# Assessing the mean output rate (MOR) of past effusive basaltic eruptions – a look at the postglacial volcanism of the Reykjanes Peninsula in Iceland

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**Abstract**

Volcanological approaches for assessing the effusion rate of past effusive volcanism are of great importance, to enable proper evaluation of the eruption magnitude and past tectono-magmatic conditions which are relevant for mitigating future volcanism. The reactivation of volcanism on the Reykjanes peninsula in 2021 after an 800-year hiatus, has incited the need for assessing the potential scale and size of future effusive eruptions on the peninsula. With a compilation of the planimetric area of 154 postglacial monogenetic lava fields, and volcanological constraints on these fields, the heat flow model of Pieri and Baloga (1986), as utilized in Harris and Rowland (2009) was used to assess the mean output rate (MOR) of these eruptions, providing insights into the overall effusive capacity of the peninsula. Methods for a qualitative evaluation of the eruption duration of past eruptions are introduced, along with a power regression derived from a the surface temperatures and time extracted from recent eruptions in Iceland, allowing for a theoretical approach to the thermal stage of lava fields with unknown emplacement history. Our first-order assessment on the Reykjanes peninsula indicates that 10% of the eruptions have MOR $< 1$ m$^3$/s, 35% in between 1 and 10 m$^3$/s, 44% between 10 and 50 m$^3$/s, 8% between 50 and 100 m$^3$/s and 3% between 100 and 200 m$^3$/s.

The eruption frequency has undergone minor variations in postglacial time, the only significant variation being the occurrences of long-lived (<5 years) shield eruptions in early and mid Holocene, but short-lived (days to months) fissure-fed volcanism dominated in the late Holocene, with MOR 10–50 $m^3$/s. The results show the potential scales of future effusive activity on Reykjanes if current tectono-magmatic conditions remain the same.

**Keywords:** Mean output rate, Past effusive volcanism, Reykjanes peninsula

# 1 Introduction

Effusion rate (discharge rate) is defined as the amount of lava erupted at a given time in effusive eruptions (e.g. Harris et al, 2007). The rate is controlled by subsurface conditions such as density buoyancy (Mériaux and Jaupart, 1998; Hartley and Maclennan, 2018), local stresses (Gudmundsson, 2006), overpressure in magma chambers or reservoirs (Geshi et al, 2020), the anatomy of the plumbing system and dynamics of magma ascent (Geshi, 2005), and give an indication of the tectono-magmatic processes controlling volcanism at each place (e.g. Tibaldi, 2015). Today, effusion rates is a key parameter for modeling lava flow emplacement (e.g. Harris and Rowland, 2001; Vicari et al, 2009; Bilotta et al, 2012; Cappello et al, 2016; Chevrel et al, 2018; Pedersen et al, 2023), therefore assessing the effusion rate is important for understanding volcanic systems in general, with great implications for hazard assessment. During an effusive eruption, the instantaneous effusion rate is measured on-site, in open channels or skylights (e.g. Pinkerton and Sparks, 1976; Calvari et al, 2002), or the time-averaged discharge rate (TADR) estimated from temporal volumetric measurements using satellite data (Harris et al, 2000, 2011) or vertical aerial imagery (Pedersen et al, 2022). After the eruption, or for past eruptions with documented duration, a mean output rate (MOR) can be estimated derived from the total volume of the lava field divided by the total eruption duration (Harris and Rowland, 2009), or eruptions without a record of duration or even volume, estimates of the MOR can be assessed from the relationship between the planimetric area of the lava field and effusion rate. One equation that shows this relationship is the equation of Pieri and Baloga (1986), built on studies on length of lava flows versus effusion rate (e.g Walker, 1973) further developed in (Harris and Rowland, 2009) that includes the radiative history of the eruption reflected in instantaneous or average surface temperatures, imperative to controlling the cooling-limit of the flow.

Renewed volcanism on the Reykjanes peninsula, with the eruption of Fagradalsfjall in 2021, after an 800 year hiatus, has raised concerns about the imminent risk of the reactivation of all volcanic systems. Previous volcanic episodes in the Reykjanes peninsula, cycling at intervals of 800–1000 years, activated volcanism in all volcanic systems (Sæmundsson and Sigurgeirsson, 2013). Thus, a new episode may lead to widespread volcanism on the peninsula, imposing hazards on the population of the area, including popular tourist destinations, the international airport and significant risk to other essential infrastructure. To evaluate the potential magnitude of future eruptions in the peninsula that can be used for risk management and simulating lava emplacement, a realistic estimate of the MOR of past Reykjanes eruptions is needed.

This study explores the usage of a thermal model presented in Harris and Rowland (2009) for assessing the eruption capacity from the MOR, that hinges primarily on two unknown parameters, planimetric area and surface temperature of the flow. The area of the lava flows can be measured directly or estimated, however, the thermal history expressed in the surface temperature of the flows has not been investigated for past and prehistoric eruptions on these terms. This study explores ways for assessing the thermal history from the degree of maturation of lava fields using field-based volcanological and morphological observations. These observations are then compared to a theoretical relationship between surface temperatures and time extracted from documented eruptions in Iceland. Knowing the time it takes for a lava to achieve certain maturity and surface temperatures, allows for a qualitative correlation between emplacement time and the time that it takes to form morphological features within the flow fields. This relationship opens for further constraints on the nature and time of emplacement of unknown eruptions, and assessment of MOR giving a more comprehensive evaluation of the eruption history of volcanic regions in general.

## 2 Geological Setting

The Reykjanes peninsula in Iceland is part of the Western volcanic zone (WVZ) the onshore continuation of the mid-Atlantic ridge that transects the country southwest to north (Gudmundsson, 1986; Sigmundsson, 2006). The spreading center on the Reykjanes peninsula overprints a transform zone, which results in divergent spreading combined with north-south right-lateral slip faulting (Keiding et al, 2009; Sæmundsson et al, 2020) with *en echelon* volcanic systems bearing SW–NE 25–35° oblique to the spreading center. The volcanic systems that are 30–50 km long and 5–8 km wide have been divided into six after the presence of fissure-swarms, grabens, seismic activity, volcanic edifices, craters and geothermal activity, and are: Reykjanes, Svartsengi, Fagradalsfjall, Krýsuvík-Trölladyngja, Brennisteinsfjöll, and Hengill (Sæmundsson and Sigurgeirsson, 2013). However, the boundary between adjacent systems is not clear and different arrangements have been presented (Jakobsson et al, 1978), for example, Reykjanes and Svatsengi have sometimes been classified as the same system (), and Fagradalsfjall was only recently recognized as a system (Gee, 1998; Sæmundsson and Sigurgeirsson, 2013). The Reykjanes peninsula is the most active segment of the WVZ with over 200 eruptions in postglacial times, while the northern segment around Langjökull only facets about 26 eruptions but with lava flows of larger areal coverage and volume (Jakobsson, 2013). The exposed basement rock of the peninsula is of Plio-Pleistocene age with alternating hyaloclastite deposits and lava flows, the latest Pleistocene subglacial eruptions form prominent ridges and tuyas on the peninsula.

Effusive eruptions in the last 3500 years BP have been cyclical, with intervals of 800–1000 years, each period lasting 200–400 years, the latest eruption period occurring from 800–1200 BP (Sæmundsson and Sigurgeirsson, 2013; Sæmundsson et al, 2020). Postglacial volcanism is basaltic, lava shields being either picrite or olivine tholeiite in composition and fissure volcanism being tholeiitic (Jakobsson et al, 1978). The picrites and some of the shields on the peninsula form the oldest formations of postglacial volcanism and have been interpreted as the result of enhanced partial melting of the Icelandic mantle with isostatic crustal adaptations following the Weishelian deglaciation (Jull and McKenzie, 1996; Andrew and Gudmundsson, 2007; Maclennan et al, 2002; Rees Jones and Rudge, 2020).

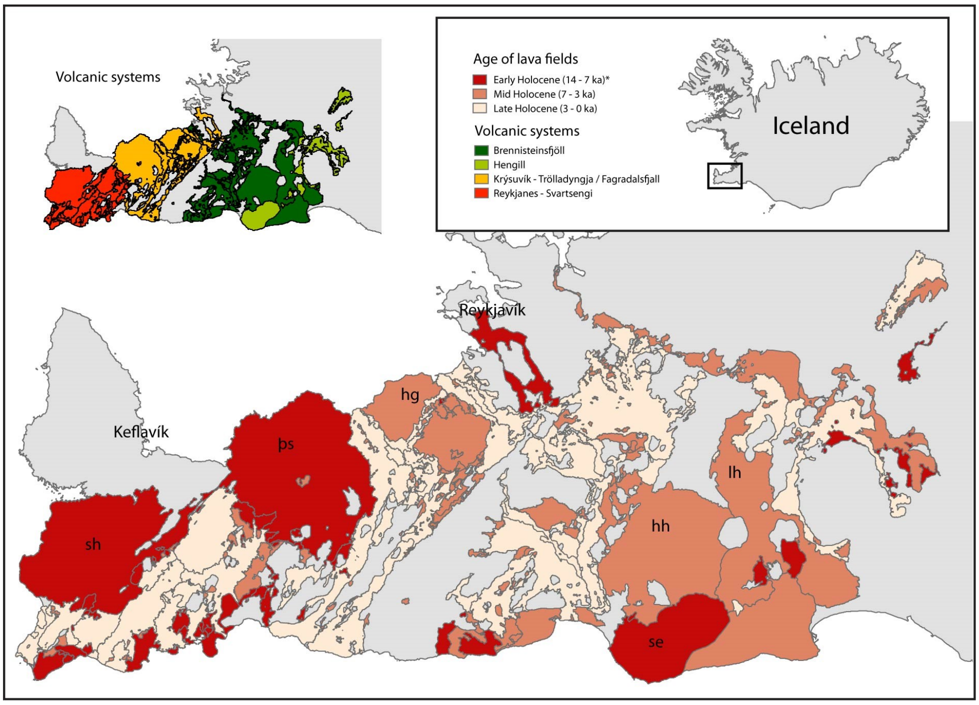


**Fig. 1** Map of the Reykjanes peninsula. The map shows the lava fields of this study classified after age and volcanic systems. Ages are inferred from carbon dating, tephrachronology and stratigraphy. Late Pleistocene lavas from 14-12 ka are classified with early Holocene, and not differentiated for simplification. Acronyms of largest shield volcanoes shown for reference: sh - Sandfellshæð, þs - Þráinskjöldur, hg - Hrútagjá, hh - Heiðin Há, se - Selvogsheiði and lh - Leitahraun.

# 3 Methods

This study compiles the planimetric area of 154 monogenetic lava fields from eruptions within the Reykjanes peninsula, published by the Icelandic Institute of Natural History (https://serstokvernd.ni.is/) and available in the repository of the National Land Survey of Iceland (https://gatt.lmi.is/). The database includes shapefiles with polygons of the lava fields, information about the volcanic system to which the lava fields belong, and their estimated age. The ages are historical or determined with C14 dating and tephrachrnology (e.g. Jóhannesson and Einarsson, 1988b,a; Einarsson et al, 1991; Sinton et al, 2005). Other ages were inferred from the position of the lava flows in the stratigraphy. Additional information about the type of lava, vent types and locations and predominant morphologies were extracted from aerial imagery (Loftmyndir ehf.) and miscellaneous publications (maps, thesis, reports, and articles). The geological map and report of Jónsson (1978) provided most information on each lava field's vents. The most up-to-date information on age and stratigraphy was found in the 2016 geological map of Reykjanes from Iceland GeoSurvey (Sæmundsson et al, 2016). The area of lava fields that were partly buried by other lava fields were estimated from the visible extent of the lava fronts or from kipukas. For simplification, the lava fields in this study are subdivided into four areas comprising the six systems, Reykjanes-Svartsengi are placed together, Krýsuvík-Trölladyngja and Fagradalsfjall, Brennisteinsfjöll, and Hengill systems.

## 3.1 Equation

To assess the MOR, the equation of Pieri and Baloga (1986) as adapted in Harris and Rowland (2009, eq. 20) was rewritten to:

$$E = \frac{A[\sigma\varepsilon(T_{surf}^4 - T_{amb}^4) + h_c(T_{surf} - T_{amb})]}{\rho(\Lambda\phi + \Delta T c_p)}. \quad (1)$$

The equation is built on a relationship between effusion rate E and/or thermal insulation $T_{surf}$, which is expressed in the potential of the area A of a lava field to grow with increasing insulation before coming to halt. The function also shows that for a given eruption rate, after the flows reach their maximum cooling-limited length, with added volumes the flow will begin to pond and widen increasing the flow area (Lopes and Guest, 1982). For the purposes of assessing the MOR of past effusive eruptions with little knowledge of their eruption history, the parameters are selected theoretically and not on a case-to-case basis. The parameters used which would be representative for Icelandic basaltic eruptions are from Krafla flows (Harris et al, 2007) and are summarized in Table 1.

**Table 1** Lava parameters used in this study

| | |
|---|---|
| Stefan Boltzmann constant $\sigma$ | 5.67 x $10^{-8}$ W $m^{-2}$ $K^{-4}$ |
| Emissivity $\varepsilon$ | 0.95 |
| Density $\rho$ | 2600 kg $m^{-3}$ |
| Latent heat of crystallization $\Lambda$ | 3.5 x $10^5$ J $kg^{-1}$ |
| Crystallization $\phi$ | 45 % |
| Heat capacity $c_p$ | 1230 J $kg^{-1}$ $K^{-1}$ |
| Convective heat transfer coefficient $h_c$ | 10 W $m^{-2}$ $K^{-1}$ |
| Ambient temperature $T_{amb}$ | 277.15 K (4°C) |
| $\Delta T$ | 200 K (200°C) |
| Surface temperature ($T_{surf}$) | 323.15 K (50°C) Shield volcanoes (1330 days, 3.6 years) |
| | 363.15 K (90°C) Fissure eruptions and smaller shields (180 days) |
| | 471.15 K (198°C) Short-lived eruptions (20 days) |
| | 673.15 K (400°C) Short-lived eruptions (2 days) |
| | 803.15 K (530°C) Short-lived eruptions (1 day) |

For example the convective heat transfer coefficient is set to $h_c$ 10 W $m^{-2}$ $K^{-1}$ but can be greater if the lava is affected by wind and rain. Ambient temperature during the eruption $T_{amb}$ is set to 277.15 K (4°C), the annual mean temperature of Iceland (Einarsson, 1984), although actual ambient temperatures may have been in the range from subzero temperatures to warmer summer temperatures. Nevertheless, slight changes in $T_{amb}$ are not significant in affecting the MOR estimate. A maximum post eruption crystallization is assumed to be 45% (Harris and Rowland, 2009). Two values that are significant and inferred in our calculations, are the surface temperature ($T_{surf}$) which is an expression of the crustal maturity and thermal insulation of the lava field during the eruption, and the $\Delta T$ which is the temperature difference between eruption temperature and core temperature for the flow to reach its cooling-limit and come to halt. $\Delta T$ is usually set to be around 200 K (200°C) but could vary slightly between flows after emplacement style (Harris and Rowland, 2009). Because our eruptions have unknown history and duration, we need to rely on best estimate of $T_{surf}$. Eruption rate is based on bulk volumes and thus requires further corrections for voids and vesicles if used in other contexts, as for calculating volatile emissions.

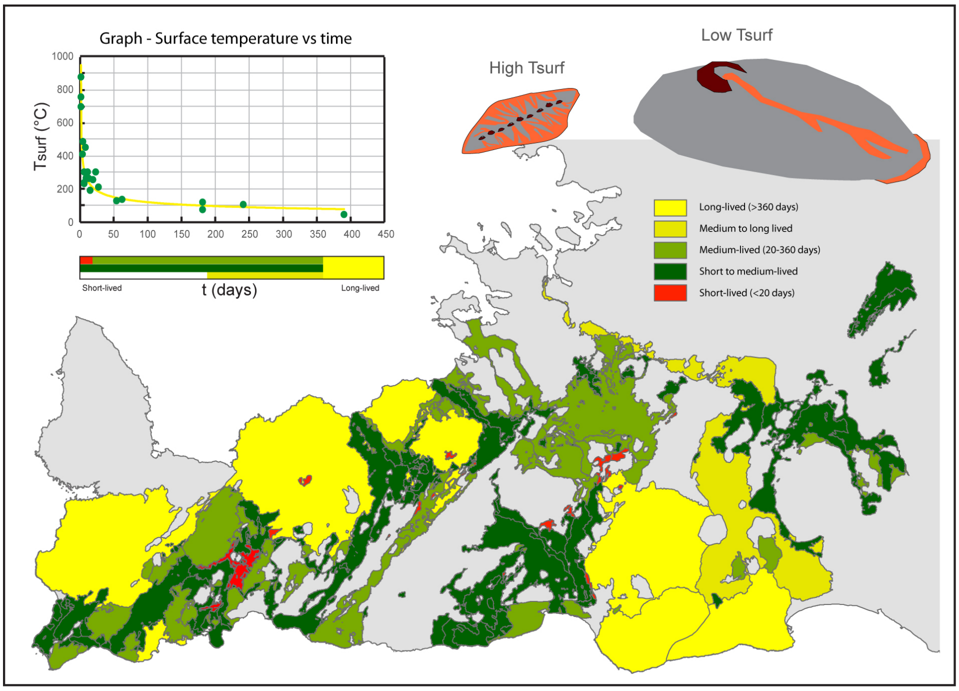


**Fig. 2** Map of the Reykjanes peninsula showing based on a qualitative assessment of the longevity of the eruptions from the morphology of the vent systems and lava fields. The assessment is used for selecting the best range for $T_{surf}$ derived from the power equation (top left). Top right corner: Illustration of how the crustal maturation of the lava fields through the course of the eruptions induces insulating emplacement and affects the surface temperature.

# 4 Results

The lava fields used in this study are distributed within the following volcanic systems (see Table S1 of the supplementary file): 50 (32.5%) in the Reykjanes-Svartsengi volcanic systems, 45 (29.2%) in the Krýsuvík-Trölladyngja systems, 48 (31.2%) in the Brennisteinsfjöll system and 11 (7.1%) in the Hengill system. The total number of lava fields formed since postglacial times is not known but in the report of Jónsson (1978) additional 50 or so lava fields are counted, of which eight are interpreted as being lava shields, thus the total number is over 200. The morphological analyses of the lava flows shows that 61.3% of the lava fields are pahoehoe, 8.1% a'a, 14.4% mixtures of pahoehoe and brecciated facies, and 16.3% was undefined. Areal coverage of the lava fields ranges from 0.008–147 km$^2$ with average of 10 km$^2$. Estimated volumes for 51 lava fields give ranges from 0.0013 km$^3$–6.8 km$^3$ and an average of 0.7 km$^3$ (Jónsson, 1978). Of the lava fields, 148 area single lava flows or small shields with volumes $<$0.7 km$^3$ and 6 are large shields $>$ 1 km$^3$. 28 lava fields have documented lava tubes according to the interactive map of the Icelandic Institute of Natural History (www.ni.is) including the 2021 lava field at Fagradalsfjall.

## 4.1 Evaluating the planimetric area of the lava fields - Cooling or volume-limited flows?

Of the 154 lava fields, 58 are partly or almost entirely buried underneath other lava flows and their planimetric area had to be estimated. Of these, 42 have over 50% of their estimated fields buried, 7 had between 30–50% buried and 9 under 30%. Most of these buried lava fields have lava fronts or kipukas that are well mapped and correlated with eruption vents or areas (Jónsson, 1978; Sæmundsson et al, 2016), but 18 lava fields with vent areas buried needed to have their source vents inferred, and they were drawn to the nearest fissure system. The areal sizes derived from the estimations are approximations only, but do fall well into the sizes of the lava fields that are entirely exposed.

About 40 lava fields extend to the ocean, meaning part of the lava that erupted was lost into the ocean. The bathymetry map of southwest Reykjanes shows that the lava field of Eldvörp extends 3.3 $km^2$ into the ocean (or 15% of its total area) and Ögmundarhraun about 8.9 $km^2$ (or 30% of its total area) (Ögmundur Erlendsson pers. com. 2021). Judging from the location of the majority of the volcanic vents that are found towards the central areas of the peninsula and the areal distribution of the lava fields, most lava flows seem to have reached their cooling-limit before entering the ocean, indicating that those eruptions that entered the ocean and were volume-limited (ocean-limited), were potentially close to their cooling-limit and the subaqueous area lost is considered small. The vents closest to the ocean are found within the Reykjanes-Svartsengi systems, where 20 lava fields seem to have entered the ocean and their subaqueous area loss is more significant. However, from the small size of these fields, even if the areas of these flow fields were doubled, the MOR would be largely confined to 1–10 $m^3/s$ which is likely representative of the volcanism of this region, as discussed below. Another factor affecting the cooling-limit of lava is topography. Reykjanes peninsula has a general shallow increase in slope inland with low-relief planes in between the small 100–300 m high hyaloclastite tuyas and ridges which indicates most of the flows did flow towards the ocean and were not confined by topographic barriers. But as observed in Fagradalsfjall eruption in 2021 where lava filled valleys until spilling over (Pedersen et al, 2022), eruptions of longer duration (weeks to months) should be expected to overcome local topography and extend to reach their cooling-limit.

## 4.2 The relationship between crustal surface temperatures and time - a theoretical approach

In this study, we derived by iteration $T_{surf}$ from equation 1 using data from recent eruptions in Iceland with known emplacement history, duration, and MOR and using the physical parameters above for Icelandic lava flows (see Tables 1 and 2). From these results, Newton´s law of cooling (Newton, 1929) is seen expressed in the power regression of $T_{surf}$ and time (Fig 1),

$$T_{surf} = 529.38t^{-0.328} \tag{2}$$

where t is time in days and $T_{surf}$ is temperature in degrees Celsius. The regression has a strong correlation ($R^2 = 0.91$), and is thought to portray the gradual maturation and increase insulation of the lava fields during the course of the eruptions. Interestingly, the type morphology of the lava flows and the compositional variation from basaltic to andesitic has minimum effect on the correlation. This equation shows that the most significant variation in $T_{surf}$ occurs during the first days of the eruption, eruptions lasting a day have $T_{surf}$ of about 500°C, while eruptions reaching about 20 days have $T_{surf}$ about 200°C. Passing 20 days to about an year the temperature slope declines gradually within a narrower range of $T_{surf}$ 200–70°C, and to reach crustal temperatures of 30°C the duration is greater than 17 years. These crustal temperatures would reflect the maturation and cooling of the core of the flow fields with time (Fig. 2). The regression has been tested against the MOR determined from volumetric calculations from photogrammetry surveys in the recent eruptions on Reykjanes (Pedersen et al, 2022, 2024) with good results, and can become a useful tool in lava simulation and forecasting, a topic discussed for another publication.

The differing type of emplacement mode and magnitude of output rates in the eruptions of Table 2 explains the minor variation in $T_{surf}$ between flows with same

**Table 2** Time-based surface temperatures derived from documented volcanic eruptions in Iceland

| Eruption | Area ($km^2$) | MOR ($m^3/s$) | Duration (days) | $T_{surf}$ (°C) |
|---|---|---|---|---|
| Holuhraun 2014–2015 | 84.0 | 90[1] | 180 | 72 |
| Fagradalsfjall 2021 | 4.8 | 9.5[2] | 180 | 117 |
| Merardalir 2022 | 1.2 | 7.2[7] | 18 | 253 |
| Litli-Hrútur 2023 | 1.5 | 6.7[7] | 26 | 209 |
| Sundhnúksgígar 2023 | 3.4 | 50.0[7] | 2.5 | 409 |
| Laki 1783–1784 | 600 | 700–1000[3] | 240 | 103 |
| Fimmvörðuháls 2010 | 1.3 | 10[4] | 22 | 300 |
| Hekla 1947–48 | 38.9 | 22[5] | 389 | 43 |
| Hekla 1970 | 17.1 | 40[5] | 61 | 134 |
| Hekla 1980 | 22.6 | 479[5] | 3 | 484 |
| Hekla 1981 | 4.4 | 78[5] | 7 | 449 |
| Hekla 1980–81 | 24.5 | 197[5] | 10 | 300 |
| Hekla 1991 | 24.7 | 53[5] | 53 | 125 |
| Hekla 2000 | 14.6 | 92[5] | 12 | 261 |
| Krafla 1975 Dec 20 | 0.36 | 18.5[6] | 0.21 (<6 hr) | 695 |
| Krafla 1977 Sept 8 | 0.8 | 77.8[6] | 0.17 (<5 hr) | 875 |
| Krafla 1980 Mar 16 | 1.3 | 83.3[6] | 0.25 (<7 hr) | 755 |
| Krafla 1980 Jul 10–18 | 5.3 | 34[6] | 8 | 263 |
| Krafla 1980 Oct 18–23 | 11.5 | 59[6] | 5 | 230 |
| Krafla 1981 Jan 30–Feb 4 | 6.3 | 50.9[6] | 5 | 300 |
| Krafla 1981 Nov 18–23 | 17 | 91.9[6] | 5 | 236 |
| Krafla 1984 Sept 4–18 | 24 | 91[6] | 14 | 189 |

[1] (Pedersen et al, 2017)
[2] (Pedersen et al, 2022)
[3] (Thordarson and Self, 1993)
[4] (Edwards et al, 2012)
[5] (Pedersen et al, 2020)
[6] (Harris et al, 2000)
[7] (Pedersen et al, 2024)

eruption duration differing slightly in their thermal history. For example the difference in $T_{surf}$ of Holuhraun and Fagradalsfjall, eruptions that lasted the exact number of days or 180 days, is of about 45°C, Holuhraun being ten-times larger in terms of effusion rates and predominantly rubbly and a'a (Pedersen et al, 2017; Voigt et al, 2021) and Fagradalsfjall predominantly pahoehoe with mixtures of flows with disrupted and brecciate crusts.

Yet the time-dependent relationship is clear from the regression. The Hekla lava fields of basaltic andesite and andesite compositions (Pedersen et al, 2020), flows formed in eruptions of long duration (over 50 days), had $T_{surf}$ around 125°C, while lava flows that formed in eruptions of short duration (1–10 days) have $T_{surf}$ in the range of 200–500°C. In addition, Krafla fissure eruption, which had a maximum longevity of 14 days (Harris et al, 2000), have $T_{surf}$ range from 189°C for the longest eruption to 875°C for the shortest (a few hours). Thus, $T_{surf}$ of 70–200°C seems apply for flows that are medium-lived and developed crustal maturity with insulation, while higher crustal temperature values are expected from short-lived lava flows which are more difficult to ascertain without knowledge of the history of that eruption. On the other end, values of $T_{surf}$ around 30–70 °C would apply to lava fields formed over several years, as expected for the largest shield volcanoes.

## 4.3 The duration of past eruptions analyzed qualitatively

For the purposes proposed, $T_{surf}$ needs to be pinpointed for each eruption and the power relationship can aid us in finding a value of $T_{surf}$ that reflects the eruption duration, established qualitatively from the morphology of the lava fields and vents. For example, the occurrence of well-preserved rows of small scoria and spatter cones along well-delineated fissures would indicate the eruption was relatively short-lived with minimal fissure shortening and coalescence of vents. The occurrence of fewer and larger scoria cones would suggest the eruption duration was prolonged enough to allow for closing of the fissures and coalescence of vents, while a large single crater would indicate a moderately to long-lived eruption. The subsequent burial of the vents by lava flows from the central crater would indicate further a prolonged eruption. The aspect ratio (the length of the vent system divided by the length of the lava field) can also indicate eruption duration, where a field with a low aspect ratio (a.r. $<1$), where the vent system is much shorter than the length of the flow field, would be indicative of a longer eruption, while a vent system equal or larger than the width of the flow field (a.r. $>1$) would be indicative of a short-lived eruption. The morphology of the lava fields can also give an indication of duration, and it could be argued that because >70% of the lava fields are pahoehoe with numerous anastomosing lobes placed horizontally and sometimes vertically as in the case of the lava shields, and showing crustal maturity with insulated emplacement and inflation structures such as lava-rise plateaus, lava-rise pits and tumuli, that these eruptions were relatively long-lived (Hon et al, 1994). In the Holuhraun eruption, documented bulged inflation structures first appeared after 26 days, while the northern and oldest sector of the lava field was heavily inflated in the fourth-month (Pedersen et al, 2017). Brecciated fields would suggest origin by high fountaining, vent instabilities and/or a topographic control inducing higher cooling rates with respective shearing and brecciation (Sparks and Pinkerton, 1978; Soule et al, 2004), eruption phases usually associated with immature systems and short to moderately-lived eruptions. Lava-tubes would also be indicative of greater longevity whereas well-developed internal pathways take time to be established, despite this, hollow sheet lobes may start forming within a few days of emplacement (Hon et al, 1994).

With the morphological aspects assessed, a map was drawn showing inferred eruption duration for each field (Fig. 2), that aids in selecting a $T_{surf}$ that approximates the respective thermal state of the lava fields. The map shows that the majority of the fissure eruptions fall into short to medium longevity (dark green to green). $T_{surf}$ is classified into four categories as seen in Table 2 spanning representative eruption duration. Due to the shallow slope of the regression for the medium range, a value for $T_{surf}$ of 93°C is likely to approximate the true $T_{surf}$. This value approximates the MOR for Holuhraun 2014–15, Laki 1783–84 and Fagradalsfjall 2021 even though they differ to some extent in composition ranging from primitive olivine tholeiites to more evolved tholeiites, and differ in morphology and emplacement history. This adds confidence that the selected value applies to the medium-lived lava fields. Fields in the category short-lived (red) would fall in the range with larger variability of higher $T_{surf}$, which is more difficult to assess, and a value of 400°C was used for very short

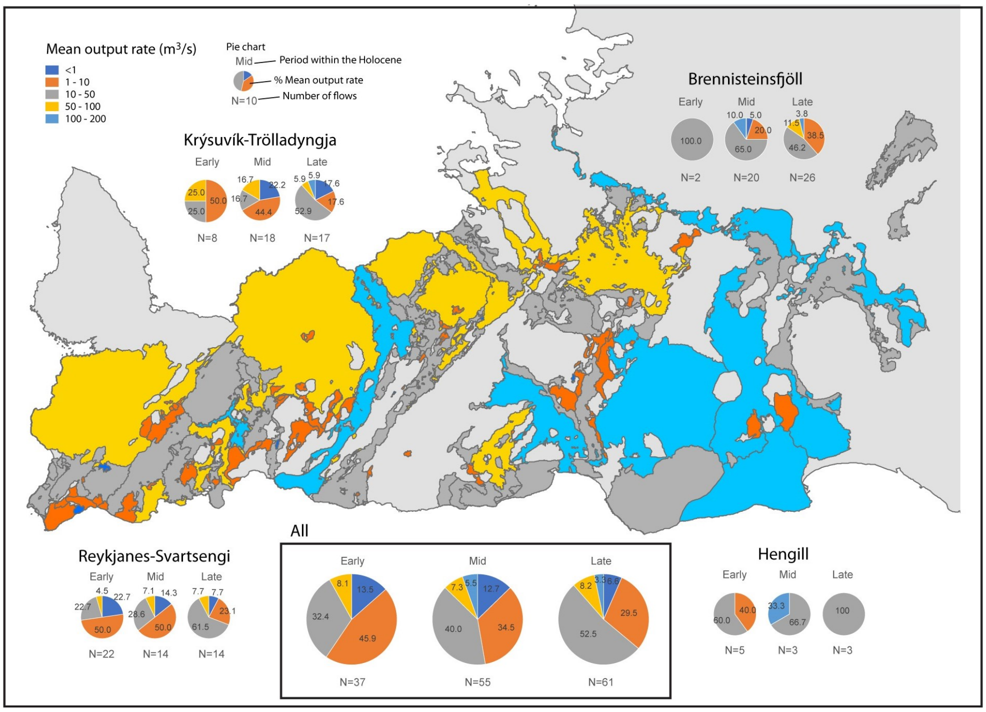


**Fig. 3** Map of the Reykjanes peninsula showing the calculated MOR for all lava fields and pie-charts showing the percentage MOR distribution within each system and for all the systems. Inferred age of the lava fields is given in Figure 1 and the volcanic systems they belong.

eruptions between 1 and 2 days and 198°C for eruptions inferred to 20 days. The small red fields may represent single eruption events, although they seem likely remote segments of larger fissure eruptions. The yellow fields are long-lived shield volcanoes, and a value of $T_{surf}$ of 50°C which would represent 3.6 years of eruption was used. This value is potentially more applicable to the shields, but for simplification was used for all shields with volumes larger than 1 km$^3$. Smaller shields under 1 km$^3$, due to their resemblance with the 2021 Fagradalshraun, were included in the medium-lived category.

## 4.4 Estimated mean output rates

The combined qualitative assessment given in Table S1, and best estimate of $T_{surf}$ (Table 2) yielded the following results: 10% of the eruptions have MOR $< 1$ m$^3$/s, 35% in between 1 and 10 $m^3/s$, 43% between 10 and 50 $m^3/s$, 8% between 50 and 100 $m^3/s$ and 3% between 100 and 200 $m^3/s$. These values can be further evaluated after age and a summary is given in Figure 3. Table S1 also provides the uncertainty range for each eruption, based on the $T_{surf}$ of two adjacent time slots. The time slots were 1 day, 2 days, 20 days, 50 days, 180 days, 365 days, 1330 days (3.6 years) and 6320 (17 years). If for example the assigned $T_{surf}$ was 93°C, the temperature at day 180, the uncertainty range used would be from day 50 to day 365 and so forth.

The westernmost systems have the largest percentage of eruptions under 10 $m^3/s$ while the number of eruptions in between 10–50 $m^3/s$ increases to the east and in late Holocene. The distribution of eruptions with MOR above 50 $m^3/s$ is even throughout the Holocene, the only difference is the size and volume of the formations, the largest shield-forming eruptions confined to the early and mid-Holocene. Many fields with MOR lower than 1 $m^3/s$ may have been segments of larger fissures or belong to events with multiple eruptions, "fires" within the same event, similar to the Fagradalsfjall fires that formed Fagradalshraun in 2021, Meradalir in 2022 and Litli-Hrútur in 2023, Krýsuvík fires that formed Kapelluhraun, Ögmundahraun, Mávarhlíðarhraun and Lækjarvellir (Einarsson, 1991) and not represent single eruptions. Lava fields that flowed both north and south as Afstapahraun and Leitahraun, with MOR up to 200 $m^3/s$ will have lower MOR if each branch was unidirectional and formed at different times. In the same manner, if Kapelluhraun, Mávarhlíðarhraun and Ögmundahraun erupted simultaneously, the the MOR would approximate the MOR of Afstapahraun. Slightly different ages for the north and south of Leitahraun lava fields suggest that the eruption comprises more than one eruption episode (Sæmundsson et al, 2016), which would lower the MOR by about half.

# 5 Discussion

## 5.1 The eruption capacity of the Reykjanes Peninsula

Assessing the MOR on a regional scale is a useful way to acquire an overview of the potential or past effusive capacity of a given area, even though some uncertainty is expected. The general picture from this assessment on the Reykjanes peninsula is of moderate background activity on which about 80% of the eruptions is under 50 $m^3/s$, yet this eruption activity is punctuated with larger eruption episodes in all volcanic systems that reach >100 $m^3/s$ which would have imposed greater hazards (Fig. 3). Both the largest fissure eruptions and the shield forming eruptions did give similar range of MOR, which indicates that the range represents an upper limit to the expected effusion rate in the region, the only differing factor being the duration of the eruptions. What controls the longevity is thus an important factor to be explored. Most eruptions have been relatively short to medium-lived fissure eruptions with vents centralized in the Peninsula, whereas shield-forming eruptions were predominantly found in the early and mid-Holocene with vents more scattered within the Peninsula. From the mid-Holocene the frequency of fissure eruptions with higher MOR increases, but none are long-lived enough to develop into shields. The early picritic and shield forming phase has been explained with high melt production the result from isostatic uplift following the deglaciation (Gudmundsson, 1986; Maclennan et al, 2002), yet the shield volcanism in the middle Holocene has an unclear causation. Judging from the volume of the hyaloclastite ridges and tuyas on the peninsula which give a window into the pre-deglaciation volcanism and would reflect to some extent the background volcanism, the volume and areal distribution of these edifices increases from west to east. A similar picture is acquired from the MOR assessment when the effect of the deglaciation is sieved out, with volcanism being more frequent and voluminous in the eastern systems (Krýsuvík and Brennisteinsfjöll) within the peninsula. As discussed in Sinton et al (2005), what controls high-volume eruptions is either tapping of large magma reservoirs or tapping reservoirs with continuous recharge. The former would favor eruptions with homogeneous compositions and potentially overpressurized eruptions resulting in high initial effusion rates, while the later more heterogeneous compositions tapping different mantle sources and with more stable effusion rates, as in Fagradalsfjall eruption in 2021 (Halldórsson et al, 2022; Pedersen et al, 2022). Jakobsson et al (1978) points out that the olivine tholeiite shields and the tholeiite fissure eruptions on Reykjanes do indeed have more homogeneous compositions indicating origin within magma storage systems while the picrites have more heterogeneous compositions, indicating tapping of deeper mantle sources. Jakobsson posited that the surface expression of shallow magma reservoirs was the pronounced graben structures in the volcanic systems, the occurrences of geothermal fields and the evolved composition of the lava fields. He also postulates the role of crustal thickness permitting storage, that is, most tholeiitic lava flows have originated near the central areas of the Peninsula around the spreading center, where crustal thicknesses are greater. The eruption forming Sandfellshæð shield within the western province, could be evidence of this (Fig. 4). It can be added that crustal thickness also increases rapidly inland (Darbyshire et al, 2000) and the eastern part of Reykjanes is likely controlled by greater storage capability within the crust, increasing the potential for long-lived eruptions. Yet this same factor would mean eruption frequency is lower in the easternmost system, the Hengill system, where more time is needed to replenish larger reservoirs.

## 5.2 Time of formation of the lava shields

The MOR values attained for the shield eruptions, e.g. 31 $m^3/s$ for Selvogsheiði to 102 $m^3/s$ for Heðin Há is considerably higher than usually attributed to shield eruptions, which are often given to be in the range of 5–15 $m^3/s$ (e.g. Rossi and Gudmundsson, 1996). A lower value of $T_{surf}$, 50°C, is used for the lava shields, a temperature that would be reached in 3.6 years according to equation 2, as it is assumed that lava shield-forming eruptions are long-lived. This can be inferred from their greater volume and geometry with a steeper cone and an circumscribing apron (Thordarson and Sigmarsson, 2009), with mature lava fields and crusts - displaying tumuli and lava-rise features (Rossi and Gudmundsson, 1996), and with evidence well-developed internal pathways or tubes (Peterson et al, 1994). The MOR nevertheless will be underestimated if the eruption duration were shorter, however, not greatly as $T_{surf}$ of 75°C reached in 1.3 years, is only slighly higher, and within the uncertainties of this type of assessment. However, The usage of lower $T_{surf}$ as of 30°C, that would be applicable for eruptions lasting over 17 years, is a time frame that is deemed unrealistic because the lava shields are low profile half-shields, in which most have low volumes (<3 $km^3$) compared to other Icelandic counterparts. The dimensions and thicknesses of the lobes (100´s m wide and 1–10 m thick) in some of the shields also suggest larger eruptions, e.g. Hrútagjá (Óskarsson, 2005), which are comparable to the distal flows within Holuhraun lava field that had MOR 90 $m^3/s$ (Pedersen et al, 2017). Furthurmore, the length of the flows, such as, Leitahraun that reaches over 20 km seems to imply relatively high effusion rates, and from the width and thickness of the largest lava tubes, e.g., in Raufarhólshellir in Leitahraun, with diameter up to 10 m in height and 30 m in width, that seems to have easily accommodated the estimated MOR of 200 $m^3/s$.

Although the estimated MOR accounts to some extent for the total volume erupted, the vertical buildup of the shield may be oblivious to the heat model, which does not account for overbank surface flows at the crater, or resurfacing with the formation of new flows as the lava reaches its cooling-limit. With time, effusion rates may decline and flows may pile around the vent as observed in the half-shields of Surtsey island (Thordarson et al, 2009). But as seen from these MOR and the volume estimates (see Table S1), shields in the lower MOR range as Selvogsheiði could have formed within

2 years accounting for a decline in effusion rates, and larger shields such as Heðin Há would be in less than 5 years due to higher MOR. Others, such as Leitahraun could have formed within a year if the flow was unidirectional at each given time as discussed above and with a MOR in the range of 200 $m^3/s$. Hrútagjá lava flows could have widen to its size in 2–3 years. This assessment would shed new light on shield forming volcanism in Iceland but better constraints on the architecture and buildup of these shields will help improve the eruption duration.

It could also be argued from the general low MOR of most eruptions on Reykjanes that the storage capacity of the Reykjanes peninsula is low, and that would also favour rather short cycles of shield construction. In contrast, the northern segment of the western volcanic zone that is located on a thicker crust, has formed larger shields that erupt at lower frequency (Eason and Sinton, 2009).

### 5.3 Implications for hazard assessment

The isopach map of Figure 4 shows that the locus of volcanism with higher MOR, where volcanism tends to be established and form mature vents and craters, clusters near the central areas of the peninsula, and align with the spreading ridge where, potentially, magma influx is greater, and that the peripheries of the fissure swarms have lower MOR. This implies that eruptions within the higher range of MOR are likely to be confined to the central areas of the peninsula, away from most urban centers, giving time for evacuation and planning.

The MOR is only an indication of the average effusion rate, whilst many eruptions begin with effusion rates that are much higher, e.g., if the initial rate is responding to an overpressurized reservoir. The eruption of Fagradalshraun in 2021 was different, and gave new insight into eruptions with sustained low effusion rates, whereby the initial effusion rate was the same as the MOR (Pedersen et al, 2022). Thus, it is not unlikely that other eruptions at Reykjanes behaved similarly. But the Sundhnúksgígar eruptions erupted overpressurized that quickly declined and ceased in only 1–2 days, yet their areal coverage was 70% of the area covered by Fagradalshraun in six months. If some of the largest events erupted lava from pressurized reservoirs, such as the largest early Holocene eruptions of Reykjanes e.g., Heiðin Há and Leitahraun, could have had initial effusion rates much higher or in the range of 300–500 m$^3$/s as in Holuhraun 2014–15, rates that would eventually decline with time. These rates would result in fast-advancing lava flows and impose considerable danger to the population of the peninsula.

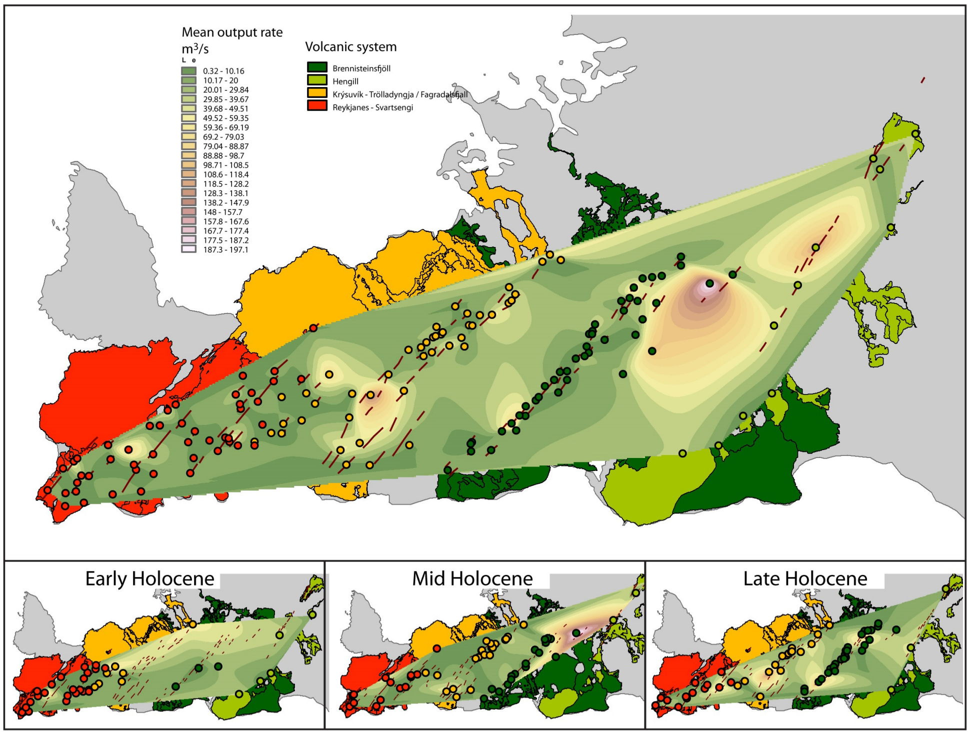


**Fig. 4** Isopach maps with the MOR distribution showing the eruption potential within the Reykjanes peninsula. Interpolation Natural neighbor.

# 6 Conclusion

The approach presented for calculating the mean output rates of past effusive eruptions provides first-order assessment of the scale and magnitude of effusive eruptions, even extending the application to a regional scale evaluating the eruption capacity of a volcanic area. The method is derived from a theoretical approximation of effusive eruptions with a range of compositions and emplacement styles and not on a case-to-case basis, thereafter the heat model shows to be applicable to other volcanic regions. The MOR of the 154 postglacial monogenetic eruptions on the Reykjanes peninsula gives moderate background activity under 50 $m^3/s$, but with recurring volcanism in the range of 50–200 $m^3/s$. The majority of these yield relatively short to medium-lived eruptions ($< 1$ year), while a few extended to be long-lived (a few years) and formed shields, the activity mostly confined to the early and middle Holocene. In recent decades, volcanism has comprised moderately large fissure eruptions of short duration rather than eruptions of long duration. Besides the role of isostatic adaptations affecting magma production following deglaciation, magma is seen to accent directly from lower crustal areas and form primitive heterogeneous lava fields or stall in storage systems which the role of crustal catchments in central and eastern regions of the peninsula where the crust is thickest.

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