Lava Flow Mapping Using Sentinel-1 SAR Data at the Fagradalsfjall Volcano, Iceland

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Abstract

In March 2021, an eruption began in the Fagradalsfjall volcanic system in Iceland after a quiescence of 6,000 years, which also marked the end of more than 800 years of dormancy in the Reykjanes Peninsula. In areas of volcanic activity, lava flow mapping and analysis play a significant role in monitoring and disaster risk management, because lava flows represent potential hazards to surrounding areas. This study used object-based image analysis (OBIA) and Sentinel-1 synthetic aperture radar (SAR) data to map the extent of the Fagradalsfjall lava flow and its evolution. We investigated two images, acquired on 18 May 2021 and 30 September 2021, syn- and post-eruption respectively. The calculated lava inundation area was 2.07 km² for 18 May 2021, and 5.03 km² post-eruption. The results of the application of the OBIA method on Sentinel-1 backscatter data reveal a high potential for lava flow mapping as they show high agreement with existing reference data (accuracies from 79% to 93%). However, the outcomes should be evaluated carefully because factors such as spatial resolution, SAR geometrical distortions and the OBIA segmentation process can influence the classification results.

Keywords:

1   Introduction

Understanding geophysical phenomena, such as volcanic eruptions and their associated processes, plays an essential role in disaster risk management. Lava flows are usually localized events that can be hazardous because of their extreme temperatures and capacity to surround or bury structures, or to create structural failures (Harris, 2015). Increasingly, assessment of volcanic parameters and their associated risks incorporate remote sensing data and techniques. This is because of the ability of Earth Observation (EO) data to capture thermal anomalies, ground deformation, and ash dispersal within different portions of the electromagnetic

spectrum (Cigna, Tapete, & Lu, 2020; Joyce et al., 2009). Effective monitoring of the development of volcanic processes requires data with a high temporal resolution that regularly document and track such events. The integration of EO data for lava flow mapping and analysis therefore enables near-real-time monitoring, and improvements to risk assessment models and decision-making processes.

The Fagradalsfjall volcano is located on the Reykjanes Peninsula in Iceland. After a quiescence of 6,000 years in the Fagradalsfjall volcanic system, an eruption occurred from March to September 2021, followed by another event in 2022. Based on aerial photogrammetric surveys and optical Pleiades stereo images, Pedersen et al. (2022) generated orthophotos, digital elevation models (DEMs), and thickness and thickness-change maps. They also manually mapped the lava flow, and calculated lava volume and effusion rates. Another study mapped the 2021 lava paths in the Fagradalsfjall volcanic system using data provided by the Fire Information for Resource Management System (FIRMS) (Vasconez et al., 2022). SAR data have been used for volcanic monitoring, deformation analysis, and lava flow mapping of various volcanic eruptions, including the 2014–2015 Holuhraun eruption in Iceland (Dumont et al., 2018; Pedersen et al., 2017), the 2017–2018 unrest at Mount Agung in Indonesia (Albino et al., 2020), the 2011–2013 and 2018 Kilauea eruptions in Hawaii (Lee, Jung, & Hong, 2023; Poland et al., 2014), and the 2014–2015 Fogo eruption in Cabo Verde (Tiengo et al., 2021). Because SAR is not weather-dependent and has day and night capabilities, it can provide data on a continuous basis, making it extremely useful for monitoring and tracking lava flow (Pinel et al., 2014). Furthermore, compared to field measurements, lava flow mapping using freely available SAR imagery is less time-consuming and more cost-effective.

Object-based image analysis (OBIA) has the potential for analysing the evolution of dynamic processes on Earth and has been widely used in geomorphological mapping. The main advantage of OBIA compared to pixel-based approaches is that it uses additional dimensions of information about geographical entities, such as spectral, spatial or textural properties (Blaschke, 2005). However, volcanic-deposit mapping using OBIA and SAR backscatter information has so far been scarce (Dabiri et al., 2023; Hölbling, Aufaristama & Dabiri, 2019). Thus, further research in this direction is needed.

The aim of this study is to assess the applicability of Sentinel-1 data for semi-automatically mapping the evolution of the lava flow extent for the 2021 Fagradalsfjall eruption in Iceland using OBIA.

2 Materials and Methods

2.1 Study Area

The Fagradalsfjall volcanic system is located approximately 40 km southwest of Reykjavik. The system was named after the Fagradalsfjall subglacial tuya volcano, which is characterized morphologically by hills with flat tops and steep sides. The 2021 Fagradalsfjall effusive

eruption lasted from March to September and marked the end of a long period of dormancy in the Reykjanes Peninsula (Global Volcanism Program, 2021; Sæmundsson et al., 2020). The low-intensity volcanic activity produced a range of pahoehoe and a'a morphologies within the basaltic lava flow field, with minor scoria deposits around the vents, which partially infilled the nested valleys of the pre-eruption topography (Barsotti et al., 2023; Pedersen et al., 2022).

2.2 Data

For the 2021 Fagradalsfjall eruption, we used syn- and post-eruption Sentinel-1B (C-band) dual-polarization Interferometric Wide Swath (IWS) Level-1 high-resolution Ground Range Detected (GRD) products, acquired in descending flight direction (Table 1). Data pre-processing included orbit file application, radiometric calibration and terrain flattening, Refined Lee speckle noise filtering, and Range Doppler terrain correction.

Table 1: Sentinel-1 data used to semi-automatically delineate and map the lava flow from the 2021 Fagradalsfjall eruption.

Date	Event	Sensor
18 May 2021	Syn-eruption	Sentinel-1B IW Level 1 GDR
27 September 2021	Post-eruption	Sentinel-1B IW Level 1 GDR

2.3 Semi-automated Lava Flow Mapping using OBIA

OBIA was used to map the lava flow of the 2021 Fagradalsfjall eruption. The analysis was performed in eCognition (©Trimble) software. The first step in the object-based mapping was the creation of objects using a multiresolution segmentation algorithm. Several layers were used for the segmentation, including the linear Gamma_VH, Sigma_VH, Gamma_VV, and Sigma_VV. A weight of 1 was assigned to each of these. In addition, a weight of 2 was assigned to the Gamma_VH_DB layer, which contained the Sentinel-1 backscatter intensity, radiometrically corrected in Gamma-0 with VH polarization and converted to decibel scale. We then created a knowledge-based classification ruleset integrating statistical parameters (brightness, mean and standard deviation) and spatial ones (area and main direction), along with Haralick textural features (Haralick, Shanmugam & Dinstein, 1973). These textural features are based on the grey-level co-occurrence matrix (GLCM) and include such characteristics as contrast, dissimilarity and entropy. Further refinement was performed using merging algorithms and relations between objects before validating the results. The parameters and thresholds used for segmentation and classification were determined by trial and error and visual assessment of the intermediate results. Table 2 provides an overview of the parameters included in the two processes for the syn- and post-eruption images.

Table 2: OBIA segmentation and classification parameters for the lava flow mapping.

Image	Segmentation Bands	Segmentation Parameters	Classification Parameters	
			Object-based feature	Threshold
Syn-eruption	Gamma_VH (1) Sigma_VH (1) Gamma_VV (1) Sigma_VV (1) Gamma_VH_DB (2)	Scale Parameter: 10 Shape: 0.1 Compactness: 0.5	Brightness	>0.063
			Mean Gamma_VH_DB	>-19.2
			Mean DEM	>220
			GLCM Dissimilarity (90°)	>8.55
Post-eruption	Gamma_VH (1) Sigma_VH (1) Gamma_VV (1) Sigma_VV (1) Gamma_VH_DB (2)	Scale Parameter: 10 Shape: 0.1 Compactness: 0.5	Brightness	>0.06
			Mean Gamma_VH_DB	>-17.88
			Std. Deviation Gamma_VH_DB	>0.01
			Mean DEM	>261
			GLCM Entropy (45°)	>8
			GLCM Contrast (0°)	>330
			Main Direction	>13

3   Results and Validation

The results of the lava flow mapping using OBIA are shown in Figure 1. The pre-eruption image (a) was used as a reference to compare how the area changed after the lava flow started to infill the Geldingadallir valley within the Fagradalsfjall area; (b) shows the syn-eruption image; (c) shows the post-eruption image. The results show the extent of the lava flow, classified after refinement and post-processing.
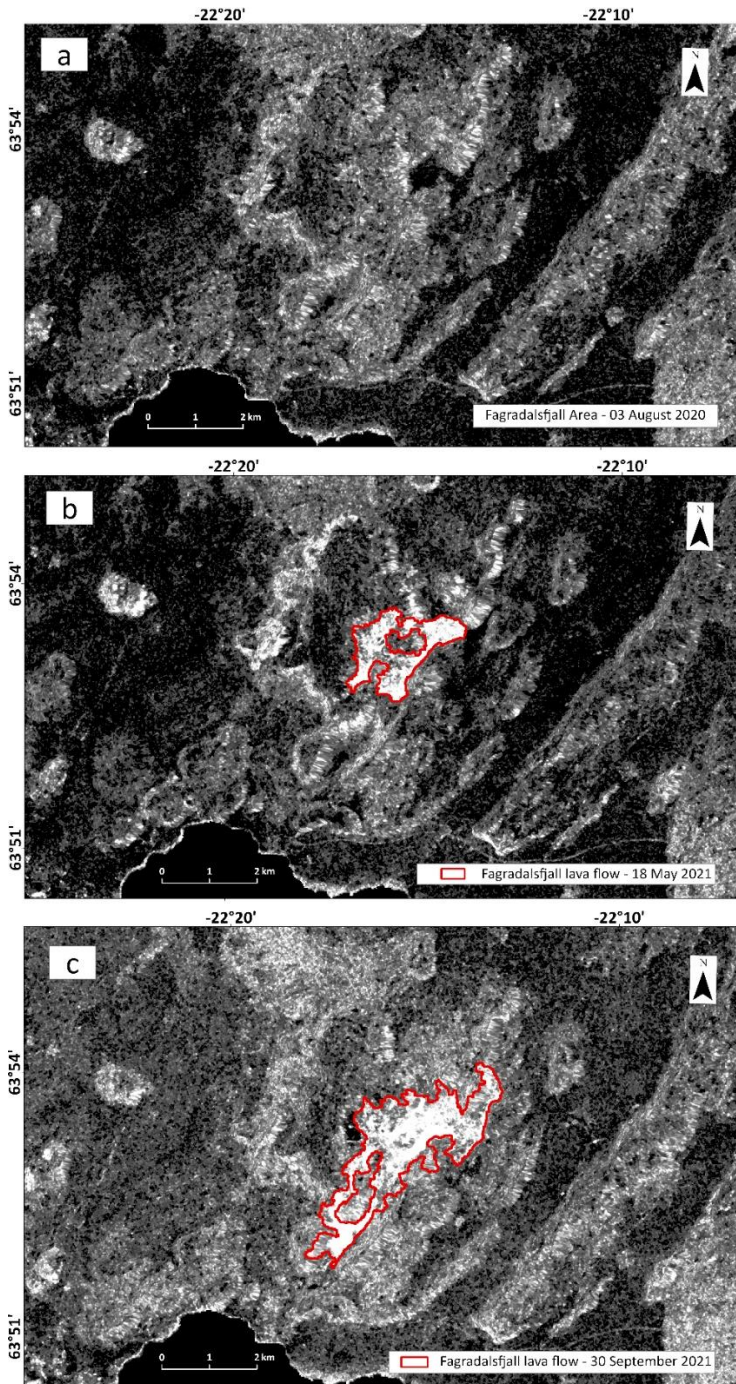
Figure 1: Object-based lava flow mapping using Sentinel-1 data. (a) shows the pre-event image; (b) shows the area covered by the lava flow until 30 May 2021; (c) shows the extent of the lava flow after the eruption ended.

The accuracy was estimated by considering the overlapping area between the results obtained with OBIA, and the lava outlines created by Pedersen et al. (2022) that used manual digitization of very high-resolution orthomosaics. The overlapping areas denote the correctly classified areas. The producer's accuracy represents the ratio between the overlapping area and the OBIA delineation; the user's accuracy represents the ratio between the overlapping area and the orthomosaics delineation. The ratios obtained are therefore a measure either of errors of inclusion for the producer's accuracy, or of errors of exclusion for the user's accuracy (Congalton, 1991).

The difference in area is larger for the post-eruption data than for the syn-eruption data. The accuracy values are similar for the OBIA and the orthomosaics classification maps for both events; however, higher ratios were achieved for the syn-eruption than for the post-eruption phase. Table 3 summarizes the validation results.

Table 3: OBIA and orthomosaics (Pedersen et al., 2022) mapped area, difference in mapping results, area of overlap, and accuracies calculated for each event.

Data	Dates	OBIA (km²)	Orthomosaics (km²)	Difference (%)	Overlap (km²)	Producer's Accuracy (%)	User's Accuracy (%)
Syn-eruption	18/05/2021[1] 18/05/2021[2]	2.07	2.05	0.97	1.91	92%	93%
Post-eruption	27/09/2021[1] 30/09/2021[2]	5.03	4.84	3.92	4.01	79%	83%

[1] Sentinel-1 data; [2] Pedersen et al. (2022) delineation dates.

4 Discussion and Conclusion

Considerable agreement was obtained between the lava flow paths identified with the OBIA approach using Sentinel-1 data on the one hand, and the manual delineation using very high-resolution airborne imagery by Pedersen et al. (2022) on the other. The performance of the OBIA approach decreased for the post-event image. Parts of the lava field corresponding to lava ponds exhibited exceptionally low backscatter values. Therefore, they were not classified. The Copernicus DEM was used for auxiliary data for the classification; however, it does not offer a multi-temporal and sufficiently accurate topographic signature for mapping the changes in the extent of the lava flow. It is possible, therefore, that the final classification includes a number of false-positive segments, and that other actual lava segments were missed entirely from the classification. Moreover, the spatial resolution is a limiting factor for lava flow delineation. The aerial photographs used by Pedersen et al. (2022) have a spatial resolution of 7–30cm, while that of the Sentinel-1 images is 10m.

The main challenges for lava flow classification using Sentinel-1 data are the geometric distortions of SAR imagery caused by its side-looking geometry, which may result in foreshortening, layover and shadow effects. Foreshortening makes objects appear smaller, and layover generates superimposition of features that can affect the segmentation. Nevertheless, terrain correction in Gamma-0 probably reduced the geometric distortions by decreasing the angle dependency of the radar backscatter. Furthermore, the background information and structure of an image can disrupt potential changes, making them harder to recognize for the segmentation algorithm.

The results of using the OBIA method on Sentinel-1 SAR backscatter data reveal the potential for lava flow mapping as they show high coincidence with the reference data. Despite this high coincidence, results obtained using OBIA need to be checked carefully because the approach is sensitive to the image objects derived from segmentation, and the process of segmentation is the foundation for classification.

Although the implementation of OBIA in semi-automated lava flow mapping is relatively new, especially when applied to Sentinel-1, the results exhibit promising accuracy. Future studies should further explore the potential of combining OBIA and automated change-detection analysis for lava flow mapping using the backscatter intensity information recorded by SAR data. Moreover, Sentinel-1 data can be used to create multi-temporal DEMs utilizing interferometric SAR (InSAR) techniques (Abad et al., 2022), which can support frequent monitoring of land surface changes and the characterization of lava flows. The resulting lava flow maps would be useful as reference data for future eruptions of Fagradalsfjall, could provide valuable information to support disaster risk management, and could be used as input data for lava flow modelling.

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