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Mapping and Assessing Surface Morphology of Holocene Lava Field in Krafla (NE Iceland) Using Hyperspectral Remote Sensing

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Abstract. Iceland is well known for its volcanic activity due to its location on the spreading Mid Atlantic Ridge and one of the earth's hot spot. In the past 1000 years there were about 200 eruptions occurring in Iceland, meaning volcanic eruptions occurred every four to five years, on average. Iceland currently has 30 active volcano systems, distributed evenly throughout the so-called Neovolcanic Zone. One of these volcanic systems is the Krafla central volcano, which is located in the northern Iceland at latitude 65°42'53" N and longitude 16°43'40" W. Krafla has produced two volcanic events in historic times: 1724-1729 (Myvatn Fires) and 1975-1984 (Krafla Fires). The Krafla Fires began in December 1975 and lasted until September 1984. This event covered about 36-km^2 surrounding area with lava, having a total volume of 0.25-0.3 km^3. Previous studies of lava surface morphology at Krafla focused on an open channel area by remote sensing are essential as a complementary tool to the previous investigations and to extend the area of mapping. Using Spectral Angle Mapper (SAM) classification approach by selecting spectral reflectance end members, this study has successfully produced a detailed map of the surface morphology in Krafla lava field EO-1 Hyperion (Hyperspectral) satellite images. The overall accuracy of lava morphology map is 61.33% (EO-1 Hyperion). These results show that hyperspectral remote sensing is an acceptable alternative to field mapping and assessing the lava surface morphology in the Krafla lava field. In order to get validation of the satellite image's spectral reflectance, in-situ measurements of the lava field's spectral reflectance using ASD FieldSpec3 is essential.

1. Introduction

The Icelandic landmass was produced by repeated volcanic activities of various type, and nearly all types of volcanoes and styles of eruptions known on earth can be found [1]. Eruption styles range from explosive (produce over 95% of tephra) to effusive (produce over 95% of lava) [2]. Iceland has a high concentration of active volcanoes due to its location on the mid-Atlantic Ridge (divergent tectonic plate boundary) in combination with its position on a volcanic mantle plume located underneath the island. Since the Norse settlement of Iceland in AD 874, 13 of 30 active volcanos in Iceland have erupted [3]. The occurrence of a volcanic eruption every fourth year on average makes Iceland one of the liveliest places in the world with regards to volcanic eruptions. Over the past 500 years, Iceland's volcanoes have erupted a third of the total global lava output [4].

2. Lava Morphology

Lava morphology is related to the characteristics of the surface morphology of a lava flow after solidification [5]. Morphology of lava is the primary basis for classification of lava flows when rheological properties cannot be directly observed during emplacement [6]. Solidified lava flows and most basaltic lavas can be identified by the terms grouped as pahoehoe, aa, and blocky [6,7]. Aa and pahoehoe lava flows can be found on all of the volcanoes of Iceland [3]. The pahoehoe and aa are by far the most common lava types in Iceland, representing 83% of the 190 lava flows analyzed so far, and fissure-fed pahoehoe are as common as shield forming pahoehoe [3]. In general, on the younger volcanoes, the pahoehoe percentage is higher [8]. Pahoehoe lava has a fairly smooth surface and continuous. Contrary, aa lava is very rough and fragmented. The detail of lava morphology is described in table 1.

Table 1. Description of morphological lava types.

Morphological lava type	Descriptions
Pahoehoe sheet	Smooth surface is divided into sub-horizontal crustal plates, sometimes slightly buckled against each other [9]
Shelly pahoehoe	Shelly pahoehoe is a very vesicular pahoehoe lava type with fragile lava crust [5]. It forms flow lobes and small lava tubes which become hollow inside as lava drains downslope or as the molten lava in the lobe-interior loses gas.
Slabby pahoehoe	This lava is characterized by a flow top of crustal slabs and a pahoehoe base [8]. The slabs are up to several meters across and a few centimetres to decimetres thick [5] [8].
Spinny Pahoehoe	Spiny pahoehoe flows are covered by a rough spiny surface different from the smooth shiny surface of normal pahoehoe [8][9]. Spiny pahoehoe flows commonly form as the last oozes outs of dying pahoehoe flows or stagnating lobes of pahoehoe flows [8]. Spiny pahoehoe also leaks from the edges and the fronts of some aa flows [8].
Cauliflower aa	This is an initial aa lava type in the transformation from pahoehoe to rubbly aa. Protrusions are initially attached to the massive lava beneath but commonly break and form loose debris on the flow surface [9]. Cauliflower aa is common in the shelly and slabby pahoehoe dominated zones where lava flows spilled out after the formation of these morphology [5].
Rubbly aa	Rubbly aa is characterized with a clinkery and blocky surface [5][9]. Surface breccia varies from sand size to blocks several meters in diameter). This lava type has high thermal maturity; the crust during flow is broken by brittle failure [9].

3. Study Area

Krafla is located in northern Iceland, approximately at latitude 65°42'53" N, and longitude 16°43'40" W. The Krafla central volcano has around 8 km wide caldera that was formed in an eruption about 100,000 years ago [11]. Since then, the caldera has widened about 2 km in the East-West direction due to the plate spreading [11]. The Krafla volcano is primarily basaltic, but silicic deposits are found in the vicinity of the caldera [11,12]. Krafla's last eruptive episode, i.e. the "Krafla Fires", resulted 21 tectonic events, and 9 volcanic eruptions [11]. The total area covered with lavas is 36 km^2 and its volume is about 0.25-0.3 km^3 [11]. Morphology of the open channel lava flows in Krafla have been mapped previously [9]. Five flow facies are recognized (1) the initial pahoehoe sheet; (2) slabby pahoehoe and aa; (3) shelly pahoehoe from the channel; (4) rubbly aa; and (5) cauliflower aa (Figure 2a). The previous study was primarily field mapping, video recording and measured pre-flow topography from aerial photographs.

4. Data and Methods

To assess the potential of using hyperspectral remote sensing for identifying lava surface morphology in the Krafla lava fields, the open access satellite data of EO-1 Hyperion was used. The EO-1 Hyperion image used is dated from the 17^{th} of July 2012, with hyperspectral band (242 bands) and 30 meter resolution. The image was geocoded using Ground Control Points (GCP) taken from the aerial photograph and georeferenced into the Lambert Conformal Conic coordinate system on the ISN 1993 Lambert 1993 datum.

The first step of the Hyperion data pre-processing consisted of the elimination of uncalibrated bands. The level 1 Radiometric product has a total of 242 bands, but only 198 of these are calibrated [13]. In this image there are only 170 bands selected due to the uncalibrated bands, bad bands and vertical stripping bands.

Surface reflectance of Hyperion was retrieved using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) algorithm which is developed in FLAASH ENVI module [13]. The parameterization of ENVI FLAASH includes entering information about the type of sensor and the date of scene, selecting an atmosphere and aerosol model for the correction, and setting the options for the atmosphere correction model. Sub-Arctic Summer Atmospheric model was used in order to characterize the water vapor present in the atmosphere. The aerosol type selected was the rural one in accordance with the Krafla scenario, not strongly affected by urban or any other industrial sources.

The next step, spectra were picked from the image at selected areas that were known to the interpreter from fieldwork and previous studies. Eight spectral endmember points from each morphological type were collected. These include five types of lava morphology pahoehoe, rubbly aa, old lava, cauliflower aa, and shelly pahoehoe. The other classes are, Holocene lava formation, upper Pleistocene formation, and vegetation. Moving average technique was used in order to smoothen the spectral reflectance curves.

Due to the fact that most of the lava in Krafla is basaltic [9], the lava spectral was further validated from a laboratory measurement, obtained from the USGS and provided in ENVI software. This basalt spectral reflectance have five major absorptions, i.e. $Fe3^{+}$ electronic absorptions in oxides/hydroxides, Fe^{2+} electronic absorptions in pyroxene, O–H vibrations in hydroxyl, H_2O and M–OH vibrations in clay minerals (Figure 1) [15]. This USGS sample of weathered basalt has a higher reflectance and also has relatively strong absorptions in the five bands compared to fresh basalt. These spectral will be classified in the next step using Spectral Angle Mapper (SAM).

The Spectral Angle Mapper (SAM) is a classification method which calculates the spectral similarity between the image reflectance spectrums to reference reflectance spectra [16]. In this method the spectral reference is extracted directly from the image endmember selection. This method is not affected by solar illumination factors, because the angle between the two vectors is independent of the vectors length. It takes the arc cosine of the dot product between the test spectrums "t" to a reference spectrum "r" with the following equation [13]:

$$\alpha = \cos^{-1}\left(\frac{\sum_{i=1}^{nb} t_i r_i}{\left(\sum_{i=1}^{nb} t_i^2\right)^{\frac{1}{2}}\left(\sum_{i=1}^{nb} r_i^2\right)^{\frac{1}{2}}}\right) \quad (1)$$

Finally the classification result will be assessed using accuracy assessment. The accuracy assessment shows the percentage difference between classification result and references data. Selections of 150 reference points were based on random equal-stratified sampling.

5. Results and Discussions

According to spectral reflectance curve, the results show that the absorption features of the old lava in Krafla are relatively similar to weathered basalt, except in (Fe/Mg)-OH absorption ranges due to the limited range of remote sensing data and the shifting of absorptions features (Figure 1). Shifting of absorption features in the hyperspectral data could be due to the effect of data smoothing. Figure 1 shows the effect of bad data (850 nm – 1000 nm and 1820 nm – 1951 nm), which causes a flat spectral after data smoothing. The result from the SAM method on EO-1 Hyperion data successfully discriminates the lava morphologies in the Krafla lava field (Figure 2b). The classification based on endmember spectra has an overall accuracy of 61.33% (Table 2). However, the bad data and vertical stripping of the Hyperion images does affect the ability to extract spectral reflectance and identify individual lava morphologies.

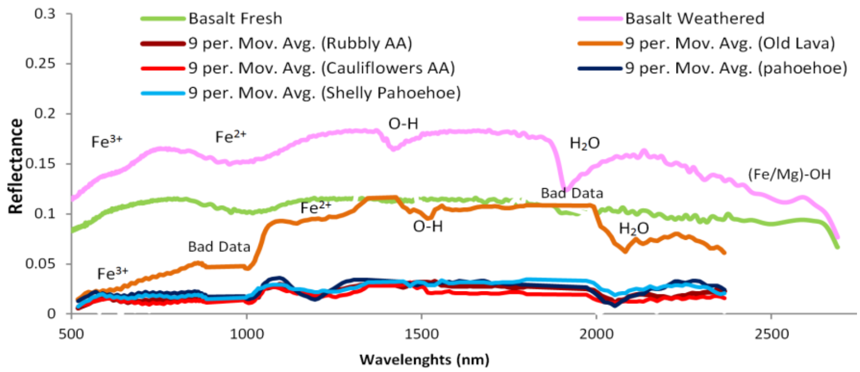

Figure 1. Spectral reflectance of lava morphology comparison between basalt from USGS laboratory measurement and basalt lava in Krafla lava field from remote hyperspectral remote sensing with the absorptions features.

Furthermore, detailed analysis of the individual lava morphology accuracy of EO-1 Hyperion reveals that hyperspectral is prospective to detect the individual lava morphology. In order to be considered, the accuracy needs to be over 50%. Cauliflower aa producer accuracy clearly show that only 43.33% of pixels classified have been identified. According to that result we also need to consider the user accuracy. The user accuracy result of cauliflower aa show 76.47%. Therefore, despite the map produces only 43.33%, a user of this map will find that the map show 76.47% the actual cauliflowers aa. This acceptable user accuracy reveals that the map is still reliable to identify cauliflower aa and the rest of lava morphology.

Table 2. Results of overall, producer and user accuracy including the Kappa statistics for EO-1 Hyperion.

Satellites Image	EO-1 Hyperion	
Lava Classes	User Accuracy	Producer Accuracy
Rubbly aa	68.57%	80%
Cauliflowers aa	76.47%	43.33%
Shelly Pahoehoe	64.29%	30%
Pahoehoe	58.54%	80%
Old Lava	75.86%	73.33%
Overall Accuracy	61.33%	

EO-1 Hyperion produces 30% producer accuracy for shelly pahoehoe. This is the only value for pahoehoe lava morphology for which accuracy falls below 40%. This is due to horizontal strip that occurred in the spectral endmember of shelly pahoehoe and also the vertical strips that appear in the western, centre (main concentration of shelly pahoehoe) and northern part in the Hyperion image. Several other issues may affect the accuracy of lava surface morphology. These include the following: (1) Medium spatial resolution (30 meter) of satellites image; (2) image acquisition differences between references and satellites and (3) small differences of spectral characteristics within lava morphology.

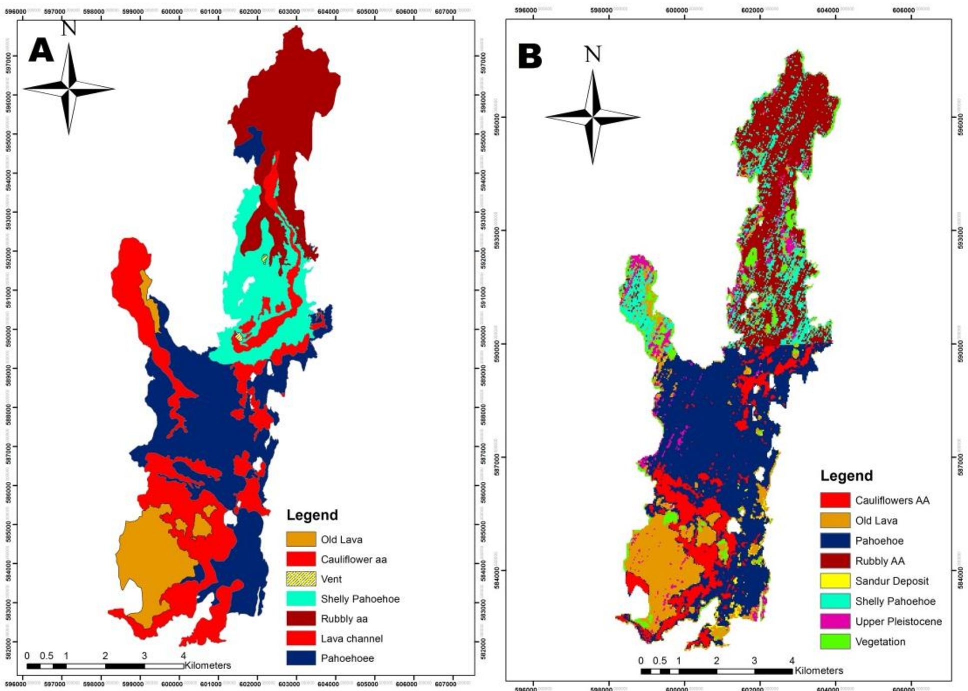

Figure 2. (a) Surface morphology reference of Krafla lava field. **(b)** EO-1 Hyperion SAM classification result successfully produces the lava morphology map within Krafla lava field.

6. Conclusion and Recommendations

Finally, the possibilities of EO-1 Hyperion to identify individual lava flow morphologies using endmember spectra collection, and spectral angle mapper classification have been handled. According to the results, in general hyperspectral remote sensing is capable of mapping and assessing of detail lava morphology in Krafla lava field. The real ground truth in situ measurement of lava field reflectance spectra using ground remote sensing such as ASD FieldSpec3 [17] would be essential to collect from the study area in order to validate the Hyperion images. Spectroscopy laboratory measurements of the Krafla lava field would give the reference of absorptions features of basaltic lava in Krafla lava field. Another option of using airborne hyperspectral image data such as HyMap and AVIRIS could possible to improve detail of reflectance spectra, spatial resolution and quality of data.

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