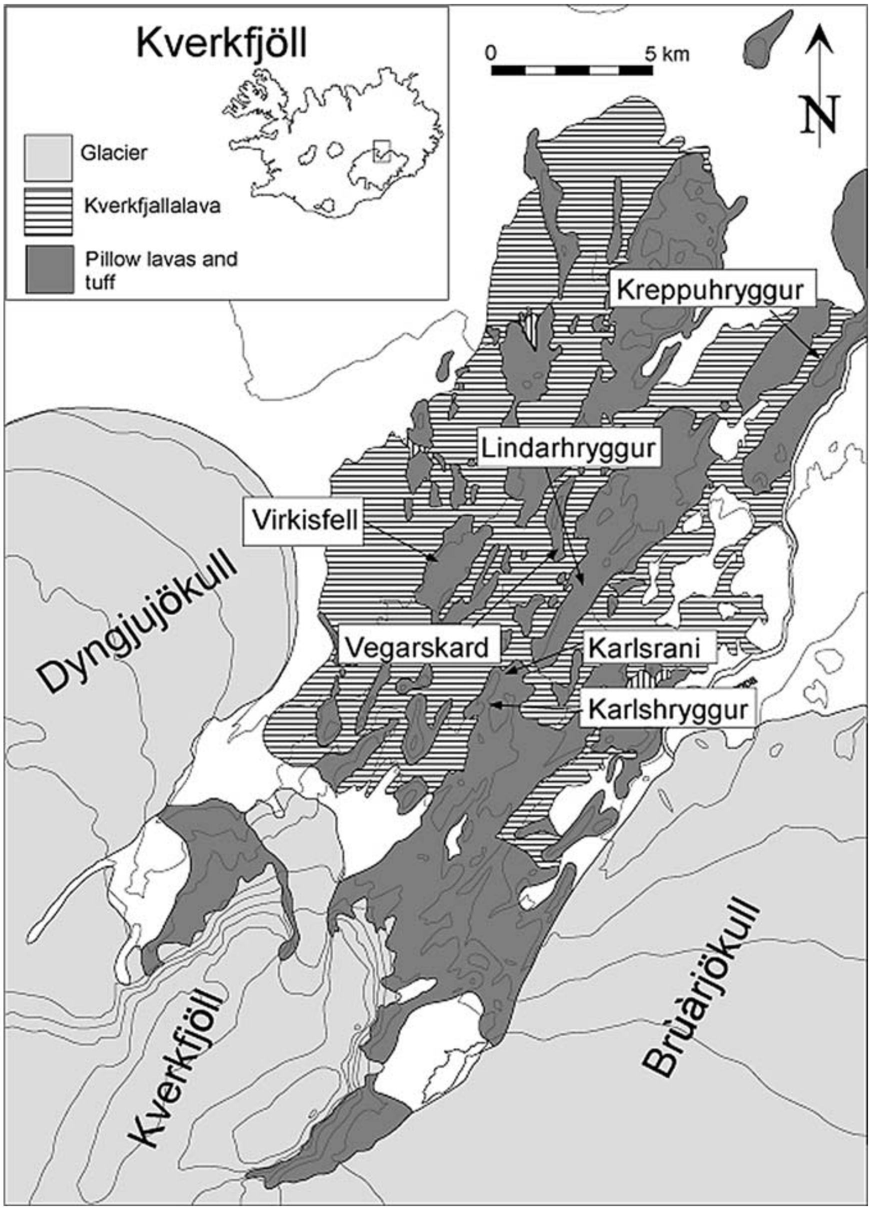

Fig. 1 Simplified geological map of the Kverkfjöll area in north Iceland. Pillow and hyaloclastite formations are Quaternary. Holocene lava flows and sediments fill up the land between Quaternary formations. Pillow ridges are elongated along the strike of the fissure swarm, NE-SW. Locations of the 6 pillow ridges studied are shown. Location within Iceland is shown on the inserted figure

Table 1 Dimensions and volumes of the pillow ridges at Kverkfjoll

	Virkisfell	Kreppuhryggur	Lindarhryggur	Vegarskard	Karlshryggur	Karlsrani
Length (km)	3	7	8	1.5	2.5	0.25
Width (km)	2	1.5	1	0.5	0.5	0.1
Height (km)	0.3	0.2	0.3	0.15	0.3	0.05
Volume (km^3)	0.7	0.7	0.5	0.1	0.04	0.001
Volume (km^3) (DRE)	0.49	0.49	0.35	0.035	0.028	0.0007

Volumes are estimated by assuming a cone with an elliptical base. Dense rock equivalent volumes (DRE) assume an average porosity of the pillow pile of 30%. Note that no correction has been made to estimate volume that has been eroded away

% SiO_2 at Lindarhryggur (Table 2). The ridges are composed of pillow basalt with highly fractionated compositions, characterised by low MgO and Mg numbers. The compositions of the basalts are within the quartz-tholeiite field. Phenocrysts of plagioclase up to 1 cm in length were observed in all samples except Karlsrani. The plagioclase crystals were commonly concentrated at the bottom at the pillows. However, they were also observed in lower concentrations in the glassy rim and the first few cm of the upper crustal zone of the pillows. At the Virkisfell location plagioclase phenocrysts are absent in the vesiculated cores. The glassy rims contain acicular plagioclase up to 300 μm

Fig. 2 A typical pillow lava section in Virkisfell. Hollows between pillows are filled with sediments and pieces of glassy rim that have been spalled off the outer crust. Vesicular bands and vesicular cores are common in Virkisfell pillows. Person for scale

in length. The pillows become more crystalline towards the core. The vesiculated cores at the Virkisfell location, however, are tachylitic with plagioclase needles.

The Mount Virkisfell pillows

Individual pillows at Virkisfell are characterised by two contrasting zones. Most pillows have a thick outer zone with poor to moderate vesicularity and a highly vesiculated core. The outer zones typically display concentric and alternating bubble-rich and bubble-poor layers. The contact of the outer zone with the highly vesicular core is abrupt (Fig. 3). In general the pillows show two distinct sets of jointing, which divide the outer zone into two sub-zones. The outermost 3–10 cm of crust is finely jointed with spacing as large as 1.5 joints per cm. Joint spacing then becomes wider towards the interior of the pillow, typically being 0.2 joints per cm.

The pillow shapes (Fig. 4) are most frequently ellipsoidal (46% of pillows) to spherical (31%), with the rest (16%) having a sagged base or forming flat sheets (7%) (Fig. 4). Measurements of the pillow shapes show vertical V-axes to be generally shorter than horizontal H-axes (Fig. 5). The average sizes of all pillows at each location have the range of H-axis 1.3–1.6 m and V-axis 0.7–1.2 m. The pillows in

Table 2 Chemical analyses of glass from rims of Kverkjoll pillow lavas

Sample	Karlshryggur *n*=40	Lindarhryggur *n*=10	Vegarskard *n*=11	Karlsrani *n*=9	Kreppuhryggur *n*=10	Virkisfell KG[a]
SiO_2	49.91	48.09	49.50	49.34	49.31	50.10
TiO_2	3.41	3.72	3.57	3.51	3.45	3.51
Al_2O_3	12.79	12.97	13.10	12.98	12.84	12.40
FeO_t	14.88	15.36	15.53	15.79	14.32	15.30
MnO	0.25	0.31	0.31	0.34	0.26	0.27
MgO	4.55	4.83	4.81	4.77	4.81	4.71
CaO	8.94	9.34	9.24	8.93	9.41	9.95
Na_2O	2.36	2.84	2.76	2.83	2.37	2.75
K_2O	0.63	0.69	0.67	0.67	0.72	0.65
P_2O_3	0.46	0.72	0.83	0.83	0.52	0.45
SO_3	0.26	0.34	0.34	0.36	0.34	
FO	0.10	0.30	0.33	0.32	0.16	
Cr_2O_3	0.01	0.02	0.01	0.02	0.02	
NiO	0.02	0.03	0.03	0.03	0.02	
Total	98.57	99.56	101.03	100.72	98.55	100.09
Mg#	23	24	24	23	25	24

All analysis carried out on the microprobe in Bristol, except for the analysis. Analyses are averages of n number of analyses, indicated by n. Analyses are not calibrated to 100

[a]KG that was furnished by K. Grönvold at the Institute of Earth Science, University of Iceland Reykjavík

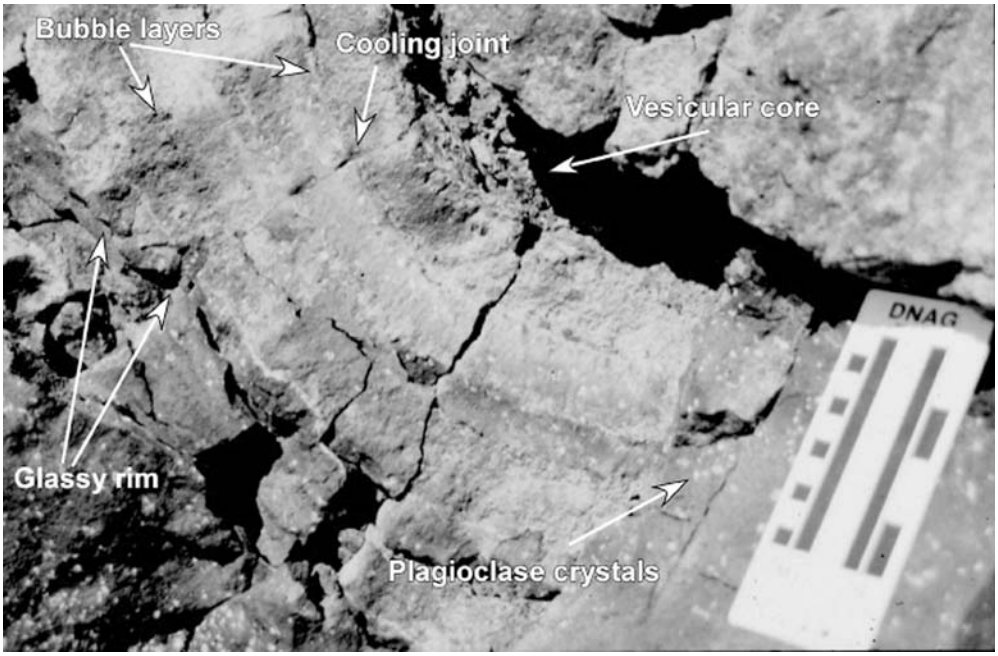

Fig. 3 Close up of a pillow in the Virkisfell pillow pile, showing the glassy rim, bubble bands, jointing and a vesiculated core. Dark lines on the card on the left side of photograph have a length of 10 cm

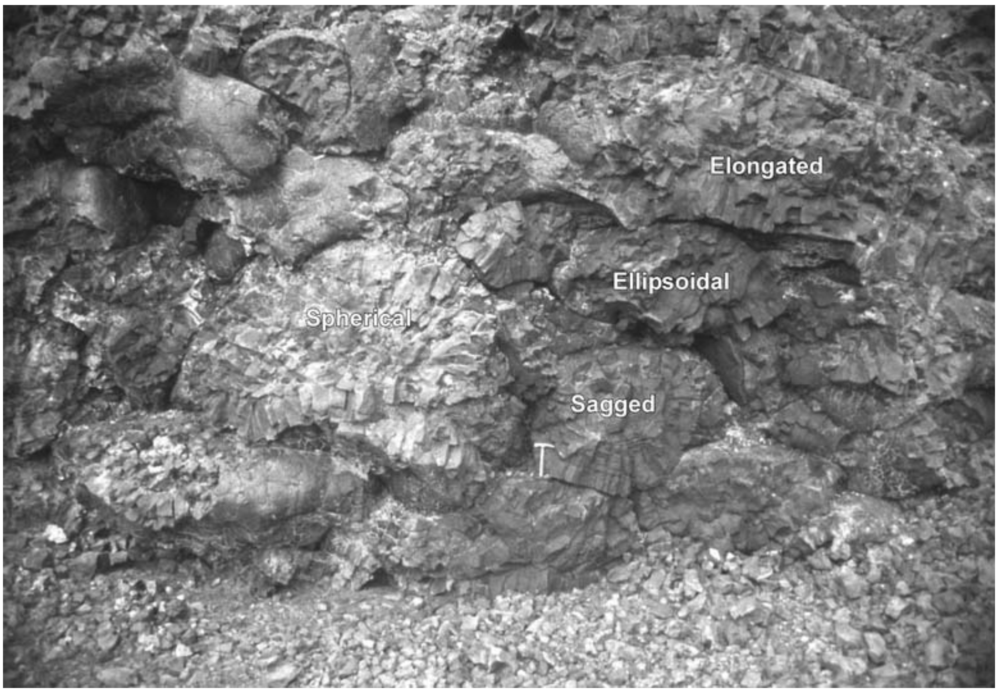

Fig. 4 Close up of a pillow section in Virkisfell. The pillows are randomly set in the pile and their size varies. Figure illustrates the forms of pillows, spherical, elongated, ellipsoidal and sagged. Geological hammer for scale

Virkisfell are significantly larger than those that have been previously described from southern Iceland where average H- and V-axes are 0.64 and 0.39 m (Jones 1968; Walker 1992). Their larger size may reflect the evolved composition of the basalt and, as a consequence, the relatively high viscosity of the lava.

The pillows have well-formed basaltic glassy rims with thicknesses ranging from 7 to 0.1 cm. On average the glassy rims are 1.5±0.5 cm thick based on 101 measurements. In these measurements we do not take into account chilled crust that has fallen off the pillow. Glassy crusts were frequently observed to be incorporated into the pillow interior, such that the outermost glassy crust overlaps glassy zones inside the pillow (Fig. 3).

Radial prismatic cooling joints are prominent in the outer zone of each pillow (Fig. 6). In the majority of pillows with vesiculated cores the joints stop abruptly at the margin of the vesicular interior (Fig. 6). In some cases the joints do not penetrate through the outer zone and thus there is a subzone of massive lava around the vesiculated core. Joints can, however, penetrate to the centre of those pillows that lack vesiculated cores. Maximum length of an individual joint was measured at 0.44 m in a pillow measuring 1.1 m along the H-axis. The shortest joint measured was only

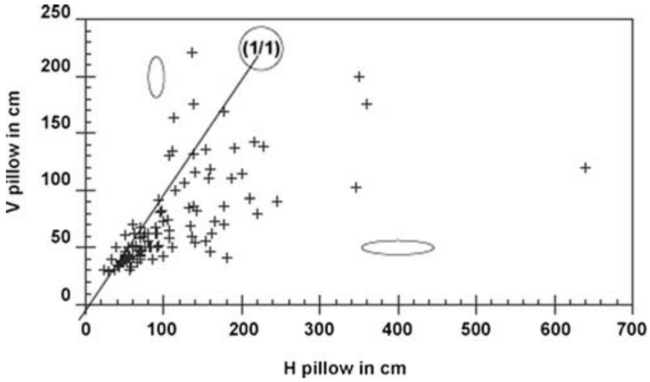

Fig. 5 Scatter diagram of pillow height (*V*) versus pillow width (*H*) from Kverkfjöll. The overall tendency in the scattered data set is that pillows get flatter as they get bigger

4 cm in a pillow measuring 30 cm along the H-axis. Bubble layers (Fig. 3) are best developed along the sides and top half of the pillows. There is a 1–7 cm massive zone between the bubble layers. Pipe vesicles described from southern Iceland pillows (Jones 1968; Walker 1992) were not observed in the Kverkfjöll pillows. About 80% of the pillows contained a highly vesicular core, having a sharp boundary with the vesicle poor margin. Typical dimensions of the cores range from a few tens of cm to a maximum of 170 cm by 60 cm (Fig. 7). In a few cases the pillows were observed to be hollow, with one or more lava terraces.

We converted the field data on pillow and core dimensions to a circle with an area equivalent to that of the pillow cross-section to derive an equivalent radius to characterise average pillow size and crustal thickness. There is a correlation between the equivalent radius of the vesiculated core, r_{core}, and the equivalent radius of the pillows, r_{pillow}, (Fig. 8a). Pillows without a vesiculated core plot on the *x*-axis. The thickness of the outer zone is calculated as the difference between the equivalent radius of the pillow and of the core. This crustal thickness does not show a good correlation with pillow size (Fig. 8b). This plot also shows that the pillows tended to have grown a crust between 5 and 40 cm before the interior vesiculated. The data show that pillows lacking vesicular cores are confined to those with an equivalent radius of less than 0.6 m, with the exception of one example. Those pillows with vesicular cores have outer zones ranging between 0.2 and 0.5 m, with the exception of two examples.

Vesiculation in the pillows

Vesiculation in the pillows is present from the rim to the core. The glassy rims have total vesicularity of 10–20% and show well-shaped bubbles with homogeneous distribution. The bubble-rich layers in the outer rim have a vesicularity of 10–25%, although the bubbles are not as regular in shape and distribution as in the glassy rim. In the bubble-rich layers gas pockets are common. In the outer zone the massive crystalline rock between the vesiculated bands has a vesicularity less than 5%. Vesicularity increases markedly in the core of the pillows, ranging from 40% to 60% with an average of 49±5% (Fig. 9). The shape of the cores in general correlated with the shape of the pillows (Fig. 10). However, cores tend to be significantly flatter than the host pillow. We attribute this feature to heat loss through the top surface of the pillow being greater than that through the sides and base where the pillow is insulated by neighboring pillows prior to burial.

Vesicle shape varies from the glassy rims to the outer zones and then again to the vesicular cores. Vesicles in the cores are typically larger, averaging around 2 mm in diameter. The most common major/minor-axis ratio for single vesicles in the cores is close to 1.0 and that for coalesced vesicles 1.1. Vesicles in the core are evenly distributed throughout the core. The vesicles in the glassy rim and the bubble layers are smaller, around 0.8 mm in diameter (Fig. 11). The bubble size distributions in the pillow rims and in the banded zone are similar to one another (Fig. 12). Bubbles in the size range of 1.5 mm and smaller make up most of the bubbles in sections from the rims and banded zones. Regression analysis suggests that bubbles exceeding 3 mm in size are present in the rims, although none were observed directly. The size distribution of bubbles in the pillow cores shows that the bubbles are much larger than in the rims or in the banded zones. Bubbles smaller than 1.5 mm are absent, while most of the bubbles are in the range 2–3.5 mm. BSD regression indicates that bubbles as large a 5 mm could be present in the cores, although none were observed (Fig. 12).

FTIR measurements

FTIR measurements were carried out to determine the water contents of the glassy rims of Mount Virkisfell pillows and the 5 other pillow formations in the Kverkfjöll area. Table 3 shows the results of the FTIR measurements. The glass making up the rim is fresh and unaltered and the FTIR measurements indicate water contents ranging from 0.85±0.03 wt % for the Vegaskar pillow margins to the highest value of 1.04±0.03 for the Karlsrani samples (Table 3). FTIR measurements of glassy pillow rim material showed no CO_2 above the detection limit (<30–40 ppm). All water was measured as OH^- and standard deviation (1σ) calculated from 10 analyses on each sample.

The water content in the glassy pillow rims can be used, together with the solubility law, to estimate the prevailing pressure (proportional to overlying water/ice thickness) when the basalt was quenched. Independent study of glass H_2O/K_2O values suggests that all samples we analyzed, except the sample from Karlsrani, had already undergone minor amounts of degassing (Nichols et al. 1998). The glassy margins were also quenched with 10–20% vesicles. These observations and results show that the magmas were saturated on eruption, a necessary condition if measured water content in the glass is to be used as a pressure meter.

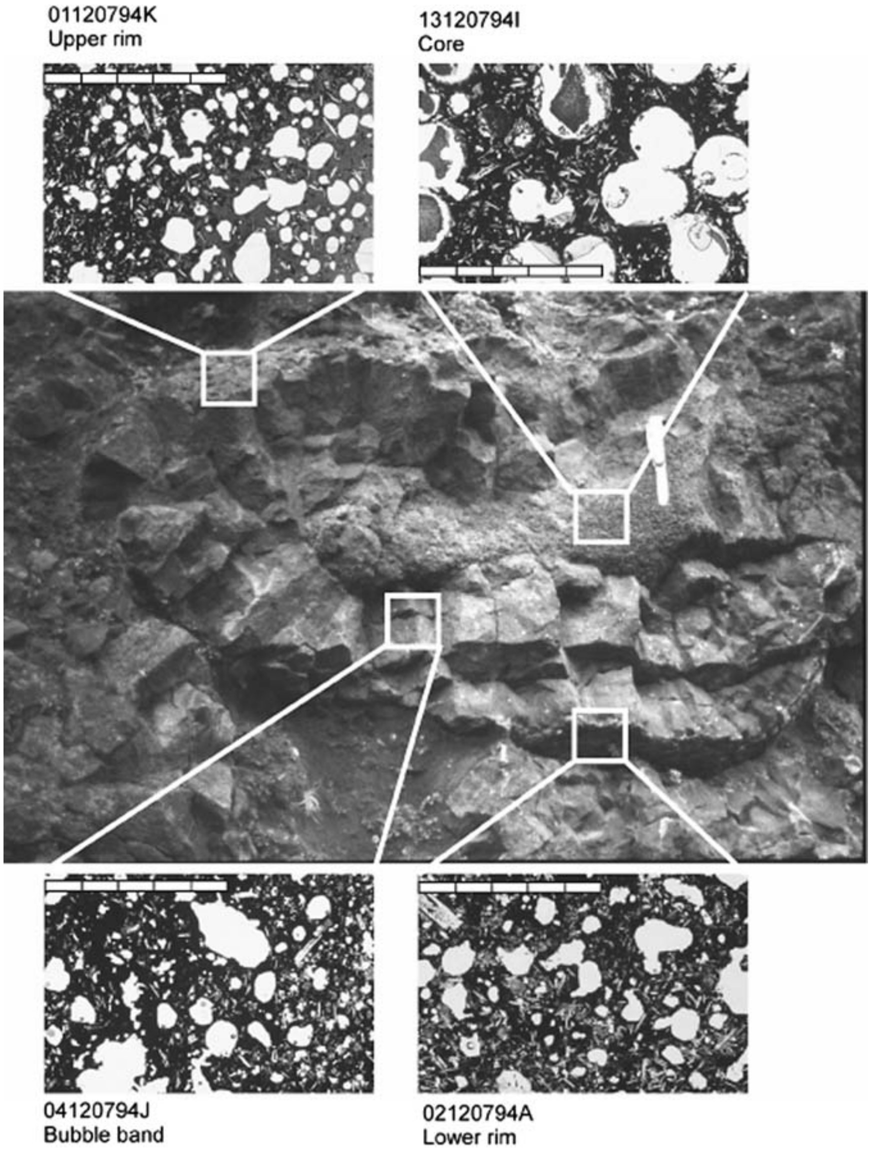

Fig. 6 A pillow in the Virkisfell pillow pile showing a well-developed vesiculated core. Note also the double jointing sets and that joints do not go through the core. Inserted figures: 1 Microphotograph of upper rim, 2 microphotograph of core, 3 microphotograph of bubble band and 4 microphotograph of lower rim. Note the changes in bubble size and crystallinity of the rocks. Swiss army knife for scale in pillow, scale bar on microphotographs is 5 mm long

Table 3 Calculated eruption pressures and ice thickness for pillow lavas of Kverkfjöll

	Sample					
	Virkisfell	Karlshryggur	Kreppuhryggur	Lindahryggur	Karlsrani	Vegaskard
water contents (wt %) H_2O	0.89±0.03	0.95±0.04	0.96±0.03	0.92±0.02	1.04±0.4	0.85±0.03
P (MPa) at 20 ppm CO_2	11.8±0.6	12.9±0.8	13.2±0.6	12.7±0.1	14.8±0.8	11.2±0.5
P (MPa) at 30 ppm CO_2	14±0.6	15.1±0.8	15.3±0.5	14.6±0.4	16.9±0.8	13.3±0.4
Ice thickness (m)	1314±66	1436±92	1467±63	1412±12	1643±86	1239±52
Max ice thickness (m)	1556±66	1674±87	1705±57	1617±43	1881±88	1478±49

Discussion

Estimation of eruption pressures and ice thickness

In order to calculate pressure from measured water contents in the glassy rims we used the solubility model of Holloway and Blank (1994), which is based on the earlier models of Spera and Bergman (1980) and Silver and Stolper (1985). Solubility parameters for H_2O in basaltic melt were taken from Dixon et al. (1995). The results are quite sensitive to CO_2 content of the melt. We used the calibration method of Dixon et al. (1995) to calculate saturation pressures as functions of H_2O, CO_2 and SiO_2 in the melt. We have no direct measurements of CO_2 content, except that the detection limits of the FTIR method indicate concentrations below 30–40 ppm. Observations of ocean ridge basalts (Fine and Stolper 1985; Dixon and Stolper 1995) indicate concentrations of hundreds of ppm CO_2 at pressures equivalent

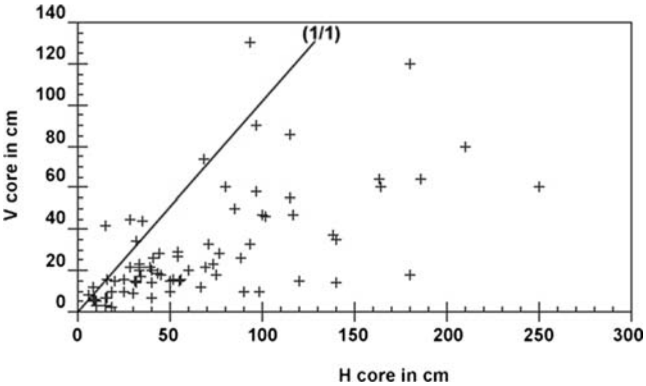

Fig. 7 Vertical and horizontal axis of the core. The *V*/*H* of the core in general reflects the shape of the pillow

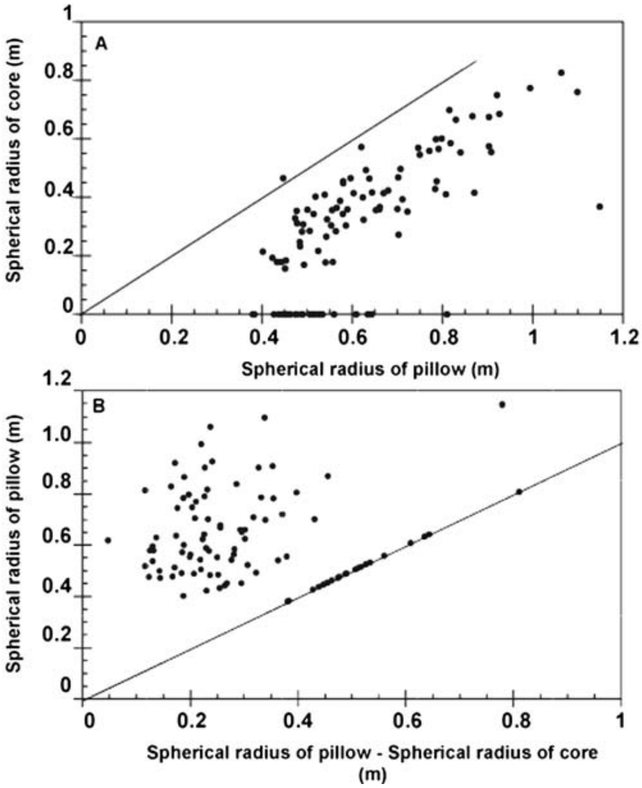

Fig. 8 **a**. Scatter diagram of the spherical radius of the core versus the spherical radius of the pillow. A level of slope 1 is shown. All pillows fall below the line indicating the time that the pillow had for cooling before the core started degassing. **b**. Scatter diagram showing the thickness of the upper crust versus (spherical radius of pillow – spherical radius of core) the spherical radii of the pillows. Drawn on the diagram is the line along which solid pillows fall. Most of the pillows have a crust from 5 to 40 cm thick. The crustal thickness indicates the time for which the pillows had to crystallize before vesiculation

to water depths of 3 km. Thus equilibrium CO_2 concentration can be estimated at the lower pressure environment of a subglacial eruption for a given magma water content by assuming that the ascending magma follows a closed system degassing path. Dixon and Stolper (1995) present a closed system degassing model of a basalt with 1% water

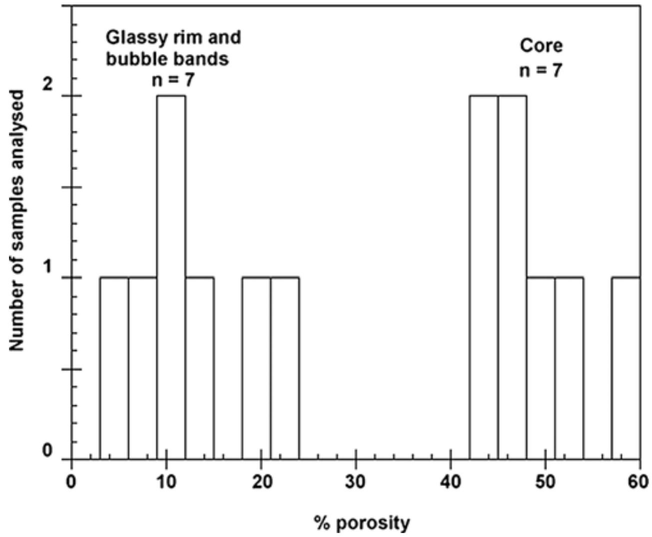

Fig. 9 Porosity measurements of pillows in Virkisfell. The porosity was measured from the rim towards the core in 14 samples. There is a striking increase of up to 30% in porosity when the core is reached

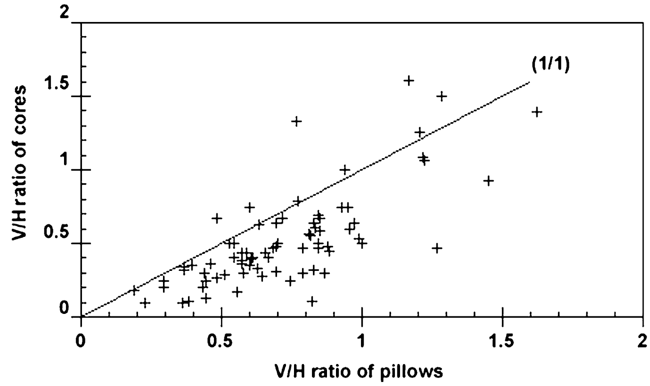

Fig. 10 Scatter diagram of height/width ratios of cores versus pillows. The data set shows how the size of the molten cores in the pillows is affected by the size of the pillow tube

and 500 ppm CO_2. Their calculations yield approximately 20 ppm CO_2 at 10 MPa pressure, which we will show *a posteriori* is close to our evaluation of the environmental pressures of the Kverkfjöll eruptions. We thus assume a CO_2 content of 20 ppm. We also calculate pressures for the case of 30 ppm, which provides an upper limit on the confining pressure.

We calculate pressures from the measured H_2O contents of glassy pillow rims ranging from 11.2±0.5 MPa to 14.8±0.8 MPa if 20 ppm CO_2 present. The upper limit pressure estimates (based on 30 ppm CO_2) range from 13.3±0.4 MPa to 16.9±0.8 MPa (Table 3). The uncertainties quoted here reflect both the analytical uncertainties in H_2O content and model parameters. All of these estimates must be considered as maximum pressures because it is possible to quench supersaturated melts during eruption.

The local pressure at the site of pillow eruption is assumed to be the overburden of the ice sheet and any subglacial

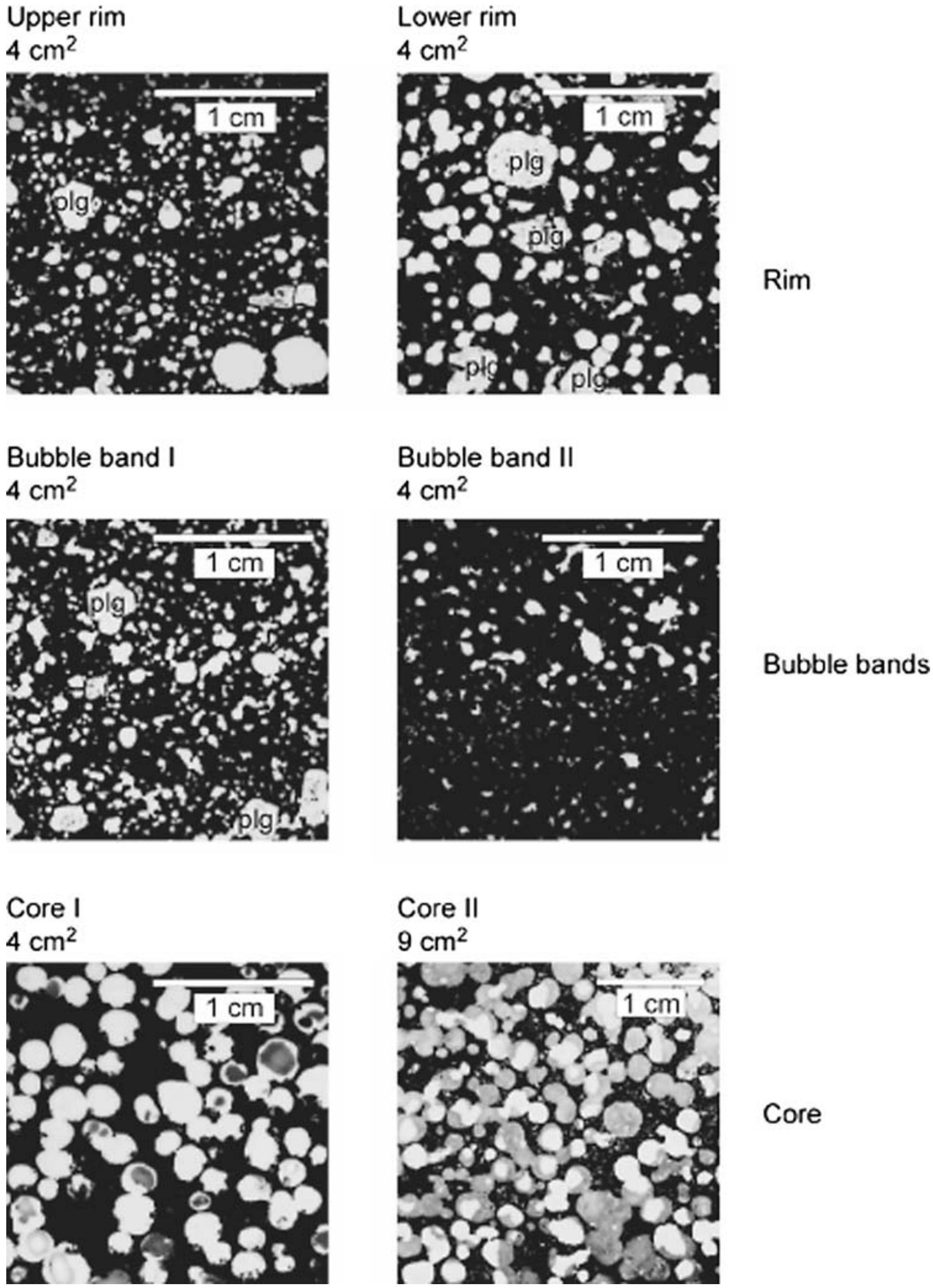

Fig. 11 Six different thin sections taken from the Virkisfell pillows. First set show sections from top and bottom rim of the pillow. Bubbles are larger and less regular in the bottom rim. Plagioclase also accumulates in the bottom of the pillow. Bubble bands show similar bubble size distribution. The two sections in the core show a drastic change in bubble population. Uniform distribution of bubbles indicates that bubbles have not had time to rise in the liquid before it was quenched (tachylitic texture)

water occupying the cavity formed in the eruption. The pressure, P, is thus defined as

$$P = \rho_i g h_i + \rho_w g h_w \quad (1)$$

where ρ_i is the density of ice (917 kg/m^3), ρ_w the density of water (1000 kg/m^3), h_i the thickness of the ice and h_w the height of the water column. The thickness of the water column is unknown and is expected to evolve with time (Hoskuldsson and Sparks 1997), so for simplicity we here calculate an equivalent thickness of ice from the pressure estimates. From Eq. (1) we estimate that Virkisfell erupted under an ice thickness of 1.3 km using the lower limit of CO_2 to 1.6 km using the upper limit. Other formations give estimated thicknesses ranging from 1.2 to 1.6 km for a melt concentration of 20 ppm CO_2 and 1.5 to 1.9 km for a melt concentration of 30 ppm CO_2 (see Table 3). The upper values are similar to estimates of 1.5–2.0 km maximum ice thickness during last glaciation (Walker 1965; Sigmundsson and Einarsson 1992; Einarsson 1995).

Magma degassing and jökulhlaup generation

The sudden increase in porosity towards the core of the pillows suggests that some environmental factor changed drastically during the eruption of Virkisfell and the other pillow ridge formations investigated. Porosity increases have not been observed in pillows of mid ocean ridge basalts (MORB) (Ballard and Moore 1977; Wells et al. 1979; J Karson pers. com.). Since pressure and crystallization principally control magma degassing, one of these must change in the subglacial Icelandic environment. We can exclude crystallization since it occurs both in Iceland and in MORB. Furthermore the vesicular cores of the Virkisfell pillows are poorly crystalline. Pressure in the MORB environment is approximately constant, but the dynamics of subglacial eruptions are such that draining of melt water from above an erupting vent can change confining pressure drastically.

Jökulhlaups in Iceland occur when melt water trapped within a glacier escapes (Björnsson 1988; Gudmundsson et al. 1997; Hoskuldsson and Sparks 1997). Melt-water flow under an ice sheet is affected by its thickness and the landscape underneath the ice. Melt water flows towards low values of fluid potential, which can be calculated along a given direction (x) according to:

$$\nabla\Phi = \rho_i g\left[\frac{dz_i}{dx} + 0.1\frac{dz_g}{dx}\right] \tag{2}$$

where ρ_{i} = ice density, g = acceleration due to gravity, z_{i} = ice thickness, z_{g} = the bottom topography and $0.1=\rho_{\mathrm{w}}-\rho_{\mathrm{i}}$ (Björnsson 1988 , 2002; Gudmundsson et al. 2004). For melt water to accumulate above or close to an eruptive vent, low value fluid potential conditions are needed above or in the vicinity of the vent, otherwise melt water will flow away. Within a large, relatively flat, ice sheet two conditions can favor melt water accumulation in the vicinity of the vent: surface subsidence of the ice due to melting and subsurface topographic high within the ice sheet (Fig. 13). In the case of Mt. Virkisfell both conditions are plausibly met. First, melting of the ice is expected at the beginning of the eruption. Höskuldsson and Sparks (1997) calculated that if 80% or more of available magma heat were transferred efficiently with the ice, a depression should form above the vent, resulting in conditions favoring water accumulation above the vent. Second, Mt. Virkisfell is situated on the slopes of the Kverkfjöll volcanic centre (Figs. 1 and 13). The Kverkfjöll volcanic centre forms a topographic high in the subsurface. Breach of the ice dam would cause a jökulhlaup and a drastic pressure drop above the erupting vent.

Similar conditions occurred in the Gjálp fissure eruption in 1996, when the fluid potential within the ice lowered towards the nearby Grímsvötn caldera, causing water to flow to Grímsvötn and accumulate (Gudmundsson et al. 1997). As the melt water accumulated, the Grimsvötn caldera and the eruption site tended to piezometric equilibrium, which finally lead to a breach in the ice dam at Grímsvötn and a jökulhlaup started (Gudmundsson et al. 1997, Gudmundsson et al. 2004). In Gjálp it was observed that when the jökulhlaup occurred, about 3 weeks after the main eruption ended, volcanic explosions followed. This observation is consistent with the interpretation that magma stored within the volcanoclastic pile was remobilized due to the pressure decrease above the vent. Magma at such a shallow depth must have reached saturation with regard to water and thus was highly sensitive to any external pressure changes.

In the case of Virkisfell we can estimate the pressure change that took place in association with the vesiculation of the pillow cores. We consider a pillow tube with a molten interior that vesiculates as a consequence of a pressure decrease. Therefore porosity in the cores is representative of the absolute depressurization. We can describe the volume of exsolved gas in relation to pressure under isothermal conditions as

$$VP = \text{constant} \tag{3}$$

where V is the volume of water and P is pressure. The Virkisfell magma contained about 0.89 wt % dissolved H_2O at time of quenching. Taking into account the water already exsolved, as indicated by the porosity of the glassy rim, the total water content of the magma prior to eruption is estimated at about 1 wt %. Knowing how water solubility varies with P, we can estimate the amount of water released during depressurization from the initial values of 12 MPa (for 20 ppm CO_2 in the melt) and 13.6 MPa (for 30 ppm CO_2 in the melt), the estimated minimum and maximum quenching pressure of Virkisfell magma. The specific volume of water at 1 atm and 1200°C is about 6.7 m^3/kg. Using Eq. (3) we can estimate the volume which the released water will occupy. Hence we can calculate the porosity increase in the magma during depressurization. Then by comparing these calculations with the observed porosity of the Virkisfell pillow cores we can estimate the pressure drop necessary to cause the observed vesicularity. The average porosity of the pillow rims is 20% and of the pillow cores is 49±5%, this gives a net vesicularity increase of about 29%. This represents about 4.4 to 4.7 MPa depressurization or a drop in the water level in the range 440–470 m.

Time constraints on eruption dynamics

We now make inferences about the growth of a basaltic pillow pile and the timing of the inferred jökulhlaup. Several of the observations can be used to provide time constraints based on the dynamics of pillow lava emplacement, cooling mechanisms, and estimated melting rates of the overlying ice sheet.

Here we assume that vesiculation took place in the still-molten cores of the pillows within the pile in an abrupt decompression event due to the jökulhlaup. Thus this event quenched the condition of the pillow pile at a moment in time. The bubbles in the vesiculated cores are not deformed, indicating that the movement in the still-molten core had ceased by the time the jökulhlaup took place. This inference is consistent with the time scales of the emplacement of individual pillows, which are observed in Hawaiian eruptions to be of order 1 h or less (Sansone 1990) and calculated to be of order thousands of seconds by Klingelhöfer et al. (1999). As we will develop below, the time scales of pillow cooling

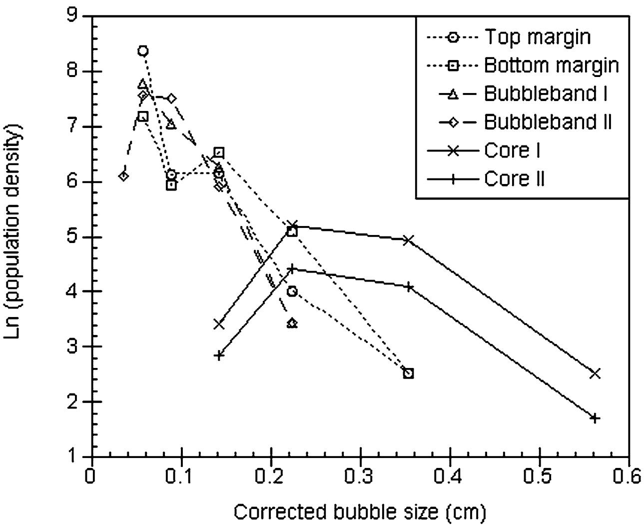

Fig. 12 Diagram showing corrected bubble size distribution (BSD) in the six different thin sections. While rims and bubble bands show similar size distributions but a distinct pattern, the cores are clearly distinct. The larger size of the core bubbles indicates that the pressure decrease to which the magma is responding is much larger than in the case of the rims and the bubble bands

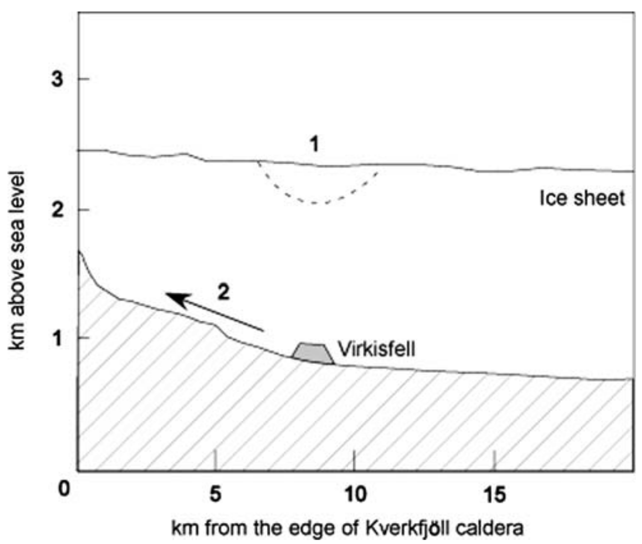

Fig. 13 Cross sectional diagram of the Kverkfjöll massif. An ice sheet of 1300 m covers the area. The ice sheet is relatively flat and thus the subsurface topography plays a major role in melt water accumulation. Two cases are discussed in the text. The first involves subsidence of the ice above the eruptive vent and the second involves flowing of melt water towards the Kverkfjöll centre

and pillow accumulation are both likely to be much longer than the emplacement time of individual pillows. The bubbles are also uniformly distributed through the core with no tendency to segregate to the top of the pillow. Further, the cores have a tachylitic texture, consistent with rapid cooling, in contrast to the more crystalline character of the outer pillow zone. Thus the cores must have been quenched over a time that is much shorter than the time it takes 1 mm bubbles to rise a few tens of cm. Using Stokes law for the ascent of a spherical bubble of diameter 1 mm and melt viscosities in the range 100–1000 Pa s we estimate that the bubbles should have moved noticeably (i.e. 10 cm or more) in times of the order 100–1000 s. This time is much shorter than any conductive cooling time for the cores with dimensions of 0.4–1.6 m (Fig. 8a), which is calculated at many hours to days. Thus it seems that there must have been a rapid quench of the cores. One possibility is that the vesiculation caused the surrounding fractured crust to expand, allowing ingress of water and rapid flooding of the vesiculated cores.

The thickness of the outer zones to the pillows and the observation that many of the smaller pillows lack vesicular cores allow some constraints to be inferred on the time between the emplacement of the pillows and the jökulhlaup. The evolution of a pillow pile can conceptually be divided into three stages with respect to cooling as developed below.

In the first stage of active emplacement of an individual pillow tube heat loss occurs from the pillow surface resulting in the formation of a thin crust. Heat loss to the surrounding water is counteracted by advection of hot lava through the interior of the pillow (Klingelhofer et al. 1999). As the pillow advances to form an elongate tube the crust will tend to thicken with time, but the molten interior repeatedly bursts out of the flow front (Moore 1975). Thus it might be anticipated that the crust is thicker close to the source of the pillow. When the pillow stops, crustal thickness will be a function of both distance and the duration of pillow emplacement. Observations and modeling indicate time scales of tens to hundreds of seconds for stage I (Klingelhöfer et al. 1999). In the second stage the pillow ceases motion and crustal growth continues by heat loss to the surrounding water. In the third stage the individual pillow becomes buried by other pillows and becomes part of the interior of the pillow pile. At this stage the pillow is partially thermally insulated by surrounding pillows, which may still be hot. The individual pillow will lose direct contact with open water, and heat loss will be by water or steam convection through the pillow pile. It might be expected that heat loss rates would decline significantly, although there are no models to help assess the magnitude of the decline.

An upper limit to the time interval between initial pillow accumulation and the jökulhlaup can be estimated by assuming that crustal growth is by conduction through stages 2 and 3, and using the following observations. Many smaller pillows less than 0.6 m in equivalent radius lack a vesiculated core (Fig. 8b). In the pillows with vesiculated cores the outer zone crust in most examples is less than 0.4 m thick (Fig. 8b). Thus we can estimate the time, t, for forming a crust of thickness X=0.4–0.6 m from the approximation:

$$X = (ckt)^{0.5} \tag{4}$$

where c is a constant which we take as 2 (Jaeger and Carslaw 1965), and κ is the thermal diffusivity (taken as 8×10^{-7} m^2 s^{-1}). The calculated time is in the range 1.1–2.5 days. There are many uncertainties in this estimate. The radial fractures in the outer zone of a pillow might allow penetration of water or steam and thus enhance crustal growth rates. On the other hand in stage 3 the insulating effect of other pillows and the slower convection of water expected in a porous medium might reduce heat loss rates. However, the calculation is sufficient to show that a significant amount of crustal growth takes place after motion of individual pillows has ceased. The calculation also indicates that the jökulhlaup must have taken place a few days after initial pillow emplacement.

The cooling time constraint also allows some inferences to be made about the accumulation rate of the pillows. The inference that all the molten cores of the pillows vesiculated simultaneously indicates that the pillow pile at an outcrop with a height of about 5 m had all accumulated in a period less than the crustal cooling time (of order 1–3 days). If a typical pillow is 1.0 m in diameter then, on average, a pillow is buried about every 5 to 15 h, a time somewhat longer than the typical emplacement times of individual pillows (Klingelhöfer et al. 1999). Following Hoskuldsson and Sparks (1997), we calculate the accumulation rate for a pillow ridge erupting over an area of 8 km^2 (see Table 1 for area of Viskisfell) and assuming that pillows pile up layer by layer. An accumulation rate of greater than 5 m/day over this area corresponds to an eruption rate of more than 400 m^3/s. This rate is within the typical range of effusion rates of typical Icelandic fissure eruptions (Thorarinsson 1967; Thordarson and Self 1993). Of course such calculations are merely indicative as many assumed parameters could be changed within the constraints of the observations.

A final constraint can be derived from the inferred change of pressure associated with the jökulhlaup. The calculated water depth of 440–470 m can be used to estimate the time from the melting rate of the ice cavity. Values of melting rate between 10^{-3} and 10^{-4} m s^{-1} are estimated from theory and observation of the eruption of the Vatnajokull in 1996 (Hoskuldsson and Sparks 1997; Gudmundsson et al. 1997; Gudmundsson et al. 2004). The time required to melt a depth of 400 m of ice is thus estimated to be in the range 4 to 46 days. Since the estimate of the time interval between pillow emplacement and the jökulhlaup is 1–3 days an upper limit to the melting rate of about 10^{-3} m/s can be estimated.

Conclusions

We have documented basalt pillows lavas emplaced during six different subglacial fissure eruptions in the rift zone associated with the Kverkfjöll volcanic centre during the last major glaciation in Iceland. The glassy rims of the pillows lavas contain 0.85 to 1.04% water suggest eruption under ice depths in the range 1.2–1.9 km. These depths are comparable to ice depths during the last major glaciation estimated from other field methods and theoretical models. Many of the pillows examined in detail at the Virkisfell location have vesiculated cores, which are interpreted as due to a sudden pressure decrease when melt water drained away from the eruption sites in a jökulhlaup. The amount of vesiculation indicates pressure decreases equivalent to water depths of 440–470 m in the water cavity created by melting the ice during the eruption. Observations of the thickness of crusts formed in the pillows prior to the vesiculation event indicate times of the order of 1 to 3 days between emplacement of the pillows and the jökulhlaup. An upper limit to the melting rate of the ice of 10^{-3} m/s can be inferred and is consistent with melting rates estimated from theory and the 1996 Gjálp eruption. The observations also indicate pillow accumulation rates of at least 5 m/day during the eruption of the Virkisfell pillow ridge. These observations support the concept that jökulhlaups can reactivate volcanic eruptions.

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