**Emplacement and inflation of the Al-Halaq al Kabir lava flow field, central part of the Al Haruj Volcanic Province, Central Libya**

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**Abstract**

Numerous of lava rise plateaus and tumuli developed in the medial and distal portions of the Al-Halaq al Kabir lava flow field during the last (Holocene) eruption in the central part of the Al Haruj Volcanic Province (AHVP). These inflation structures provide important data on the lava-emplacement mechanism in this part of the Al Haruj region where the widespread occurrence of tumuli and lava rise plateaus are good indicators of the mode of emplacement. We report the results of detailed measurements of the maximum and minimum diameters in plan-view of 551 lava-rise plateaus and 289 tumuli from the distal part of the Al-Halaq al Kabir lava field using ArcGIS and field observations. Tumuli and lava rise plateaus may be divided into subpopulations according to abrupt changes in the scaling exponents on log-log plots of their frequency versus diameter. Using the estimated stiffness (Young’s modulus) of the basaltic rocks in the study area of 10-34 GPa, numerical and analytical results show that theoretical maximum tensile stresses in the inflated upper (solidified) crustal layers of the developing tumuli and lava rises at tens of mega-pascals (MPa). This theoretical stress is orders of magnitude higher than typical in-situ tensile strengths of rocks (0.5-9 MPa) and thus high enough to rupture the crustal layers of the lava rises and tumuli. The high tensile stresses are generated during crustal doming driven by a magmatic overpressure of only about 1 MPa. Our results partly explain the abundance of tension fractures at the surface of the Al-Halaq al Kabir lava flow field. Tumuli observed in the area are remarkably similar in morphology and aspect (height/width) ratios to the flow-lobe tumuli in Holocene lava flow fields in Iceland, suggesting an analogous mechanics of formation. There appears to be a coincidence between the age of an initial volcanism in the AHVP(7.9-5.3 Ma) and a local fauna and flora disappearance in the As-Sahabi area, NE Sirt Basin, during Messinian-Zanclean time (7-5 to 5 Ma). We speculate that the volcanism may have had a local negative environmental impact and contributed to the reported decline in the fauna and flora in the area.

Keywords: Libya; basalt; tumuli; pahoehoe; inflation structures; tensile stresses

**1 Introduction**

Volcanic activity has commonly produced extensive basaltic lava flows, ranging from pahoehoe to aa types (Walker 1991, Kilburn 2000; Nemeth et al., 2008). Lava flows the most common volcanic features on Earth and several of the planets and their satellites, particularly on Mars and the Moon (Glaze et al., 2005; De Wet et al., 2014; Scheidt et al., 2014, Foroutana et al., 2019 ). The inflation structures, such as lava rise plateaus and tumuli, are abundant in pahoehoe lava flow fields (Hon et al 1994; Self et al 1996; 1997, 1998; Walker, 1991;Keszthelyi&Pieri 1993; Chitwood, 1994; Rossi and Gudmundsson, 1996;Thordarson and Self 1998; Duraiswami et al., 2001) but much less so in aa lava flow fields (Calvari and Pinkerton, 1998; Ducan et al., 2004). Pahoehoe lava flows are commonly associated with low effusion rate and relatively long-lived eruptions (cf. Glaze et al., 2005).

The Al Haruj Volcanic Province (AHVP) represents the largest of the four extensive Gharyan – Nugay volcanic provinces in Libya which are considered to be typical intraplate provinces ( Fig. 1a; Busrewil and Suwesi, 1993; Peregi et al., 2003; Less et al., 2006). The AHVP developed during the end of Miocene up through Holocene time and has been linked to the rifting and tectonic evolution of the Sirt Basin (Busrewil and Suwesi, 1993; Cvetkovic et al., 2010; Busrewil, 2012). The AHVP shows many similarities with the other three main mafic volcanic fields in the Libyan Territory (Gharyan, As Sawda and Nuqay volcanic fields), particularly as regards volcano-tectonics, volcanic style, and production of materials. For example, the Libyan lava flows of the Neogene – Quaternary are primarily basaltic rocks with a minor amount of phonolites at Gharayn Volcanic Province (GVP). Lava rise plateaus, tumuli, lava-rise pits and inflation clefts are common inflation structures on the lava flow surfaces of the Al Haruj Volcanic Province (AHVP), central Libya, as will discussed later in detail and can be used in deciphering the emplacement mechanism of lava flow field (cf. Peregi et al., 2006; Nemeth et al., 2008).

Nixon et al.(2011) used ³He age dating method to conclude that the last eruption in the Al Haruj volcanic province is much younger (2.31±0.081 ka) than earlier studies indicated (≈0.1 Ma) (e.g., Peregi et al., 2003; Less et al., 2006). Also, recent geophysical data indicate the presence of partial melt at the crust-mantle boundary in central Libya (Lemnifi et al., 2017; 2019). These indications together with a series of high-magnitude earthquakes along the margin of the NW-SE-trending Hun Graben, western Sirt Basin (Fig. 1) suggest that the Al Haruj region may still be volcanically and seismically active (Lemnifi et al., 2017, Elshaafi and Gudmundsson, 2018). It follows that it is of fundamental importance to improve our understanding the lava emplacement processes that generated the Al-Halaq al Kabir lava flow field.

 Inflation structure is a positive topographic feature having various shapes with wide ranges of slope angles and characterised by three-part structural division of flow lobes: upper vesicular crust, crystalline core zone, and lower vesicular crust (e.g., Hon et al., 1994; Thordarson and Self, 1998; Thordarson, 2000). The three-fold structural division is considered a key for assessing the emplacement duration and the mechanism of pahoehe flow lobes (Hon et al., 1994, Thordarson and Self, 1998). The crustal doming or inflation occurs due to sustained supply of lava under an insulating crust (Rowland and Walker, 1987;Thordarson, 1995;Thordarson and Self, 1998, Duncan et al., 2004;Pedersen et al., 2017). The term inflation for pahoehoe flows was first introduced by Macdonald (1953) who gave a brief description of inflation features without mentioned any mechanism or a model. Subsequently, Theilig (1986) and Walker (1991) described the formation of inflation structures. However, the first comprehensive models on the generation of inflated pahoehe lava flows were provided by Hon et al. (1994) who measured and observed low effusion an emplacement of active lava flows on Kilauea volcano, Hawaii. Subsequently, many studies have used the results of Hon et al. (1994) and for improved and refined models on the development and emplacement of pahoehoe lava flow fields around the world (e.g., Thordarson 1995, Rossi and Gudmundsson,1996; Self et al 1996, 1997, Keszthelyi et al 1997, Thordarson and Self, 1998; Thordarson, 2000; Thordarson et al., 2003; Mattsson and Höskuldsson; 2005; Glaze et al., 2005; Thordarson, Sigmarsson, 2009;Pedersen et al., 2017).

Walker (1991) described various types of the tumuli and lava-rise plateaus of pahoehoe lava flow-fields in Hawaii and distinguished between three types of tumuli: (i) shallow-slope tumuli, (ii) moderate-slope tumuli, and (iii) flow-lobe tumuli. Subsequently, Rossi and Gudmundsson (1996) studied the morphology and formation of tumuli and lava rise plateaus on monogenetic shield volcanoes in Iceland and provided a model as to their formation. They noticed that the flow lobe tumuli are mainly located at the medial and distal parts of the flow filed (≈9.5km from vent) whilst the lava-coated and upper slope tumuli are essentially occurred at the proximal parts of flow fields. Also, they found that the internal structure within the flow-lobe tumuli is identical to that of P-type flow lobes.

Most tension fractures form at the surface of the pahoehoe flows during inflation processes rather than being cooling joint fractures (Anderson et al., 1999; Self et al., 2000). Inflation cracks represent brittle failure of the upper lava crust in response to expansion and associated tensile stresses whereas columnar joints represent cooling when the flow of fresh lava terminated and the molten core became stagnant and the flow solidified. The, commonly, irregular jointing of the lava crust is partly due to instability of the lava crust during the inflation processes (Thordarson and Self,1998; Thordarson, 2000). The difference in jointing styles indicates that joints form at several stages during the emplacement pahoehoe lava flow fields and can be explained in the term of inflation rather than rapid turbulent emplacement (Thordarson and Self, 1998; Thordarson, 2000). Thordarson and Self (1998) used the geometry of the joint systems (and patterns of vesicles, and crystallinity) in the Roza Member, Columbia River Basalt Group (CRBG), to provide a threefold structural division of P-type flow lobes and subsequently used these data to estimate the duration of the eruption that generated the lava-flow field. The overall morphology and general arrangement of internal structures of lava flow fields in the AHVP show characteristics analogous to those of the inflated pahoehoes flows described by Rossi and Gudmundsson (1996) on monogenetic lava shields in Iceland as well as those described by Thordarson (2000) on the distal sectors of the lava flows on the island of Surtsey offshore South Iceland.

The plan aspect (length/width) ratios of lava rise plateaus and tumuli within the Al-Halaq al Kabir flow field have been measured at the distal portion of the flow field where the surface morphology shows various inflation structures. We refer to the maximum diameter as length, and the minimum diameter as width, in plan-view, in order to distinguish between various types of tumuli and lava rise plateaus and the modes of emplacement. These parameters are a important because of they can be applied to an improved understanding remotely sensed data of lava flows on other planetary surfaces (e.g., Moon and Mars) (cf. Self et al., 1998; Glaze et al., 2005; De Wet et al., 2014; Scheidt et al., 2014, Foroutana et al., 2019). Mapping of the lava flow field was made by importing geological map and georeferenced images of the Al-Halaq al Kabir into ArcMap GIS software package. Shapefiles were used to trace margins. The Al-Halaq al Kabir flow field is representative the last volcanic eruption in this part of the Al Haruj region, without subsequent flows overlying the portion investigated. Therefore, it can precisely be tracing and mapping lava rise plateaus and tumuli on satellite imagery through ArcGIS 10.1.

The main aim of this paper is to present data on morphological, structural characteristic and quantitative analysis of lava rise plateaus and tumuli that are located within distal portion of the Al Haruj Volcanic Province (AHVP) using a combination of Landsat imagery and field observations. Analytical and numerical modelling of inflation mechanism is used for improving our ability to interpret inflation features which led us to obtain definitive information on the evolution of volcanism in the central part of the AHVP. The implication of these observations for the characteristic lava emplacement mechanism will be discussed in the future work for the other volcanic fields at the Libya’s volcanism in general and AHVP in particular.

**2 Geological background of the Al Haruj Volcanic Province (AHVP)**

The AHVP is one of the largest volcanic provinces in the North Africa, covering an area around 42,000 km2 in the central part of Libya (Fig. 1b) (Elshaafi and Gudmundsson, 2016;Elshaafi and Gudmundsson, 2017, 2018, Lemnifi et al., 2019). Field observations of a vertical succession of basaltic flows indicate a total thickness of the lava pile of several tens of meters. Geophysical studies, however, indicate that the thickness of the lava pile is on average as much as 145 m in the central part (Peregi et al., 2003), thinning to a few metres in the marginal parts (Fig. 2). The AHVP is thought to have been erupted during the period from the end of Miocene and well into the Holocene (Nixon et al., 2011).The AHVP is constituted dominantly of transitional to alkaline basaltic lava flows (Al-Hafdh and Elshaafi, 2015). The basaltic flows are intruded by (many presumably feeder) dykes in a number of lava shields, scoria cones, spatter cones and volcanic fissures. The AHVP is widely believed to have erupted through numerous volcanic fissures (fed by dykes) and spread laterally over considerable distances. In addition, there are major eruptive centres located mainly in northern and southern parts of the volcanic province (Elshaafi and Gudmundsson, 2016; 2017).

Although inflation structures are common in basaltic lava flows of the AHVP and extremely well-preserved, these structures have received hardly any attention except by Nemeth et al. (2008) who describe the tumuli in the southernmost of the AHVP (Al Haruj al Abyad subprovince). Nemeth et al. (2008) also mention a similarity between the type of tumuli in this part of the AHVP and the type of tumuli identified in Iceland by Rossi and Gudmundsson (1996). By contrast, considerable work has been done on the AHVP in the past few decades on geochronology, petrology, and geochemistry.

Lithostratigraphic classification of basaltic lava flows on the AHVP has been made by Busrewil and Suwessi (1993), Peregi et al. (2003), and Less et al. (2006). Basaltic flows have been grouped into six major volcanic phases based on their field relations and colour-tonal variation of the lava flow fields, as seen on the aerial photographs, with further support from age determination and paleomagnetic measurements. There are no significant petrochemical variations between these six volcanic phases (Peregi et al., 2003; Less et al., 2006). It should be emphasised that each volcanic phase has been subdivided into the different mappable volcanic unit but with same age (Peregi et al., 2003, Less et al., 2006). Hummocky flows are quite common in the central part of the AHVP. They display a strong evidence of endogenous growth or inflation (Ninad et al., 2003) where flow-lobe consists mainly of a vesicular upper crust and a dense core zone but the lower vesicular zone is absent (Fig. 2).

The Al-Halaq al Kabir lava field has been mapped by Busrewi and Suwesi (1993) as a mappable unit 6 and generated during the last volcanic phase (phase 6). In the present study we treated this mappable unit as an individual flow field and remapped it as unit II (Fig. 3a, b). The terminology used in this paper to describe inflated pahoehoe lavas is revised from Walker (1991), Hon et al. (1994), Self et al. (1998), Rossi and Gudmundsson (1996) and Thordarson and Self (1998). The lava flow field is defined as a complex body that contains several lava flows (eruptive episodes) produced by individual volcanic eruptions and identified in the field on the basis field relations (Thordarson and Self, 1998; Thordarson and Hoskuldsson, 2008; Fig. 4a). A single volcanic eruption may consist of several eruptive episodes, each of which may last several months to years (Fisher and Schmincke, 1984;Thordarson and Self, 1998; Thordarson, 2000; Murcia et al., 2014; Németh and Kereszturi, 2015; Kereszturi et al., 2016). The lava flows commonly consist of many flow lobes (Thordarson and Self, 1998). The flow lobe represents the smallest unit in a pahoehoe flow field and has a characteristic three-part internal structural division, as mentioned above. The Al-Halaq al Kabir lava field is mostly restricted to the central part of the AHVP (Fig. 3a, b). Surface morphology of the Al-Halaq al Kabir lava-field is made complex by the existence of large inflations structures that apparently developed over long time. Busrewil (1996) proposes that the Al Haruj volcanic activity may have continued up through pre-historic time, with some recent lava flows (volcanic phase 6) possibly being of post-Neolithic age. Field observations indicate that these more recent basaltic lava flows on the AHVP did not re-use of pre-historic eruptive sites, a common feature in some of the older volcanic phases (i.e., they re-use existing sites, presumably forming multiple dykes).

Busrewil and Suwesi (1993) describe this lava flow field as pahoehoe, with delicate ropy structures. By contrast, a similar flow unit in the south part of the AHVP is described by Peregi et al. (2003) as fresh coal-black aa lavas, having a rough, clinkery or spiny surface that is covered by sharp edges, lava blocks, and containing large tension fractures - but with small scattered pahoehoe lavas in-between. The texture and mineral composition of this lava flow field, however, are quite similar to those of basaltic rocks from the earlier volcanic phases. The petrographic differences between the basaltic rocks at the AHVP are greater significant in samples taken from the upper vesicular and deeper part of the single lava flow lobe than between the different flow fields and this may be taken as evidence for long-duration (several months to years) of lava flow emplacement (cf. Thordarson and Self, 1998). The relative abundance of vesicles and high crystallinity together with joints are the good indicators of three-part division of pahoehoe flow lobe (Thordarson and Self, 1998). The basaltic lavas at the AHVP generally consist of porphyritic intersertal texture where olivine is the main phenocryst, but which also contains clinopyroxene, laths of plagioclases, and scattered glass. Later-formed calcite occupies vesicles, forming amygdales.

The Al-Halaq al Kabir lava field (unit II) is generally thought to have been erupted from fissures; yet, some basaltic flows seem to have been issued the summit area of the Al-Halaq al Kabir volcano. For example, on the north-eastern flank of the Kabir volcano a lava flow erupted at around 933 m.a.s.l (meters above sea level) is seen to extend down-slope to an altitude of around 800 m.a.s.l. (Fig. 3c). As this lava flowed down the gentle slope it spread out and entered an endogenous growth mode as a result of inflation during sustained supply of fresh lava beneath the thickening upper thin solid crust. The lava inflation lead to the development of axial and circumferential clefts in response to the uplift and rupture of the brittle uppermost crust (Duraiswami et al., 2001).

The Al-Halaq al Kabir flow field has systematic growth patterns suggesting it represents a single, long-lasting volcanic eruption (cf. Mattsson and Hoskuldsson, 2005). Notwithstanding the thicknesses of these inflation features they are difficult to measure precisely because of lack of cross-sectional exposures. The thicknesses of lava rise plateaus were estimated roughly using the difference of the altitude between inflation features and surrounding area (e.g., Fig. 5). This method is likely to underestimate the thickness because it does not take into account the older flow-lobes that are buried inside the lava field. The thicknesses of some tumuli and lava rise plateaus, however, could be measured accurately in the field (Fig. 6a, b) and these data were used for comparison with those from other volcanic fields. This flow field covers an area of around 220 km2 and its thickness estimated as 10-15 m (Busrewil and Suwesi, 1993); accordingly, its volume is about 2.2-3.3 km3. The lava flows reach lengths of up to 20 km (Fig. 3c).

Figure (4b) provides data on the volumes and lengths of many lava flow fields from difference volcanic provinces around the world for comparison with the Al-Halaq al Kabir flow field. The volume and length of the Al-Halaq al Kabir lavas are clearly much closer to monogenetic pahoehoe lava shield and pahoehoe lava fissures in Iceland than polygenetic Large Igneous Province (LIP), created through flood basalt, such as Columbia River Basalt Group (CRBG).

The Al-Halaq al Kabir lava flow field most likely formed through subsurface inflation processes. Of particular interest is whether the Al-Halaq al Kabir was primarily one event lasting many months or composed of many events (several episodes) spread over years or even decades. Geochemical variation and field observations cannot provide us to answer this question (e.g., Busrewil and Suwesi 1993; Peregi et al., 2003). Therefore, although the Halaq al Kabier lava field may be composed of several overlapping flows which travelled tens of kilometres from different vents and vent system, the upper surface of most the flow-field preserves distinctive inflation features such as tumuli, lava rise plateaus, lava inflation clefts and lava rise pits that certainly formed over long period of time by endogenous processes beneath insulating crust during emplacement.

**3 Data and methodology**

**3.1 Inflation process and associated features**

The Al-Halaq al Kabir flowfield contains large number of inflation features. During the present work we used both satellite imagery and field observations in order to measure the dimensions (maximum and minimum diameters) in plan-view (plan aspect ratios) of 551 lava rises and 289 tumuli on the north-eastern flank of the flow field at an elevation of about 100 m below the crater and at around 22 km from the main vent system that issued most of the pahoehoe flows hosting the inflation features (Fig. 7). In analysing the surface morphology of the lava flow field, we determine the following: i) flow-coated tumuli, ii) flow-lobe tumuli, iii) tumulus ridges, iv) lava rise plateaus, v) lava-rise pits and vi) lava inflation clefts. The flow-coated tumuli are observed within a few hundred meters from vent system and typically about 4 m high, with a plan-view aspect ratio of 1.5 and no clear lava-inflation clefts (Fig. 8a). The flow-coated tumuli in the AHVP are similar to those observed in Iceland by Rossi and Gudmundsson (1996). Other tumuli types, however, are abundant in the medial and distal portions of the Al-Halaq al Kabir flow field, and constitute the main part of the surface flow field (Figs. 8b, 9).

Flow-lobe tumuli are generally cupola-shaped and marked by development axial cracks in the central part and circumferential cracks around margins and attributable to the stresses that develop during inflation (Figs. 6a, 8; Walker, 1991; Rossi and Gudmundsson, 1996, Thordarson, 2000; De Wet et al., 2014; Scheidt et al., 2014). The tumulus ridges are created by inflation above relatively straight sections of preferred internal lava pathways (Thordarson and Hoskuldsson, 2008). Tumulus ridges (elongated tumuli) are marked by the presence of a prominent axial cleft and lesser clefts that develop sub-parallel to the long axes. They act as thermally efficient tube-systems for the channelling of lava to the middle and distal parts of flow field, partly as surface flows and partly within the distributary tube system. There are numbers of tumulus ridges recognised on the satellite imagery and in the field (e.g., Figs. 6b, 8c). Morphological study of flow-lobe tumuli and tumulus ridges in the area shows that their major axes (lengths) range from 16 m to 324 m and their minor axes (widths) from 11 m to 141 m. The flow-lobe tumuli are semi-equant and the tumulus ridges elongated, as determined by the aspect ratios of the major and minor axes in plan-view (Fig. 8b).

The tumulus ridges are genetically similar to flow-lobe tumuli, but more elongated in the direction of flow (Mattsson and Vuorinen, 2008; Nemeth et al., 2008). Flow-lobe tumuli are polygonal domes, with various plan-view shapes (e.g., rectangles, triangles, hexagons, and octagons). They are characterised by a system of inflation clefts arranged in a radial pattern and aspect ratio of major and minor axes is less than 1.5 (Fig. 8b). The range in aspect ratios of the elongated tumuli when compared with those of the flow-lobe tumuli may be attributed to the type of in-situ inflation mechanism. Flow-lobe tumuli are the result of localised inflation of the upper lava crust formed at the surface of small pools in subsurface lava pathways in response to irregular underlying topography, while the tumulus ridges are formed above comparatively linear lava pathways (Thordarson, 2000;Thordarson and Hoskuldsson, 2008).

The surface areas of lava rise plateaus are commonly an order of magnitude larger than those of both types of tumuli. The lava rise plateau is flat-topped and formed by uniform broad pahoehoe flow lobes (Walker, 1991; Thordarson, 2003). Inflation clefts in lava rise plateaus are developed along the outer margins rather than the central part, so that the main central part of the surface is uplifted as a block with little or no internal bending or deformation (De Wet et al., 2014; Scheidt et al., 2014) (Fig. 9).

The spatial distributions of tumuli and lava rise plateaus can be used to obtain information on the subsurface processes (Glaze et al., 2005). It is known that micro-topography combined with effusion rate can have a significant influence on lava flow dynamics and the ultimate emplacement and morphology of inflation produced (Mattsson and Vuorinen, 2008). Morphometric data show that the long axes of lava rise plateaus range from 88 to 717 m and short axes from 23 to 495 m. Most of lava rise plateaus are roughly oval-shaped in plan view based on an aspect ratio of the maximum and minimum axes (Figs. 5, 9).

Throughout the Halaq al kabier flow field there are numerous depressions within and between the lava rises that look like lava-rise pits (Figs. 4, 9). They are thought to form primarily where the rate of inflation was less than that of the surrounding parts of the lava flow (Walker 1991; Self et al., 1998; Whitehead and Stephenson 1998; Thordarson and Hoskuldsson, 2008). Characteristics walls of lava-rise pits are similar to the margins of lava rise plateaus (Walker 1991). Lava-rise pits in the AHVP are similar to the lava-rise pits described within the McCartys flow in New Mexico (De Wet et al., 2014; Scheidt et al., 2014). The Al Haruj region is characterised by wide flat area with numerous isolated hills so that the flat low relief areas appear to be inverted during inflation and become lava rises and high topography areas have become as lava rise pits. Furthermore, the alignment of tumuli and lava-rise plateaus in the field and from satellite imagery indicates the presence thermally efficient lava delivery system beneath the Al-Halaq al Kabir lava flow field during emplacement (cf. Duraiswami et al., 2001; Bernardi et al., 2015; Fig. 10).

The lengths and widths (major and minor axes; maximum and minimum diameters) of tumuli and lava rise plateaus show a linear correlation with a coefficient determination R2 of 0.45 for tumuli and 0.60 for lava-rise plateaus (Fig. 7.11a, b). R2, however, increases to 0.70 when all tumuli and lava-rise plateaus are plotted together (not shown here). Frequency distributions of their lengths follow roughly normal distributions. The orientations of the length axes for tumuli and lava-rise plateaus show some peaks in a NNW and NNE directions, but otherwise strike in all directions (Fig. 11 c, d). Their strikes are consistent with the dendritic drainage pattern of the central part of the AHVP. The drainage pattern is a well-integrated in the central part of the Al Haruj region formed by the main valleys with their tributaries branching and re-branching in many directions without systematic arrangement (Busrewil and Suwessi, 1993). Presumably, it partly reflects the orientation of the main feeder tubes in the lava field in various directions.

Tumuli display a characteristic of P-type flow-lobe where the upper vesicular crust and dense core zone as well as well-developed jointing are distinct whereas thin lower vesicular crust was lack observed (e.g., Fig. 12a, b). Tumuli observed in the study area are remarkably similar in morphology and aspect (height/width) ratios to the flow-lobe tumuli which have been studied in Holocene lava shields (monogenetic shield volcanoes) in Iceland by Rossi and Gudmundsson (1996). The coefficient of determination (R2) between height and width is 0.834 (Fig. 13). Rossi and Gudmundsson (1996) studied flow-lobe tumuli in the distal part of the flow field (9.5 km from source) where slopes are very low, similar to present study site (at the distal portion of lava flow field with very low slope; Fig. 3c). The results suggest that the Icelandic and Libyan tumuli were emplaced by an analogous mechanism.

**3.2 Scaling exponents**

There have been few quantitative statistical studies (e.g., Rossi, 1999; Glaze et al., 2005) on the emplacement and inflation of lava-flow fields. Here we provide the results of such studies on the trend and length measurements (maximum diameters) of tumuli and lava rises in the central part of the AHVP. The results of the measurements of a total of 289 tumuli and 551 lava-rise plateaus are given in Figures (14; 11c, d), all of which belong to the Al-Halaq al Kabir lava flow field. The lengths of lava-rise plateaus and tumuli on the Al Haruj region are here analysed through the consideration of scaling exponents in order to obtain quantitative relations for the inflation structures.

**3.2.1 Power-law length distributions**

Power laws form a part of heavy-tailed distributions and are marked by their yielding straight lines on bi-logarithmic plot (Gudmundsson, 2014). These tests have been applied to geological fracture populations by Mohajeri and Gudmundsson (2012) and Gudmundsson and Mohajeri (2013). Here we apply a power-law analysis to the frequency-length distributions of sizes of inflation features, using first the power-law equation (Williams, 1997; Mohajeri and Gudmundsson, 2012):

 (1)

where is the number of inflation features (tumuli and lava rises) in a binned or class histogram, *x* is the size of the feature (here the length or maximum diameter of the inflation structure), *C* is a constant of proportionality, and  is the scaling exponent. We then take the logarithms for both sides of the size values and their probability  in order to know if the distribution follows a straight line on the log-log plot, that is, is a power law, namely:

 (2)

The straight lines for the sizes of the tumuli and lava rises indicate that they follow power-law size distributions (cf. Mohajeri and Gudmundsson, 2012) (Fig. 14b, e). The cumulative frequency distributions of the sizes (lengths) of tumuli and lava rises display power-law distribution (Fig. 14a, d). On the log-log plots it is clear that two straight lines, with different slopes or scaling exponents, fit the size distribution better than a single line (Fig. 14c, f), as is commonly observed for the sizes of geological structures (Gudmundsson and Mohajeri, 2013).The break in slopes of the length-size distributions may be partly related to pre-existing topography combined with effusion rates (cf. Glaze, et al., 2005). More specifically, different slopes or scaling exponents are likely to denote different inflation populations. Similar conclusions were reached as regards rock fracture populations by Mohajeri and Gudmundsson (2012). Segments of tumuli that are shorter than 60 m in length have a much shallower straight line slope than those with greater lengths. Similarity, the lava-rise plateaus also show an apparent abrupt change in the slope and two straight lines on the log-log plots (Fig14f). The break occurs at around 200 m. The slopes of the straight lines for both tumuli and lava rises and their scaling exponents change from 0.37 to 3.07 for tumuli and from 0.36 to 3.56 for lava rises at the breaks between the straight lines (the different populations).

The first population for tumuli has lengths (maximum diameters) from 16 m to 60 m and is mostly composed of flow-lobe tumuli. This population represents around 72% of the total, is widely spread, and may be formed primarily due to irregular underlying topography. The second population, with sizes in excess of 60 m, consists of tumulus ridges that appear as elongated tumuli. Pre-existing depressions and valleys played an important role in their formation in the Al Haruj region. This result is in agreement with field observations by Németh et al. (2008) who documented that large flow-lobe tumuli in the Al Haruj Abyad (the southern part the AHVP) are commonly elongated.

Lava-rise plateaus also form two populations based on the abrupt change in their scaling exponents. The paleo-topography seems to be one of the controlling factors as regards their sizes. The first (smaller-size) population is confined to smaller areas than the second population. The flow may have started as narrow branches through pre-existing valleys and tended to pond in depressions due to continued inflation via thermally efficient internal pathways. The lengths (maximum diameters) of tumuli and lava rise plateaus on the lava flow surface are systematically distributed and show identical statistical behaviour.

Glaze et al. (2005) used quantitative statistical analysis technique (Poisson distribution) to examine the spatial distribution of tumuli and lava rise plateaus on lava flow fields in Mauna Ulu in Hawaii, Thrainsskjoldur in Iceland, and a lava flow Elysium Planitia on Mars in order to find relationships between the inflation structures and subsurface growth processes. They concluded that the inflation features are systematically distributed in Iceland but randomly distributed on Hawaii and Mars. The random distribution, consistent with Poisson distribution, may be the result of random variations in paleo-topography or small-scale temporary preferred pathways, combined with very gentle slopes. By contrast, the systematic distribution on the surface of lava flow field reflects permanent large-scale preferred pathways that led to establish distributary tube systems directly beneath broad lava flow for a long period of time (Glaze, et al., 2005). Also the spatial distribution of tumuli and lava rise plateaus on the surface the Al-Halaq al Kabir flow filed is different from the Poisson distribution discussed by Glaze, et al. (2005), suggesting that deterministic processes, rather than random processes, control their mode of occurrence.

**3.3 Modelling**

**3.3.1 Analytical model**

The thicknesses of inflation features on the AHVP are quite small compared with their lengths and widths. It follows that the basic assumptions in the theory of thin, elastic plates is generally valid for tumuli and lava-rise plateaus (Szilard, 1974; Gudmundsson, 1986).The main purpose of the present modelling is to calculate the magmatic overpressure responsible for the inflation and the resulting tensile stresses that generated some of the fractures. The presence of inflation clefts on the surface of lava rises and tumuli indicate that vertical crustal displacement played an important role in the formation of inflation features (Rossi and Gudmundsson, 1996). The average plan aspect (length/width) ratio for tumuli and lava rises in the Al Haruj region in range from 1.81 to 2.01, so that we use an elliptical elastic plate in the modelling, and assume the plate to be subject to steady magmatic overpressure at its lower boundary. In the model, the elliptical plate with a simply supported edge becomes bent as a result magmatic overpressure. The uppermost lava crust becomes fractured during the early stages of inflation as a result of tensile stresses. A viscoelastic crust is formed between upper brittle crust and the molten core and behaves as brittle at 800-1070oC (Hon et al., 1994)(Fig. 16b). The viscoelastic crust is un-fractured and subject partly to compressive stresses during bending and formation of the tumulus. Therefore, the viscoelastic crust acts to keep the magma inside the tumulus or lava rise during the inflation process (Hon et al., 1994; Rossi and Gudmundsson, 1996). In Hawaii, the thickness of viscoelastic has been measured as 0.2-0.4 m (Hon et al., 1994). During this study, four samples were collected from the Al-Halaq al Kabir flow field in order to measure their Young’s moduli as discussed in the next section. The Young’s moduli were then used to calculate the flexural rigidly in order to estimate the magmatic overpressure responsible for the bending and the inflation features.

Four cylindrical basaltic samples 25 mm in diameter and 38.7-26.6 mm long were obtained to calculate the dynamic elastic modulus through using ultrasonic wave velocities for the measure travel times of P and S waves in samples at the Rock and Ice Physics Laboratory at University College London (UCL). Four measurements (axial and radial) per individual core sample were prepared for these experiments for calculating the sample anisotropy by plotting the velocity as a function of azimuth. The anisotropy throughout the samples in different orientations is less than 10% which indicates that the basaltic rocks at the AHVP can be considered isotropic or weakly anisotropic. The time difference between the initial pulse and the first arrival was measured as the P-wave travelled through the sample. This procedure was repeated with polarized S-wave transducers, in order to measure the travel time of an S-wave to cross the sample. The physical characteristics of the four core samples included in this study are shown in Table (1).

The P and S wave velocities and bulk density are used to calculate the dynamic Young’s modulus based on the following equation (Jaeger and Cook, 1969; Gudmundsson, 1990):

 (3)

where  is dynamic Young’s modulus,  is compression seismic wave velocity,  is shear seismic wave velocity, and represents the bulk density of the core sample. The relationships between the static and dynamic moduli for different types of rocks are somewhat complicated (Eissa and Kazi, 1988,Christaras et al., 1994, Brotons et al., 2015). In the laboratory measurements the dynamic modulus is around twice of the static modulus, but in the field, this ratio varies from 1.5 to 9.1 for volcanic rocks (Gudmundsson, 1990). However, Eissa and Kazi (1988) performed statistical relation to estimate the static from dynamic Young’s modulus that may be crudely valid for all rock types as follows:

 (4)

The static Young’s modulus for the basaltic samples is in the range 40-59 GPa with average of 50 GPa (Fig.15), but the in-situ Young’s modulus is likely to be lower (1.5 to 5 times) than the core-sample owing to the presence of fractures, cavities and planes of weakness (Gudmundsson, 2011). We thus assumed the in-situ static Young’s modulus during this study in the range of 10-34 GPa.

The differential equation for the vertical uplift or bending of an elastic plate subject to uniform magmatic overpressure at lower boundary is given by the following equation(Gudmundsson, 1999):

 (5)

Where ∇2 is the two-dimensional Laplace operator, is a thickness of the uplifted or inflated crust, and *po* is over magmatic-pressure.  is defined as is the resistance to bending of the plate and known as the flexural rigidity and given by (Marti and Gudmundsson, 2000):

 (6)

where  is the static Young’s modulus, is the effective thickness of the plate, and  is Poisson’s ratio. We take the static Young’s modulus for basaltic rocks as in the range of 10-34 GPa, as discussed above, and the Poisson’s ratio 0.25(Gudmundsson, 2011). The effective thickness for inflation features is the thickness of viscoelastic (unfractured) rather than fractured upper crust (Rossi and Gudmundsson, 1996). Thus we assume the average thickness of viscoelastic crust (0.30 m) as the effective thickness to calculate flexural rigidity from Eq. (6) as D = 24 MNm when Est = 10 GPa, and D = 82 MNm when Est = 34 GPa.

The equation of the elliptical boundary of the inflated plate is:

 (7)

where and y are the coordinates and  is the half length of the plate and *b* is the half width of the plate (Fig. 15a).

The solution to the differential equation (Eq. 5) for the vertical uplift or deflection is given by (Gudmundsson, 1986):

 (8)

where is the magmatic overpressure. The maximum uplift or displacement occurs at the centre, that is, where  and , in which case Eq. 10reduces to:

 (9)

Therefore, the magmatic overpressure can be found from the equation:

 (10)

Using the mean values for lengths and widths in plan-view of 289 tumuli and 551 lava rises measured in this study we estimated the magmatic overpressure needed for uplift or deflection of tumuli and lava rises on the Al Haruj region. The measured dimensions are as follows:  and  and  for tumuli, whereas and  and  for lava-rise plateaus. It follows from Eq. (10) the magmatic overpressure during the formation of tumuli isis 0.05 MPa when flexural rigidity D= 24MNmand  = 0.15 MPa when D= 82 MNm. These overpressure results are similar to those obtained for tumuli in Iceland, where they obtained overpressure values are 0.2 to 1 MPa (Rossi and Gudmundsson, 1996).For the lava-rise plateaus in Al Haruj, the calculated magmatic overpressures are *po* = 0.002 MPa when D= 24MNm and  = 0.004 MPa when D= 82 MNm.

The maximum tensile stress at the surface of the uplifted or domed crustal plate can be crudely estimated from the following relation (Gudmundsson, 1999):

 (11)

where all the symbols are defined above. The maximum theoretical tensile stress at the surface of tumuli and lava rises is tens MPa. The in-situ tensile strength of all rocks is commonly in the range of 0.5-9 MPa with most values between 2 and 5 MPa (Haimson, and Rummel, 1982; Gudmundsson, 2014).Therefore, the maximum tensile stress for both tumuli and lava rises is many orders of magnitude larger than the tensile strength of the basaltic upper crust (0.5-9 MPa) even though the magmatic overpressure was very low as we inferred in this study. Thus the viscoelastic crust played an important role to maintain the lava interior of the tumulus or lava rise during the inflation processes.

**3.3.2 Numerical model**

In the recent years, there has been increasing application of finite element methods (FEM) in analysing complex geological structures and processes (Bagnardi, 2014).Numerical models based on the finite element methods can provide quantitative information on the local stresses inside and around inflation structures. Comsol Multiphysics (5.1) ([www.comsol.com](http://www.comsol.com)) is the finite element program used for the work described in this paper. We have modelled the inflation structure as a homogenous, elastic layer with Young’s modulus 25 GPa, density 2650and a Poisson’s ratio of 0.25. The magmatic overpressure used is 1 MPa (Fig. 15b), similar to the highest values obtained by Rossi and Gudmundsson 1996). We made a numerical model in order to explore the potential stress effects of uplift or deflection due to the influence of magmatic overpressure beneath the rigid upper crust. The model is regarded as complementary to the analytical solutions given above. The model results suggest that in large parts of the uplifted or domed crust of the inflated structures, the tensile stresses exceed 10 MPa (and, are in places much higher; Fig. 15.b), so as to encourage rupture and the formation of form axial and circumferential fractures. In particular, the result of the numerical model show that the maximum tensile stress occurs at the surface (Fig.15b), from where they decrease gradually towards the neutral surface (cf. Ugural, 1981; Rossi and Gudmundsson, 1996).

**4 Discussion and conclusions**

The Al-Halaq al Kabir flow field represents the last eruption in the associated part of the AHVP. Therefore, it was selected to enable complete mapping of surface morphologies and identification of well-defined boundaries without subsequent flows overlying the studied part. The new dating and field observations suggest that this eruption most likely occurred during the late Holocene (Busrewil, 1996; Nixon et al., 2011). This lava field appears to have had low viscosity (high mobility) and being fed partly by flow in lava tubes over great distances (up to 22 km) (cf. Bernardi et al., 2015.) Field observations and remote sensing data suggest that an inflation mechanism (thickening by endogenous growth) played a significant role in the emplacement of the Al-Halaq al Kabir lava field. Tumuli, lava-rise plateaus, lava rise pits and inflation clefts are common and certain diagnostic characteristics that are an indication of their emplacement mode. These inflation structures vary in their shapes and sizes in relation to their distance from the vent system. The palaeo-topography combined with the flux rate and lava composition (and rheology) all can have strong effects on lava flow dynamics, emplacement, and inflation mechanisms (e.g. Glaze et a l., 2005; Mattsson and Vuorinen, 2008). Here the paleo-topography seems to be the main controlling factors as regards size of lava plateaus in the Al Haruj area (Fig 16). There are a number of preferred pathways recognised on the satellite imagery and in the field.

The size distributions of inflation structures at the surface of the Al-Halaq al Kabir follow power laws. Differences in scaling exponents of the inflation-structure populations suggest that the structures were much influenced by variations in the pre-existing topography as well as effusion rates. The tumulus ridges are partly controlled by pre-existing channels or valleys to form elongated tumuli where comparatively long-term distribution pathways developed, whereas ordinary tumuli with smaller lengths represent localised or stationary inflations. Tumuli and lava-rise plateaus populations may be divided into subpopulations based on the abrupt change in their scaling exponents D, ranging from D= 0.37 to D = 3.07 for tumuli and from D= 0.363 to D = 3.56 for lava-rise plateaus. The spatial distributions of tumuli and lava rise plateaus can be linked to network of lava transport beneath an insulating crust (Glaze et al, 2005).

The AHVP tumuli are morphologically similar to many Icelandic flow-lobe tumuli, suggesting a similar mechanics of emplacement. The tumuli and lava-rise plateaus in Iceland are strongly related to persistent preferred internal pathways that produced a systematic distribution of inflation features. Therefore, the tumuli and lava-rise plateaus on the surface of flow field in the AHVP are most likely correlated with preferred internal and thermally efficient pathways that may be have been active at different times during the lava flow field emplacement. Furthermore, the alignment of tumuli and lava-rise plateaus are clearly discernible in the field and on the satellite imagery which indicate a distributary tube systems beneath the upper insulating crust. The pre-existing topography and flux rate are the most important factors that may influence how and where inflation existence (Thordarson, 2000; Glaze et al., 2005; Thordarson and Hoskuldsson, 2008). These factors vary from place to place and sometimes within same lava flow field. The distribution of inflation structures in space might have begun as random, over time, the formation of lava tubes results in extremely efficient delivery of lava that led to a systematic clustering of the inflation features along these internal networks (cf. Glaze et al.,2005).

From analytical and numerical models we infer that the theoretical tensile stresses at the surface of tumuli during inflation are much higher than the actual tensile strength (0.5-9 MPa) of basaltic rocks. Thus, during tumulus and lava-rise formation the crust becomes fractured, as is observed in the field and from satellite imagery. But a viscoelastic zone forms between upper crust and molten core zone and behaves as brittle at 800 - 1070oC (Hon et al., 1994). The viscoelastic zone helps to keep the magma inside the tumuli and prevented the magma from leaking out through fractures during the inflation process.

Tumuli and lava-rise plateaus are thought to be supplied with magma, partly related to overflow, from a tributary tube system that is connected with the lava sources(cf. Rossi and Gudmundsson 1996; Glaze et al., 2005). If the lava was delivered through a tube system, the magma-static overpressure is, where is basaltic magma density (around 2650 kg /m3) and  is acceleration due to gravity (9.81 m/s2) and  is the elevation difference between the source and the lava forming the tumulus. On this assumption, the elevation difference at the surface between the source lava lake and inflation structures on the Halaq al Kabier flow field (> 100 m) and the areas containing the main tumuli and lava rises should be sufficient to generate static overpressure of up to 2 MPa. This is high-enough overpressure for the formation of the inflation structures, because the analytical models presented above suggest that the overpressure needed to form the tumuli and lava rises on the AHVP was less than 1 MPa.

The Al-Halaq al Kabir flow field is most likely formed during a single volcanic eruption (probably with a number of eruptive pulses) whose duration was at least many months, and possibly several years. The duration is partly estimated on the basis of the thickness of the upper vesicular crust of inflated pahohe flow lobes, observed in the field. However, the production rate of the first volcanic eruption on the AHVP during late Miocene (7.9-5.3 Ma) (e.g., Less et al., 2006) was, however, much larger than the last volcanic eruption during Holocene For example the duration of flow lobe of elongated tumulus (Fig. 6b), according to cooling model equation $\left(t=164.8H^{2}\right) $of Hon et al. (1994) where $t$ is the time in hours and $H$ is the thickness of the upper vesicular in meters, is about 27 days. The decline in volumetric flow rate (production rate or supply) of lava with time is clear and considerable in the Al Haruj region (Elshaafi and Gudmundsson,2018).

Monogenetic lava shields, such as in Iceland and AHVP, are widely believed to be formed in single eruptions, some of which may have lasted for decades (Walker, 1965; Gudmundsson, 1986; Andrew and Gudmundsson, 2007; Thordarson and Hoskuldsson, 2008; Thordarson, Sigmarsson, 2009; Elshaafi and Gudmundsson, 2018). If we presume both eruptions (the first and the last eruptions) on the AHVP had similar emplacement mechanism, then the duration of the first volcanic eruption may have been many years or even several decades. If the eruptions would have taken many years (or decades), then porous-media flow of melt into the deep-seated source reservoirs could have contributed to largely maintaining the excess magmatic pressure in magma reservoir until the end stages of the eruption (cf. Gudmundsson, 2016).

Similarly, many studies (e.g., Thordarson et al 1996; Thordarson and Self, 1998; Self et al., 1998; Wignall, 2001;Jahren, 2002,Burgess et al., 2017;Vaillant et al., 2017) suggest that long-lived volcanic eruptions, particularly large basaltic eruptions, may have great negative climatic/environmental impacts due emission large amount of greenhouse gases (e.g., CO2, CH4). Emissions of CO2 during eruptions may have induced considerable global warming while, conversely, emissions of SO2 may induce global cooling (Olsen, 1999).There is apparent coincidence between the age of an initial volcanism in the AHVP (7.9-5.3 Ma) (e.g., Peregi et al., 2003; Less et al., 2006) and fauna and flora local extinctions in the As-Sahabi area, NE Sirt Basin, during Messinian-Zanclean time (7 to 5 Ma) (Fig. 1) (Boaz, 2009 El-Shawaihdi et al., 2016). In addition, Hounslow et al. (2017), on the basis of high-resolution chronology and magnetostratigraphy of the Neogene deposits in the Fezzan Basin, southwest of the Sirt Basin, inferred that extremely aridity was taking place at Lake Megafezzan (a giant paleo-lake) after 11 Ma (Fig. 1b). Causes of the local biological extinction and super-aridity in the Sirt Basin region are debated. Some researches connect this local effect with the dramatic Mediterranean drawdown (by as much as 1 km) during the end-Miocene (Messinian time) (5.96 to 5.33 Ma), which caused massive desiccation in the Mediterranean Sea, namely the Messinian Salinity Crisis (MSC) (Gautier et al., 1994; Bache et al., 2009; El-Shawaihdi et al., 2016).

The individual effusive volcanic eruption could not alone have caused massive aridification or local extinction. However, extensive eruptions may contribute to some local decline/changes in flora and fauna. The effects would, for example, depend on the type and amount of emitted gases and duration of eruption. For instance, Kilauea in Hawaii has been erupting almost continuously since January 1983, for 36 years, and considered as one of the most long-lived recorded eruptions on Earth. The eruption has produced close to 4 km3 of lava and emitted nearly 2000 tons of SO2 per day through a 14 year period (Elias et al 1993, Self and Thordarson, 1998). The volcanic fog caused serious eye and respiratory problems in part of the population of Hawaii but has not had much atmospheric/local climatic impact (Self and Thordarson, 1998). Another example, the 1783–1784 Laki eruption in Iceland is considered as one of the largest basaltic flood lava eruption in historical times (Thordarson et al., 2001; Thordarson et al., 2003). This volcanic eruption released more than 1.7 megatons of SO2 per day and huge amount of dissolved HCl and HF during the first weeks (8 months) (Thordarson et al. 1996). The resulting thick dry fog that extended over large areas in Europe and Asia and great environmental problems in Iceland, including death of numerous domestic animals and eventually famine in Iceland (Stothers, 1996).The remaining of sulphate aerosols in the stratosphere may be caused several years of lower-than-average temperatures and poor weather in parts of the Earth’s surface (Fiacco et al, 1994, Thordarson and Self, 1997).

The proposed link between volcanism and ecologically catastrophic climate conditions throughout the geological record are still debated in the literature and various interpretations based on new geochemical and isotope data are available (e.g., Burgress et al., 2017, Vaillant et al., 2017). In order to assess whether the duration and amount of gases released during the eruptions listed above, and other factors with negative impact on the local environment, may have contributed to the local biological changes and extinctions in the Sirt Basin area, further research in the AHVP would be needed. For example, drilled core barrels could be used to examine the changes in vesiculation structures along with petrographic texture and jointing style - indicators of the transitional from crystalline core zone to upper vesicular crust (Thordarson, 1995; Self et al.,1997: Cashman and Kauahikaua, 1997; Thordarson and Self, 1998) to get more accurate estimates of the durations of the eruptions. Also, detailed petrological studies could be used to estimate the pre and post eruption volatile material of the glass in inclusions trapped in phenocrysts (pre-eruption) and the degassed lava matrix (post-eruption) (cf. Self et al., 1998). Such data is also essential condition for forecasting and assessment hazards of the AHVP, particularly the most recently publications indicate that the volcanism in the central Libya is still potentially active (cf. Lemnifi et al., 2017; 2019).

In conclusion, the main results of the present study may be summarised as follows:

* Studies were made of tumuli and lava-rise plateaus in the Holocene lava-flow field of Al-Halaq al Kabir in the central part of the Al Haruj Volcanic Province (AHVP) in Libya.
* Most of the inflation structures, that is, the tumuli and lava-rise plateaus, have somewhat to strongly elliptical shape in plan view. The long axis of the ellipse is then referred to as the length of the inflation structure, and the short axis as the width.
* The lengths and widths of 551 lava-rise plateaus and 289 tumuli are presented in the paper. The coefficient of determination (R2) for length and width is 0.834, meaning that over 83% in the variation in width can be explained in terms of variation in length.
* Bi-logarithmic (log-log) plots of length versus frequency (number) of tumuli and lava-rise plateaus shows that each population can be divided in two subpopulations based on abrupt changes in the slope, the scaling exponent D, on the plots.
* Using an estimated Young’s modulus of 10-34 GPa for the brittle crust of the inflation structures, analytical and numerical models show that the structures can be generated (inflated) under a low magma/lava overpressure. More specifically, the pressure needed is less than 1 MPa for all the structures.
* Theoretical considerations show that magma/lava overpressure of up to 2 MPa is easily obtained in the lava-tube system, based on the fluid density and the elevation difference (about 100 m) between the source crater and that of the location of most of the inflation structures.
* The tensile stresses that develop in the brittle crust of the structures during inflation, driven by the overpressure above, are much larger than the tensile strength of the crust. It follows that the numerous tension fractures observed in the inflation structures can be explained in terms of these stresses.
* The initiation of the AHVP at 7.9-5.3 Ma may have contributed to adverse local climatic and other environmental conditions. These, in turn, may have contributed to the abrupt changes in the fauna and flora in the area during this time.

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**Figure 1.** (a) Relief map showing the locations and elevations of the main four volcanic provinces in Libya (a digital elevation model at 90 m spatial resolution is taken from ETOPO1 Ice Surface Global Relief Model, 2009). GVP: Gharyan Volcanic Province; SVP: As Sawda Volcanic Province; AHVP; Al Haruj Volcanic Province; NVP: Nugay Volcanic Province (b) Landsat ETM+ image showing the extent of the Al Haruj Volcanic Province (AHVP), footprint-shaped, in the central part of Libya. The boundary of volcanic province is indicated by white line (adapted from Satellite Imaging Corporation). Orange circles indicate the oil fields and red boxes towns in the Al Haruj region.

**Figure 2.** Field photograph showing the general morphology of a hummocky pahoehoe flow on top of Miocene calcareous sandstone of the Maradah Formation. The thickness of the lava flow does not exceed few meters. The inset photograph showing the upper vesicular flow-lobe zone and the dense core zone provided of evidence of endogenous growth during emplacement. The person provides scale.

**Figure 3.** a) Simplified map showing the location of the study area in the central part of the AHVP. b) Schematic map showing the extent of the Al-Halaq al Kabir flow field (dark colour) covering partly the older volcanic unit I (grey colour). This lava flow field most likely originated from a vent system and generally flowed NE over a distance of around 20 km. Both volcanic units have been identified and mapped by Busrewil and Suwessi (1993). c) Profile illustrating the extent of the Al-Halaq al Kabir flow field in cross section. The slope angles along profile are indicated, the location of the cross-profile is shown in Figure 1b. Sites of figures (8a, b, 9) are shown.

**Figure 4.** a) Cartoon of the development lava flow field. The lava flow field consists of two lava flows where each flow formed during effusive episode and is composed of many flow lobes. Lava is transported through a vent system to active flow front via thermally efficient lava tubes (modified from Thordarson and Hoskuldsson, 2008). b) Graph showing the relationship between volume and length of the Al-Halaq al Kabir lava flow field, is indicated by red arrow, and, for comparison, 33 lava flow fields from various monogenetic and polygenetic volcanic provinces around the world (data sources: lava shields and pahoehoe fissures in Iceland are taken from Thordarson and Hoskuldsson, 2008, and 2014-2015 basaltic fissure in Iceland from Pedersen et al., 2017, whereas the rest of data are taken from Self and Thordarson, 1998).

**Figure 5.** Large lava-rise plateau with its surveyed cross-profile that is marked by a number of lava-rise pits. The structure is plateau-shaped with marginal inflation clefts. The thickness or height is estimated at around 15 m above the surrounding relief (adapted from Google Earth). The inset field photograph shows lava inflation cleft.

**Figure 6.** a) Photograph (left) and a schematic illustration (right) of a tumulus. Note the axial and lesser fractures that formed during the inflation process. b) Photograph (left) and a schematic illustration (right) of an elongated tumulus or tumulus ridge which is characterized by large long and deep axial fracture. The formation of this flow lobe took around 27 days based on cooling model equation $\left(t=164.8H^{2}\right) $of Hon et al. (1994) where $t$ is the time in hours and $H$ is the thickness of the upper vesicular in meters. The duration is probably an underestimation due to the upper vesicular crust being partly covered by sand dunes.

**Figure 7.** The lower map (on the right) shows the areal distribution of 289 tumuli and 551 lava-rise plateaus in the distal part of the Al-Halaq al Kabir lava flow field (volcanic unit II). The geometry and area of these inflation features have been measured using ArcGIS. Dashed red square in the upper map (on the left) indicates the location. The flow direction is broad to the northeast.

**Figure 8.** a) Satellite imagery (adapted from Google Earth) showing flow-coated tumuli located at a proximal part of the source. Note the absence of axial and circumferential cracks. b) Satellite imageries (adapted from Google Earth) showing various forms of flow- lobe tumuli at the distal part of the Al-Halaq al Kabir flow field. Note the abundance of axial and circumferential cracks (lava-inflation clefts) and the gradual transition in the morphology of the tumuli from near source to the distal portion of the lava field. The locations of both images(a, b) are indicated by the yellow box on the cross-profile. c) A preferred pathway to drain lava lakes may use pre-existing drainage pattern, a common feature in the Al Haruj region.

**Figure 9.** Satellite imageries (adapted from Google Earth) showing various forms of lava-rise plateaus in plan-view. They are marked by flat-topped surface and circumferential cracks at the margin that indicate bending during the inflation process. Circular and semi-circular lava-rise pits are likely formed during inflation process.

**Figure 10.** Panorama view showing lava-rise plateaus and several tumuli.

**Figure 11.** Graphs showing the correlation between the length and width in plan-view of lava-rise plateaus (a) and tumuli (b). Both graphs show a positive correlation between two parameters. N is the number of inflation structures, and R2 is the coefficient of determination. Frequency distribution of lengths of lava rise plateaus (c) and tumuli (d) which follow approximately normal distributions. The rose diagrams for lava rise plateaus (red colour) and tumuli (green colour) that are consistent with dendritic drainage pattern of the central part of the Al Haruj region. Note despite the various dimensions between tumuli and lava rise plateaus, they have generally similar statistical behaviour.

**Figure 12.** a) Field photograph and graphic log display of the upper vesicular crust of tumulus. The tilting or dip is around 14oto WNW. The frequency of vesicles decreases with depth and the crust is characterised by prismatic and irregular jointing. The thin lower vesicular crust and core zone are not exposed. The uppermost of lava crust is characterised by horizontal cooling cracks that may be also followed vesicle alignments. The duration of this flow lobe is approximately two months based on cooling model equation of Hon et al. (1994). b) Field photograph showing lava flow which consist of pahoehoe flow lobes. VZ is vesicular zones within the upper vesicular crust that formed during inflation processes. The flow lobe sheet seems to be overlapped the flow-lobe tumulus with flank tilting around 22°. The duration of this lava-flow emplacement is estimated at roughly ten months.

**Figure 13.** Graph showing the correlation between height (thickness) and width in cross-section of flow-lobe tumuli in the AHVP measured in the field, and in Iceland for comparison. The graph shows a near-linear correlation between height and width in both volcanic provinces, with the overall coefficient of determination (R2) of 0.834. Note the dimensions of flow tumuli in the Al Haruj region are located within the same field of the dimensions of flow-lobe tumuli in Iceland. The data for Iceland are taken from Rossi and Gududmunsson (1996).

**Figure 14.** Scaling exponents for tumuli (upper diagrams) and lava-rise plateaus (lower diagrams).a) The cumulative frequency distribution of 289 tumuli lengths using bin width of 10 m. b) A bi-logarithmic (log-log) plot of 289 tumuli lengths. The straight line suggests that the length-size distribution follows a power law. N is the number of inflation structures, Std. dev is standard deviation, R2 is the coefficient of determination, and D is the scaling exponent. c) The whole population of tumuli can be divided into two populations based on an abrupt change in the scaling exponent or slope. d) The cumulative frequency distribution of 551 lava-rise plateau lengths using bin width 50 m. e) A single line on a bi-logarithmic plot of the whole lava-rise plateau population. f) The population of lava-rise plateaus can be divided into two populations based on abrupt change in slope or scaling exponent.

**Figure 15.** a) Elliptical plate with freely movable edge subject to bending due to magmatic overpressure. The length of the major axis is 2a and length of minor axis, the width,is 2b. b) FEM (finite element model) results. Colour contours represent the maximum principal tensile stress. The entire model is shown on the grey rectangular diagram in the lower right inset. The model is fixed at the lower part, indicated by red crosses, to avoid any rigid-body rotation and displacement. The maximum tensile stress concentrates in the uppermost part of the crust and is high enough to cause the tension fractures observed in the field and on satellite imagery. From the surface of the crust the tensile stressdecreases gradually downward until it reaches the neutral surface (cf. Ugural, 1981; Rossi; Gudmundsson, 1996). It is probably at this level that the viscoelastic crust acts to keep lava inside during inflation processes.

**Figure 16.** Cartoon showing the development of tumuli and lava-rise plateaus in the study area. Cross sections are on the left and plan views in the middle. Field photographs on the right to display natural of topography on the Al Haruj region that consists of a nearly flat-wide area within numerous isolated hills (upper right photograph). a) and A) Lava flow spreads out through the low relief and thin crust is formed. b) The lava sustained a supply of magma/lava beneath insulating crust and inflation begins. A viscoelastic layer/crust forms(beneath the brittle crust) with thickness 20-40 cm at 800- 1070o C (cf. Hon et al., 1994). The viscoelastic crust plays an important role in keeping magma inside during inflation process. c) The tensile stress at the surface is much higher than the tensile strength of basaltic rock (0.5-9 MPa) so that tension fractures will form during the inflation. B) The plan-view of the present day of the Al-Halaq al Kabir flow-field where the paleo-topography inverted where the high relief becomes low relief (depression) and vice versa, as seen in the lower (right) field photograph.

**Table 1.** P and S-wave velocities, densities, dynamic and static moduli for four basaltic rock samples from the study area. The values of static Young’s modulus inferred from dynamic Young’s modulus based on the equation of Eissa and Kazi (1988).