Unsupervised classification of lava flows in Harrat Lunayyir using remote sensing and GIS

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Abstract

Mapping of lava flows based on remote sensing data of high accuracy has become a common tool for exploring volcanic eruptions in greater detail. Mapping data based on remote sensing data provides information on the location and flow direction of lava flows as well as their areas and enables the localisation of volcanic vents—valuable knowledge for pre- and post-eruption volcanic activity and behaviour estimations. The current research seeks to expand the understanding of the volcanic and tectonic processes in Harrat Lunayyir, Saudi Arabia. In view of this, remote sensing data was classified using iterative self-organising data analysis technique (ISODATA) algorithms. The aim of the classification is to identify spectral top-of-atmosphere (TOA) reflectance values to distinguish layers of old and recent lava flows based on differences. As a result, three distinct basaltic units were identified to have the following ages: 15.1 ± 6.1 ka (4%), 15.0 ± 8.4 ka (6%), and 14.6 ± 23.1 ka (10%). The differences in the calculated areas of the lava flows as mapped based on the remote sensing data and earlier modelling are captured and identified in relation to the local geomorphologic and geologic structures. The differences can be partly explained as being related to a considerable weathering of the observed geological formations at 800–1600 nm, with reflectance of 12%. The limitation of the methodology relates to the lack of accurate geochronological timeline, that is, an inability to identify accurate age of the samples.

Keywords ISODATA · Morphology classification · Remote sensing · Top-of-atmosphere (TOA)

Introduction

The factors that affect the flow of lava and its morphology include its rheological properties, the rate of discharge or effusion, the topography, in particular the slope, and the external environment in which the flow of lava takes place. As the lava flows, its temperature falls, which affects its rheology (Griffiths 2000; U.S. Geological Survey 2008). The most important rheological properties of lava include the yield strength, viscosity, crystal fraction, composition, and

vesicularity (Loughlin et al. 2014). Yield strength is strongly dependent upon the lava's temperature.

Mapping to delineate the nature of the expansion of lava flows and flow fields is directly associated with factors such as the improved understanding and identification of vents, including their locations, as well as lava-flow volumes. Moreover, forecasting possible hazards and risks associated with lava flows can only be performed through obtaining information concerning the geographical position and direction of these flows (Trusdell 1995). Estimation of the volume of lava can be performed by utilising a combination of the information derived from the areas of lava flow with that derived from the measurements of the thickness of the flow of lava, which can be observed in the field (Shaw and Swanson 1970; Self et al. 1997; Crown and Baloga 1999).

In the last two decades, researchers have studied Holocene volcanic events and mapped the distribution of associated lava at several locations, including some of the world's most volcanically active regions. For example, Rossi (1997) and Rossi and Gudmundsson (1996) mapped lava flows in Iceland, Head et al. (2012) mapped lava flows in Central Africa, and

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Guest et al. (1987) and Calvari et al. (Calvari and Pinkerton 1999) mapped lava flows in Mt. Etna, while Murcia et al. (2013) studied lava flows in the Harrat Rahat region of Saudi Arabia. Most of these studies employed field mapping techniques to gather data. While field measurements and analysis are accurate, they are also time-consuming and laborious, particularly when lava flows are extensive (Cashman et al. 1998; Crown and Ramsey 2016). One viable alternative mapping method, which is potentially as reliable and accurate, and certainly more efficient, is remote sensing.

Urban landscape planning has many benefits in terms of the environment. Urban landscape planning means making decisions about the future situation of urban land. In this case, it is necessary to predict how the land has changed over time and the effects of natural factors and human activities on the land. In this way, successful and sustainable landscape planning studies can be achieved. Land cover and green area change related to urban area and its immediate surroundings were determined: Land use change is due to human activities and natural factors. Land cover is one of the most important data used to demonstrate the effects of land use changes, especially human activities. Production of land use maps can be done by using different methods on satellite images. Some studies have produced land cover maps of the controlled classification technique over Landsat satellite imagery. By using land cover maps, the changes in urban development and green areas over time have been evaluated. At the same time, the relationship between changes in the land cover over time and changes in the urban population has been (Cetin 2015; Cetin 2016a, 2016b; Cetin et al. 2018; Kaya et al. 2018).

Remote sensing technology for geological surveys is a rapidly developing field and has been cited as a highly reliable alternative to traditional approaches such as field mapping (Head et al. 2012). It provides spatial, spectral, and temporal coverage for both the monitoring and geological mapping of broad regions of volcanic terrain. In the supervised classification of volcanic morphology, image processing is guided by the user to specify morphological classes of interest. The user defines areas of the mapped region that are known to be representative of a particular volcanic cover type for each class of interest. The software then determines the spectral signature of the pixels within each specified area and uses this information to define the mean and variance of the classes in relation to the entire imaged region. Each pixel in the image is then assigned, based on its spectral signature, to the class it most closely matches. In unsupervised classification, image processing software classifies an image based on natural groupings of the spectral properties of the pixels, without the user specifying how any portion of the image should be classified. Conceptually, unsupervised classification is similar to cluster analysis, where observations (pixels) of the same values or value ranges are assigned to the same classes. For example, Shen et al. (2008) used a remotely located device to detect and

measure electromagnetic radiation (EM). The most important parameters of such radiation are the wavelengths and spectral reflectance of resulting EMs. More often than not, satellite images are used in both supervised and unsupervised classification. In these cases, the wavelength spectrums for an object are represented as bands.

Remote sensing has been applied in the mapping of lava flows some time ago (James et al. 2009; Harris et al. 2011; Dietterich et al. 2012; Kubanek et al. 2015; Slatcher et al. 2015). Recent studies reveal that several types of satellite images can be used for mapping, including radar, thermal infrared, and optical images (Bonne et al. 2008; Millington et al. 2012; Nicolas et al. 2008; Tarquini and Favalli 2011). Bymes et al. (Bymes et al. 2004) used remote sensing technology to characterise the surface morphology of Mauna Ulu in Hawaii. They employed ASTER and MASTER (multispectral) techniques to map and interpret lava emplacement. Their survey concluded that pahoehoe lava flows have a higher reflectance than 'a' lava flows. One reason for this is pahoehoe crystalline structure providing a greater reflective surface. Pahoehoe is more crystalline than A; due to its slow moving nature, it is able to cool slower due to heat being retained at depth within the flow, thereby allowing the formation of larger crystals.

The present paper aims to present the results of the remote sensing-based classification of flows of lava at Harrat Lunayyir in western Saudi Arabia (Fig. 1). This classification was performed in an unsupervised manner through the utilisation of remote sensing data based on ISODATA algorithms. This technique is effective in that it outlines the number of different classifications in which the data obtained can be categorised. The purpose was to form data clusters within each of the areas of land coverage. The study of the behaviours of spectrums being emitted from various volcanic regions, which is known as 'TOA Reflectance', also forms an element of the present research. The objective here is to consistently outline the various categories and characteristics of both recent and old flows of lava through an evaluation of the properties of spectral reflectance. The validation of these classifications has been performed through sampling, which involved the results of the ISODATA classification.

Study area

Harrat Lunayyir is located in the western part of the Arabian Plate, which is situated in close proximity to the African Plate, being separated from it by the Red Sea rift zone. A Proterozoic shield constitutes the core of the western part of the Arabian Plate. The major tectonic changes that formed the macro-tectonic structures in the area occurred during the African Rift formation. Thus, the Red Sea and the Gulf of Aden formed at around 25 Ma ago (Stern and Johnson 2010).

Fig. 1 Location map for the Harrat Lunayyir volcanic field, western Saudi Arabia

Throughout the process of the spreading of the Red Sea, which has been active over the past 30 million years, some parts of the Arabian Shield became extended along the Red Sea rift boundary (Bailey 2009). This process was accompanied by continental collision between the Arabian and Euro-Asian Plates, which has been taking place since the Miocene (Hansen et al. 2013). The result of these processes was active deformation and magma generation that created the conditions for the formation of volcanic fields within the areas adjacent to rifting zone (Al Damegh et al. 2005; Rodgers et al. 1999).

The main geological structures that constitute the Arabian Shield in the area of interest include pre-Cambrian crystalline rocks, Phanerozoic sedimentary rocks, and Cenozoic flood basalts. Harrat Lunayyir is one of those fields that represent an instance of Cenozoic flood basalts. The average crustal thickness of the shield is around 40 km (Al Damegh et al. 2005) with a tendency to decreased thickness towards the Red Sea. Thus, in the areas around Harrat Lunayyir, crustal thickness is as little as 23 km. A similar degree of crust thickness can also be observed in the Nubian Shield, which is situated towards the western region of the Red Sea. Within Egypt, the thickness of the crust is 25–26 km, and this continues up to a distance of 50 km towards the coastal region of the Red Sea.

During the Cenozoic period, there was considerable volcanic activity in the western section of the Arabian Plate. This activity took place during two principal episodes. The first was during a period from around 20 to 30 Ma ago, while the later one began 12 Ma ago and continues to this day (Camp and Roobol 1992). The common name of *harrats* is mostly attributed to the fields of lava (Pint 2006). These are also known as the Harrat Al-Shaqa. These areas are amongst the smallest alkali-basaltic fields of lava generated during the Holocene and are generally located towards the western margin of Saudi Arabia. More specifically, the location of the field is at the coordinates of 25° 10'–25° 17' N latitude and 37° 45'–37° 75' E longitude. The field of lava is located approximately 60 km from the eastern section of the Red Sea coastal regions and 150 km to the east from the central section of the red sea (Al Amri and Fnais Al-Amri and Fnais 2009; Baer and Hamiel 2010; Al-Zahrani et al. 2013; Duncan and Al-Amri 2013) (Fig. 1).

The region of Harrat Lunayyir is characterised by the alkali-olivine-basalt lava flows that formed during the Cenozoic geological period (Duncan and Al-Amri 2013). This region, and its formation period, involved approximately 50 monogenetic craters of volcanic cones of various measures (Baer and Hamiel 2010). There are two specific segments that

could characterise the basaltic flows of lava. The first is the Tertiary unit, which is considerably older (Jarad basalt), and the second is the Quaternary unit, which is comparatively younger and is also known as Maqrah basalt, according to Al Amri et al. (Al-Amri et al. 2012) (Fig. 2).

The eastern, northern, and southern sections of Harrat Lunayyir are composed of Precambrian rocks. The central section of the region is composed of a multiplicity of rocks, of which only isolated sections have rocks from the Precambrian period as their constituents. The seismic as well as the volcanic events of Harrat Lunayyir began approximately 0.5 Ma ago (Duncan and Al-Amri 2013). An informed estimation suggests that the flows of lava that occurred most recently could have taken place approximately 5000 years ago (Al-Amri et al. 2012). In this respect, it could also be presumed that some recent eruptions could have taken place in the region, since a specific cone of craters was formed here approximately 1000 years earlier, as pointed out by Baer and Hamiel (2010).

Methodology

Nicolas et al. (2008) observe that the use of remote sensing is invaluable in volcanic monitoring. Sensors are devices that record the amount of electromagnetic radiation energy that strikes them at a specific wavelength range. Remote sensing can be accomplished from air-borne and space-borne platforms. Crown and Ramsey (2016) suggest that space-borne platforms are the most widely used in the unsupervised classification of lava flow. The scattering or reflection of an energy signal by lava flows is dependent on a number of factors, including conductivity, permittivity, and surface roughness (OSU 2015). Surface reflectivity is the ratio of reflected power to direct power and is critical in the monitoring and classification of lava flows (D'Alessandro 2006).

Satellites are the principal remote-sensing instruments used by geoscientists to monitor geographic data on the Earth's surface. Satellites map events use optical instruments (OSU 2015). Despite the general reliability of this technology, cloud cover can hinder satellite mapping. As a result, it is essential that users utilise satellite imagery from various sources gathered over an extended period (U.S. Geological Survey 2008). Landsat imagery is widely used in unsupervised classification, owing to the large number of Landsat satellites that have increased coverage of the Earth's surface.

Digital image classification techniques

Bernard (2013) reports that digital image classification techniques are the main tools used in grouping pixels to represent land-cover features. The main purpose of remote sensing is the interpretation of observed data and classification of features. Pixels are the smallest units of an image that are used in classification (Nicolas et al. 2008). As such, images are classified according to the reflectance statistics of their pixels. There are two major image classification techniques, namely unsupervised and supervised classifications (Head et al. 2012). In practice, supervised image classification involves the input from the user, who classifies objects in correspondence with the features known or observable in the satellite imagery, while unsupervised image classification is automated and performed by software. A brief description of unsupervised classification is provided below.

According to Bonne et al. (2008), the unsupervised classification of images entails the clustering of pixels according to their reflectance properties (Fig. 3). Users then determine the number of clusters to be generated and the bands to be used (Millington et al. 2012). This information represents an input into image classification software, which uses clustering algorithms to identify clusters with morphological features. This approach is most effective in instances where no sample sites

Fig. 2 Volcanic geology of the Harrat Lunayyir volcanic field. **a** Volcanic ash partly covering a hill. **b** Basaltic lava flow of Quaternary age (Maqrah basalt)

Fig. 3 Digital image classification techniques. Input patterns are shown in (a), and the desired clusters are shown in (b). Clusters assigned the same label (Jain et al. 1999)

exist (Nelson 2016). In summary, image analysis algorithms identify related pixels and group them into different classes without any human guidance whatsoever. Joyce et al. (2008) report that unsupervised clustering is a fundamental tool in image processing, particularly for remote sensing and geoscience applications.

General overview

It is advisable to crop the chosen images to include the area around the lava flow of interest in order to permit accurate and faster classification, since fewer pixels will need to be evaluated and grouped into classes under these circumstances (Head et al. 2012). This procedure can be used to determine the location and number of unimodal spectral classes. One common approach in unsupervised classification is the migrating means clustering classifier (MMC) (Crown and Ramsey 2016). Digital image processing software, such as the spatial analysis tool in ARC GIS Imagine, is used for the unsupervised classification of lava flows. The migrating means clustering algorithm is widely used in describing flooding and lahar flow, amongst a host of other phenomena (Joyce et al. 2008). In this paper, we use the iterative self-organising data analysis technique (ISODATA).

ISODATA

One of the most significant and extensively used algorithms that perform unsupervised clustering is ISODATA. This procedure is a general process of application that is necessary to perform the classification of satellite-based imagery. A multiplicity of wavebands is used to derive spectral reflectance for the purpose of identifying the attributes of multidimensional clusters and the spaces associated with them. The classification results must then be analysed from the perspective of the

researchers. The information that these researchers possess can be understood to be integral regarding the geological structure or process under consideration; this is also significant regarding the understanding of the nature of various clusters of lava attributes. The methods of classification, which must be completely unsupervised, need to be able to identify the actual numerical extents as well as the nature of the composition of classes that cannot be related to the previously formulated conceptions regarding the structure of the geological landscape under consideration.

Techniques involving ISODATA-based analysis make it possible to reach the required level of details with identification of the number of additional classes (de Alwis et al. 2007). The algorithm of the data classification can be described in the following steps: (1) data points are assigned in accordance with the closest cluster centres; (2) the positions of cluster centres are amended so that they become centroids for the set of data points assigned to them; and (3) splitting of clusters with an abnormally large set of points and merging smaller clusters (Fig. 4).

Landsat 8 OLI data (LC81710432017063LGN00)

One image of Landsat 8 OLI data (LC81710432017063LGN00), Path 171 Row 043, which did not have much cloud cover, was made available by the website of the United States Geological Survey (USGS) for this study. The data collection took place on 4 March 2017, and the resulting acquisition of the images could be identified as the data products of the level 1 digital number. The acquisition process of the data was undertaken in the format of the zipped georeferenced tagged image file format (GeoTIFF) files, representing systematically terrain-corrected data (L1T). A number of processes needed to be utilised for the analysis, interpretation, and elucidation of the obtained data. The

Fig. 4 ISODATA techniques. Merging the clusters (A) and (B, C) into one cluster since distance between their centroids is small and then splitting the cluster (D, E, F, G), which has a large variance, into two clusters (D, E) and (F, G) (Jain et al. 1999)

advanced digital processing of images can be sorted into two parts. The first involves the sub-setting of the images, which is performed to acquire the zone of study interest. Thereafter, imagery enhancement and upgrading strategies can be used in the process of image development and interpretation with the aim of separating out valuable data.

The L8 Observatory satellite was constructed using an intricate design process with the purpose of having a 705-km, sun-synchronous orbit and a cycle of repetition of 16 days in length. The L8 completely orbits the Earth every 98.9 min. L8 carries a two-sensor payload: the OLI was built by the BATC, while the TIRS was built by the NASA GSFC. Every scene can be automatically imaged by both the OLI and TRS in a simultaneous manner; however, both are also capable of being utilised independently should any problem occur in one of the sensors. During the operations that can be undertaken under normal conditions, the sensors can scan and observe the Earth at a nadir-positional location that is optimised through the orbital circulation path of the sun-synchronous Worldwide Reference System-2 (WRS-2). Both of these sensors can be utilised to achieve greater improvements and advancements in technical measures relative to the previous Landsat equipment. The L8 Observatory is a direct reference to the spacecraft, along with the integration of both of the sensors (Zanter 2016).

Spectral reflectance

General overview

The interaction between the electromagnetic radiation and the objects situated on the Earth's surface can lead to significant variations in the absorption process, reflection of light and energy, and the transmission of energy. This entire process is also indicative of the reciprocity amongst the generated energy and the objects (D'Alessandro 2006). The amount of the

energy that can be transmitted, absorbed, or reflected in such a process can also fluctuate considerably according to the differences in the physical conditions and typology of the objects (Bernard 2013). There are therefore certain complications involved in distinguishing two separate phenomena that may be observed on the surface of the Earth involving the available spectral zones. The variations in these spectral zones can provide differential measures of undertaking such identifications of specific objects. These aspects are closely reflective of the various interactions that can highlight the differential physical characteristics associated with the light and the physical composition-based elements of the object being viewed. The following equation can thereby be extrapolated from the principle of the conservation of energy:

$$E_r + E_\tau + E_\alpha = 1 \quad (1)$$

where E_r is the light reflected back from the surface of the object, E_τ is the light transmitted through the object, and E_α is the light absorbed by the object; each is a function of wavelength. It follows that the reflected waves are primarily those that neither get absorbed nor transmitted. From the laws of reflection, it also follows that light is reflected from a surface at an angle equal to the incident angle (Farrier 2006).

The present study emphasises the properties of reflectance. The aspects related to the study topic depend on the primary evaluation of the roughness at the surface of the object; this can be closely compared with the wavelength of the emitted electromagnetic radiation, which can be observed through focusing on the object. The two primary measures of reflectance relevant in this study are diffuse and specular reflectance (Joyce et al. 2008). Diffuse reflectance is observable at rough surfaces, while specular reflectance is that emitted from surfaces that are comparatively less rough, or that are mostly smooth or flat (Fig. 5).

Radiometric corrections were performed to determine the measure of reflectance that could be observed at the surface of the object. This process is important for converting the data derived from the digital images in a successful manner. The images are mostly gathered through satellite imagery and are utilised in the calibration of the quantities and physical dimensions associated with the surface conditions on Earth. Moreover, atmospheric correction is made to recover the surface reflectance (which portrays the surface properties) from

Fig. 5 Reflection models. **a** Specular reflectance. **b** Diffuse reflectance (Farrier 2006)

remotely detected imagery by removing atmospheric effects. The strategies by which radiometric and atmospheric corrective actions are performed are clarified below.

Conversion to TOA reflectance

Based on information available from the USGS website, the data from the OLI band can be converted to top-of-atmosphere (TOA), or top of the atmosphere reflectance. The emphasis here is on planetary reflectance using the reflectance rescaling coefficients provided in the product metadata file (MTL file). The resulting equation can be applied to effectively convert the DN values to TOA reflectance values to facilitate the analysis of the data regarding OLI (Zanter 2016).

$$\rho\lambda' = M_{\rho} \times Q_{cal} + A_{\rho} \quad (2)$$

where $\rho\lambda'$ = TOA planetary reflectance without correction for solar angle, M_{ρ} = band-specific multiplicative rescaling factor from metadata, A_{ρ} = band-specific additive rescaling factor from the metadata, and Q_{cal} = quantised and calibrated standard product digital number (DN).

Note that $\rho\lambda'$ is not the true TOA reflectance, because it does not contain a correction for the solar elevation angle. The conversion to true TOA reflectance is through the following equation:

$$\rho\lambda = \frac{\rho\lambda'}{\cos(\theta)} = \frac{\rho\lambda'}{\sin(\theta)} \quad (3)$$

where $\rho\lambda$ = TOA planetary reflectance, and θ = solar elevation angle (from the metadata or calculated).

Landsat 8 OLI spectral endmember selection

In this method, spectra are selected from the images for specific areas. These regions are generally familiar to the image interpretation personnel due to their experience with previous research and field studies. The collected endmember points regarding the age groups of the lava are four points.

This spectral endmember point can be a specific spectral signature related to any surface cover of absolute measure that is visible in the satellite-derived images. This could represent individual categories, which are utilised to either classify or determine any aspect within the individual images (Fig. 6). Such uncontaminated, pure spectral endmembers are usually defined under either idealised in situ or laboratory conditions. Under such conditions, reflectance spectra may be obtained through the application of a portable spectrometer that focuses only on a single surface. At the point when in situ estimations become unrealistic, spectral endmembers can likewise be obtained from “pure” features in the imagery. The choice of such endmembers from the image itself can be carried out on the

basis of prior knowledge regarding the occurrence of materials imaged in the scene. Manual selection from image data assumes spectral homogeneity.

Sample collection and processing

This section describes the rock samples collected at the site that were used in the current study. Initially, three volcanic rock samples were submitted to Oregon State University for analysis using the $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological determination method. The samples were collected to represent the basaltic rocks in the study area. In terms of their composition, these samples are consistent with the amphibole-bearing rocks typical for the area; e.g., the trace components found in the basaltic rocks in the area are associated with the type of continental magmatism processes typical to the Arabian Shield.

The selection of the samples was based on the geological maps of the area. These show fine-grained basanites, alkali olivine basalt, and trachy basalts (Duncan and Al-Amri 2013). The groundmass of the sample rocks comprises largely glass and augite with minor olivine (Duncan and Al-Amri 2013). According to Al-Amri et al. (2012), in a study using an extended set of samples, the plateau ages of the samples showed significant variances.

Following the methodology developed by Duncan and Keller (2004), the sample rocks were processed and sieved to obtain the fractions of 300–600 nm size. The groundmass was separated from the phenocrysts and cleaned by acid leaching (Duncan and Al-Amri 2013). Thereafter, the sample units were cleaned and dried. The samples underwent irradiation in a dummy fuel rod in the reactor’s central ring at 1 MW (Duncan and Keller 2004).

Results and discussion

TOA reflectance

Weather and climate conditions influence surface weathering of lava flows and affect their reflectivity. Lavas on Harrat Lunayyir have undergone different forms of surface alteration, but primarily oxidation-based chemical weathering processes. The lava flows have erupted at different times—they are of different age—and this was analysed through spectral reflectance measurements using Landsat 8 in the range of 435–2300 nm (Fig. 7).

The elements constituting the spectral information vary considerably with the morphological attributes and the age of the lava flows. In Fig. 8, the common features of the reflectance spectra are illustrated based on the shape of the spectral curves. A noticeable sharp increase in reflectance at 435–500 nm for all the studied lava flow with reflectance of 12% was observed, while the maximum shifts were identified in shorter wavelengths for lava flows 2, 3, and 4. The steepest part of the reflectance curves in the visible blue band area of

Fig. 6 Spectral endmember points were collected from Landsat 8 OLI False colour (bands combination 7, 4, 1)

Fig. 7 Conversion to TOA reflectance. **a** Landsat 8 OLI image before conversion to TOA reflectance. **b** Image after conversion to surface reflectance

Fig. 8 Reflectance spectra. **a** Reflectance spectra of old and recent lava flows. **b** Note that lava flow 1, which has been subject to significant surface oxidation, attains high reflectance values especially in the near-infrared region

the visible range spectrum occurs at 452 nm. The reflectance curves are very flat for lava flows 1 and 2, apart from a noticeable decrease in reflectance from 1900 nm onwards. However, there is a gradual and sustained reflectance decrease in lava flows 3 and 4 beginning from the end of the visible range. We observe that for lava flow 1, there is a higher reflectance at 800–1600 nm at a rate of around 12%. A similar sustained rate can be seen for lava flow 2, albeit at a slightly reduced reflectance of around 9 to 10%.

Lava surfaces with a complete absence of any lichen (a simple slow-growing plant that typically forms a low crustlike, leaflike, or branching growth on rocks, walls, and trees) show low and flattened reflectance spectra, expanding in the visible segment and diminishing in the infrared segment

of the spectrum. This flattening is generally more evident in older lava flows, which have been subject to considerable surface oxidation (of iron). In particular, the slope of the reflectance curve from the blue to the red range of the spectrum increases as oxidation increases, a spectral feature useful for defining an oxidation index that can be used to quantify the relative degree of the oxidation of lava surfaces.

ISODATA classification

The analysis of imagery regarding the trends of reflectance and colour is average measures and can be caused by a number of factors, including the weathering of glass, oxidation of iron elements, and the gradual development of plant life and

Fig. 9 Classification results of the ISO cluster method. **a** (class 1 represents old eruption) then **b** (class 2); **c** (class 3)...etc. **j** (class 10) in the legend shows the most recent lava flow

vegetation upon the uppermost crust of the lava flow. We use ten classes for the age classification of the lava flows. We also used geological maps to identify the basement rock types on which the lava flows were erupted.

The TOA reflectance (Figs. 7 and 8) was utilised as a key to both classify the lava and to choose the number of classes. We examined different numbers of classes and found that the best number that gave us the cluster of the youngest lava was number 10. As can be seen in Fig. 10, the classification results were found to be the same as those of the TOA reflectance. Accordingly, we give the oldest lava flow as ‘class 1’ sequentially with the rest of the classes (Fig. 9).

Accuracy assessment

To validate the classification, we sampled from the sites of the ISODATA classification (classes 10-9-8) (Fig. 9) for analysis at the Oregon State University for ^{40}Ar - ^{39}Ar incremental heating age determinations (Fig. 10; Table 1). The accuracy of the unsupervised classification results is benchmarked to the output of the supervised classification, which is done with

Fig. 10 Sample locations of lavas from Harrat Lunayyir, NW Saudi Arabia

Table 1 Location of samples for lavas from Harrat Lunayyir, NW Saudi Arabia

Sample number	Type of material	Longitude (°E)	Latitude (°N)
L1	Whole rock	37.846	25.150
L2	Whole rock	37.853	25.195
L3	Whole rock	37.882	25.256

reference to the knowledge of local geographic/geological features. Firstly, we gather training data from the field. This approach requires a priori knowledge of the geographical/geological features under investigation. Here, the analysts must have extensive knowledge of the lava flows, their formation, and subsequent weathering, as such information is critical in obtaining appropriate training data.

The placement of infrastructure such as pipelines, roads, and railways is highly dependent on the rock outcrops in an area. For this reason, the supervised classification of lava flows is vital. Some of the techniques employed include, but are not limited to, band ratios, synthetic aperture radar (SAR), linear spectrum unmixing, and vegetation masking. Geologists can detect a variety of variables, such as soils and lava flows (Egorov et al. 2015).

^{40}Ar - ^{39}Ar incremental heating method

The precise dating of lava flows is crucial for understanding the characterisation of volcanic fields, which is itself essential

for the reliable reconstruction of past events that shaped the topography of the fields (Walsh 2006). Different methods are used to date lava flows in order to determine the relative ages of past volcanic events. In this study, we have relied on the ^{40}Ar - ^{39}Ar incremental heating method (McDougall and Harrison 1999) to assign ages to lava flows.

The Quaternary age of Harrat Lunayyir was indicated by a K-Ar date reported by Camp and Roobol (1992). Al-Amri et al. (2012) attempted to investigate the chronostratigraphy of Harrat Lunayyir using the ^{40}Ar - ^{39}Ar method on six basaltic flows. Their results confirm the overall Quaternary (mostly late Pleistocene) age of the lava field, yet the age spectra are virtually indistinguishable within the lack of atmospheric argon ratios. Furthermore, the authors resorted to forcing the inverse isochron through the 295.5 value, which makes the results model ages rather than reliable age estimates.

Duncan and Al-Amri (2013) reported ^{40}Ar - ^{39}Ar ages for 18 new samples from the six volcano-stratigraphic units mapped in the Harrat Lunayyir volcanic field (Al-Amri et al. 2012). One of their samples yielded a plateau age of 1.21 ± 0.13 Ma, which is considerably older than all other age estimates. The isochron for this particular sample has an age of 970 ± 29 ka, with an initial $^{40}\text{Ar}/^{36}\text{Ar}$ composition of 312 ± 4 , thus indicating the presence of excess ^{40}Ar , which renders this age invalid for the purpose of delineating the eruptive sequence. All other ages were considered acceptable and indicate an overall continuous volcanic activity from about 600 ka to the present, with putative peaks of activity at ~ 400 ka and ~ 200 ka. The relatively uniform spread of ages rules out any significant hiatus in volcanic activity.

Fig. 11 Location of young lava place sample (L1)

In this study, we obtained samples from the same sites of the ISODATA classification results (class 10-9-8) (Fig. 9) and analysed the three youngest flows at the Oregon State University in the Argon Geochronology Laboratory (Fig. 11). The results are as follows:

- L1: plateau age 15.1 ± 6.1 ka (2 s.d. error) (Fig. 12a), which represents quaternary upper basalt (stratigraphic

unit Qm5), historic to late prehistoric lava flows and scoria cones. The subunit comprises the products of four eruption sites of black scoria cones with lava flows (Al-Amri et al. 2012) surrounded by black air-fall ash covering adjacent Precambrian basement hills protruding through the lava field. One of these sites is believed to have erupted as recently as the tenth century (Al-Amri et al. 2012).

Fig. 12 Representative age spectra (plateaus) derived from $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating experiments on Harrat Lunayyir basaltic lavas. **a** represents location 1 (L1, plateau age 15.1 ± 6.1 ka); **b** represents the result of location 2 (L2, plateau age 15.0 ± 8.4 ka), and **c** represents the result of location 3 (L3, plateau age 14.6 ± 23.1 ka)

Table 2 ^{40}Ar - ^{39}Ar incremental heating method L1, L2, and L3 lava flows

Sample	Plateau age (ka)	2σ error (ka)	MSWD	Initial $^{40}\text{Ar}/^{36}\text{Ar}$
L1	15.2	6.1	0.67	295.50
L2	15.0	8.4	0.47	291.75
L3	14.9	23.0	0.38	287.03

- L2: plateau age 15.0 ± 8.4 ka (2 s.d. error) (Fig. 12b). This represents prehistoric lava flows (stratigraphic unit Qm4), with prehistoric lava flows and scoria cones, lacks erosion, and having dust ponds 3 m in diameter. Dust ponds can be defined as fine-grained deposits in topographic lows transported and sorted by intense localised electric fields acting on charged dust or by impact-induced shaking. A very black colour was observed on the aerial photographs and satellite image.
- L3: plateau age 14.6 ± 23.1 ka (2 s.d. error) (Fig. 12c); non-eroded lava flows (correspond to the stratigraphic unit Qm3): non-eroded lava flows, slight gullying on scoria cones, dust ponds up to 100 m in diameter; Qm2: eroded lava flows and scoria cones, surface structures on flows such as flow ridges intact, but erosional rivulets are present. Scoria cones have distinct gullies and dust ponds are up to 400 m in diameter.

The obtained ages are characterised by exceptionally well-developed plateaux and comprising 55–72% of the ^{39}Ar released.

The age discrepancy between the inverse isochron of L1 and the other ages is probably related to the presence of relic ^{40}Ar , as manifested by the descending age pattern of the first four steps, which contain about 40% of the released ^{39}Ar . Such an inherited component would have the undesirable effect of shifting the isochron line towards an older age (Kuiper 2002), a fact exacerbated by the clustering of data points very close to the $^{36}\text{Ar}/^{40}\text{Ar}$ axis. This same feature was observed by Duncan and Al-Amri (2013), which they attributed to the presence of small amount of excess ^{40}Ar , probably in olivine xenocrysts not completely removed.

In the current study, we identified spectral top-of-atmosphere (TOA) reflectance values to distinguish layers of old and recent lava flows based on differences. As a result, three distinct basaltic units were identified to have the parameters shown in the table below (Table 2). For this dataset, the temperature ranges fall in the same area as for the Ar testing and meet the plateau age criteria. On the other hand, the distribution of the TOR data is not homogenous in this sample set.

The value of the mean square of weighted deviates (MSWD) does not exceed the analytical value for the sample, which means that the scatter points of the sample set are consistent with the analytical model (isochronic relationship is established across the dataset).

Geographic distribution of the lava flows

The identification of basaltic units that are related to different typologies was facilitated by the conversion of the reflectance

Fig. 13 **a** Remote sensing output with lava flow areas identified. **b** Resulting map by Al-Amri et al. (2012)

values into radiance values. The low reflectance value is a characteristic of basaltic flows in the visible spectrum. The Landsat band ratios were employed to distinguish volcanologic units (ration band 5 to band 4, band 7 to band 6).

In contrast to the findings of Al-Amri et al. (2012), who found two major basaltic units—Jarad, the older Tertiary unit, and Upper Maqrah, younger Quaternary unit—with the application of remote sensing data processing, three basaltic typologies were discerned and mapped by red, pink, and turquoise colours (Fig. 13). We therefore identify three lava flows in accordance with their relative position at the timescale (the identification of exact age is not possible using this methodology, which is a limitation of the study):

- L1 – the most recent lava flows; as seen in Fig. 13. They occupy the central part of the Harrat Lunayyir basaltic field being enclaved into the area of volcanic cones. The total area occupied by these basaltic units is 25 km².

- L2 – the lava flows of intermede age that cover the peripheral zones of the epicentre and stretch over a total area of 82 km².
- L3 – the oldest lava flows, which occupy an area of 157 km² and have a NW-SE direction in alignment with localisation of the dyke (direction of its intrusion); also notably represented around the volcanic cones area.

From the map in Fig. 13a, it is evident that all three lava flows are clustered in the enclave around the volcanic cones; this relatively small cluster of 18 km² is constituted of 72% L3, 20% L2, and 8% L1 areas. This clustering towards the epicentre area may suggest that three separate volcanic events happened independently of each other. Based on this, we conclude that the area has been the site of magmatic activity over a longer period than suggested in previous research (Al-Amri et al. 2012). This is in line with recent research findings suggesting

Fig. 14 Geologic map of Harrat Lunayyir

that the 2009 dyke became arrested at a shallow depth (Al Shehri and Gudmundsson 2018).

According to the mapping results, three identified basaltic flows erupted in the same area as most of the epicentres of the earthquake swarm are associated with the dyke emplacement in the spring-summer of 2009 (Al Shehri and Gudmundsson 2018). More specifically, most of the earthquakes were located around the perimeter of the L1 (the most recent basaltic flows). This can be associated with the peculiarities of Harrat Lunayyir's geomorphology. The geomorphology of the harrat is rather restrictive, with higher (up to 800-m elevation) terrain forms located along the perimeter of the area.

In order to make more robust inferences about the geological connections, it is necessary to juxtapose the mapped basaltic units with a geologic map of the area (Fig. 14). This enables us to identify the geochronological types to which the L1, L2, and L3 lava samples belong. In contrast to Al-Amri et al. (2012) findings, we find the three samples being related to three different Tertiary-Quaternary basaltic units, where samples have larger variance in terms of their age. This is attributed to differences in methodology and the described above characteristics of the area's geomorphology. With fields being adjacent and enclaved in the limited area, the remote sensing data provides a more accurate spatiality of the magmatic intrusion processes.

Besides high clustering of both 2009 earthquake swarms and the young basaltic lava flows, the mapping also makes the northwest-southeast strike of the dyke clearly (Fig. 13a, b) observable. The determinant behind that could be the slope effect—which is localised in consistency with fault direction. This may be the basis to conclude the presence of the persistent upward magmatic movement before the swarms as well as the correlation between the volcanic events and dyke intrusion.

Conclusions

The main aim of this paper has been to improve our understanding of the spatial distribution of volcanic processes in the Harrat Lunayyir area. To achieve this, the current study employed the unsupervised classification of remote sensing inputs from Landsat 8, identifying different generations of lava flows in Harrat Lunayyir, western Saudi Arabia. The accurate dating of lava flows is important if we are to understand the eruptive nature of volcanoes and volcanic fields. There are many technical details to be worked out in order to be able to date flows accurately using satellite techniques. We have used numerical classification methods to identify the number of classes into which the data is separated for clustering within each land cover.

The utilisation of ISODATA for the segmentation of the remote sensing data has also been made. The algorithm for

performing unsupervised classification was obtained from the GIS package raster (ArcInfo). The characteristics of spectral reflectance regarding volcanic materials, which could be widely observed at the zone of analysis at Harrat Lunayyir, have been investigated, and the resultant classifications of the examined region have been spectrally classified. The data was derived through an analysis involving the counting of the pixels of randomly selected regions. This suggests that the most elevated measures of reflectance value could be exhibited by the older flows of lava. The reason for this could be related to the weathering of the same within 800–1600 nm with a rate of 12%. In contrast, the lava flow, which is considerably younger in geological age, has been analysed to contain a reflectance measure of lesser intensity and a rate of 9 to 10%.

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