Journal of Volcanology and Geothermal Research 256 (2013) 78–86

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

New insights into volcanic activity from strain and other deformation data for the Hekla 2000 eruption

Erik Sturkell [a,*], Kristján Ágústsson [b,1], Alan T. Linde [c], Selwyn I. Sacks [c], Páll Einarsson [d], Freysteinn Sigmundsson [a], Halldór Geirsson [e,f], Rikke Pedersen [a], Peter C. LaFemina [f], Halldór Ólafsson [a]

[a] Nordic Volcanological Center, Institute of Earth Sciences, 101 Reykjavík, Iceland
[b] Physics Department, Icelandic Meteorological Office, Reykjavík, Iceland
[c] Department of Terrestrial Magnetism, Carnegie Institution of Washington, N.W. Washington, DC, USA
[d] Institute of Earth Sciences, University of Iceland, 101 Reykjavík, Iceland
[e] The Icelandic Meteorological Office, Bustadavegur 9, Reykjavik, 150, Iceland
[f] Department of Geosciences, Pennsylvania State University State College, PA 16802, USA

ARTICLE INFO

Article history:
Received 12 March 2012
Accepted 4 February 2013
Available online 16 February 2013

Keywords:
Hekla
Deformation
Eruption
Strainmeters
Magma chamber
Dike

ABSTRACT

Hekla is one of Iceland's most active volcanoes; its eruptions, characterized by surface fissuring and repeated lava flows during its post-glacial activity, have built up an 800 m high elongated mountain. Since 1970 it has erupted every ~10 years; the previous repose interval averaged ~60 years. For the last eruption in 2000 we constrain the magma geometry by using a wide variety of deformation data: campaign GPS; an InSAR interferogram; dry tilt data, and borehole strain data. The dike that causes surface fissuring extends no more than ~0.5 km in depth, and the reservoir depth is ~10 km. These are connected by a conduit of small lateral extent. Data for previous eruptions are consistent with this model. We propose that the marked change in eruption interval is because this conduit remains liquid during the short interval between recent eruptions; only a small pressure increase is required to rupture the thin crustal seal. Such a state is consistent with precursory seismicity being confined to very shallow depths and may be applicable to other volcanoes that undergo abrupt changes in eruption interval.

1. Introduction

Although deformation data have been used for about half a century to study physical aspects of volcanic activity (Mogi, 1958: Dzurisin, 2007) these studies have so far given disparate results for Hekla, one of Iceland's most active volcanoes. A variety of deformation data collected before, during, and after the 2000 eruption of Hekla allow us for the first time to constrain the depth and location of the magma chamber, the geometry of the conduit and the dike feeding the fissure eruption. Our results give insight into why the repose interval between eruptions (whether for Hekla or other volcanoes) can change dramatically. Employing such a wide variety of data for other volcanoes should allow significant advances in understanding and predicting their activity.

Iceland is located on the divergent mid-Atlantic ridge, which is slowly spreading with a half rate of 9.7 mm/yr. In the south, two overlapping spreading ridges exist, the western and eastern connected in the south by a transform zone (Fig. 1). Hekla has had 18 summit eruptions during the last 1100 years, the last in 2000. The average repose period was 60 years before 1970 but then decreased abruptly to ~10 years. The sequence of events for eruptions in 1970, 1980–81, 1991 and 2000 has been well-documented (Thorarinsson, and Sigvaldason, 1972; Grönvold et al., 1983; Gudmundsson et al., 1992; Höskuldsson et al., 2007). There is a direct correlation between the repose time and size (explosivity and extruded volume) and duration of the eruption. The silica content of the initial eruptive products also increases together with repose time (Thorarinsson and Sigvaldason, 1972).

Studies of earlier recent eruptions, based on smaller deformation data sets, yielded estimated reservoir depths from 5 to 10 km. From EDM data measured before and after the 1981 eruption, a reservoir at 7–8.5 km was proposed (Kjartansson and Gronvold, 1983). GPS data spanning the 1991 eruption indicated a depth of 9 +6/−7 km (Sigmundsson et al., 1992) whereas tilt data suggested the reservoir was located at 5–6 km (Tryggvason, 1994). A study of strain data from the 1991 eruption placed it at 6.5 km (Linde et al., 1993); however we now realize (Jónsson et al. (2004), see below) that this shallow depth estimate is erroneous due to an artifact in the BUR strain data. Soosalu and Einarsson (2004) used a seismic ray model to scan for the location of a magma chamber under Hekla. The area under the volcano was well illuminated in the 8–14 km depth range, and they estimated

* Corresponding author at: Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden.
E-mail address: sturkell@hi.is (E. Sturkell).
[1] Present address: ÍSOR, Iceland GeoSurvey, Grensásvegi 9, 108 Reykjavík, Iceland.

0377-0273/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jvolgeores.2013.02.001

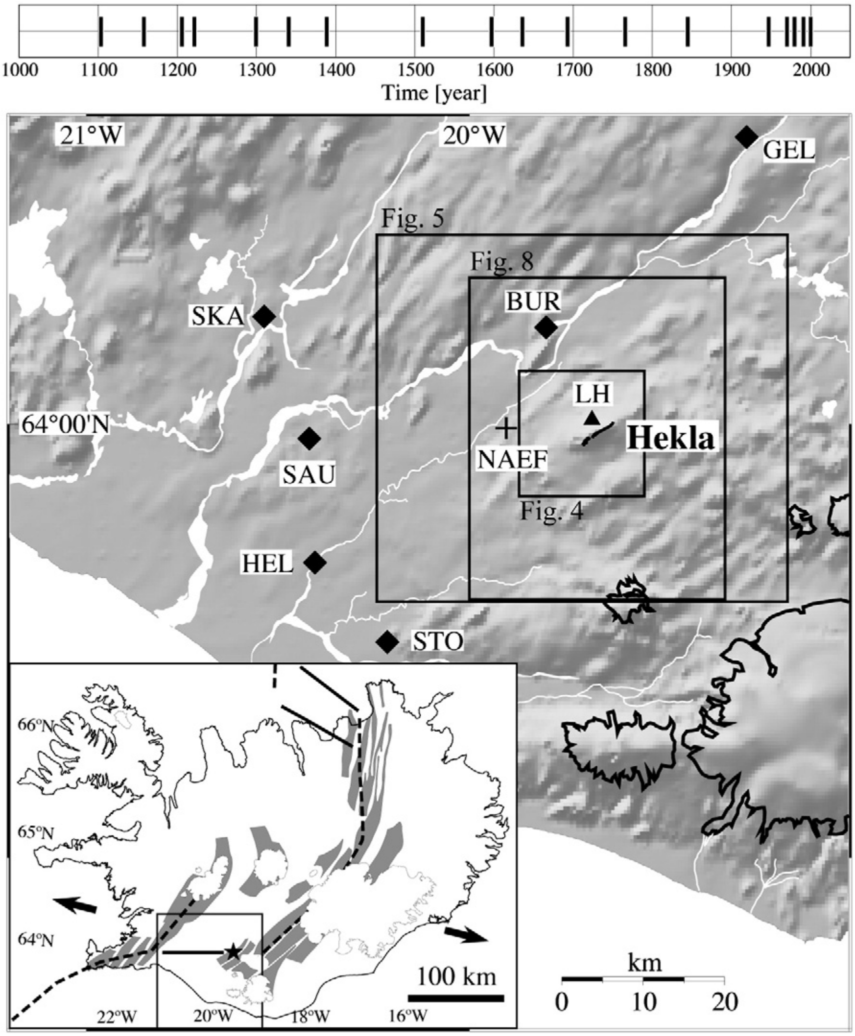

Fig. 1. Hekla volcano is located in south Iceland, marked by a star in the inset which shows the axes of the rift zones (dashed lines) and the general outline of the volcanic systems. Transform fault zones are shown as solid black lines. The detailed map shows Hekla with the eruptive fissure from the 2000 eruption in black. The thick black lines outline the glaciers. The volumetric strainmeter network (rhombs) spans an azimuthal range of 180° around Hekla. The closest strainmeter is located at BUR, 15 km from the summit; strain sites STO, HEL, SAU, SKA, and GEL are all at 35–45 km distance. The plus sign gives the location of the tilt station NAEF located 11 km due west of the summit. The seismic station LH is shown with a black triangle. The time line above the map shows the eruption history of Hekla. The data for eruptions prior to 1970 originates from Þórarinsson (1967).

that the resolution of the tomography was 800 m. They did not detect any large magma chamber in the 8–14 km depth interval. The conclusion was that if a volume with larger diameter than 800 m exists it must be above 4 km or below 14 km depth. This depth estimate is consistent with the suggestions by Ofeigsson et al. (2011).

Hekla shows a few long-term precursors to eruptions: optical tilt, GPS and InSAR give indications of upcoming eruptions. During non-eruptive periods very few earthquakes occur (Soosalu et al., 2005) so any seismic activity close to the summit is an indication that the volcano is about to erupt; in 1991 strain changes at BUR due to dike growth, could be seen about 25 min before the eruption. In June 1991 a ten hour long earthquake swarm (<M1.7) occurs at shallow depths (uppermost 3 km) located under the northern part of the volcano (Soosalu and Einarsson, 2002). An earthquake swarm without any following eruption is unusual, and they suggested this was an attempt to resume the 1991 eruption. In this study we take advantage of a larger, more diverse deformation data set and consequently are able to derive tighter constraints on the magma geometry and, additionally, are able to suggest why there are marked changes in eruption interval.

2. The 2000 eruption

The eruption of February 26–March 8, 2000, occurred after a nine year repose time. The initial phase was sub-plinian and did not last more than half an hour. The eruption began at 18:19, as visually observed from a close distance and accurately timed. The eruptive plume reached a maximum height of 12 km at 18:49 (Höskuldsson et al., 2007: Fig. 3). Seismic and strain data (Fig. 2) provided the basis for an official short-term warning. During the 2000 eruption, the first small earthquakes were observed at 17:00 GMT (Soosalu et al., 2005). At 17:45 the BUR strainmeter (Fig. 2) registered contraction, and the seismicity intensified (Fig. 3a). Strain rate at BUR, inferred to be due only to dike formation, reached a negative maximum at 18:18; this can be used (see above) to infer surface breakout and agrees within a minute with the visual observation of 18:19. The precursory earthquakes were recognized as they occurred and generated an alert 60 min before the eruption; this promoted close examination of the BUR data that allowed a 20 min forewarning for redirection of air traffic (http://hraun.vedur.is/ja/heklufrettir.html; Ragnar Stefánsson pers comm.).