

RESEARCH ARTICLE

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International geological significance of the potential Al-Medina volcanic UNESCO Global Geopark Project in Saudi Arabia revealed from multi-satellite remote sensing data

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Abstract

UNESCO Global Geoparks should be of international geological significance in terms of their scientific quality, rarity, aesthetic appeal and tourism value. At least nine Cenozoic volcanic fields are developed in the western Saudi Arabia, with a total area of 180,000 km². In this paper, the geological and geomorphological features of these volcanic fields induced by the expansion of the Red Sea are interpreted and displayed using multi-source satellite images, such as Landsat-8 OLI (Operational Land Imager) and Gaofen-2 data. Our results show that the Al-Medina volcanic field (AMVF) has great prospects as the aspiring volcanic Geopark in Saudi Arabia. This study indicates that: (1) AMVF has international geoscientific significance and rare natural attribute because the volcanic fields are induced by the rising mantle plume and rare examples of white volcanoes comprised mainly from felsic rock; (2) AMVF has abundant volcanic landscapes, including completely preserved cones and craters and multi-phase lava flows from different eruption stages, which have great aesthetic appreciation and tourism values to attract the general public; (3) AMVF is close to the second holy city of Islam-Medina, which has convenient transportation and is suitable to develop tourism to promote the development of the local economy; (4) AMVF had erupted repeatedly (the latest eruption was in 1256 AD), establishment of the UNESCO Global Geopark Project can not only prevent potential geological hazard risks to the people living in Medina city from future volcanic eruption events, but also provide better protection and conservation to geoheritage sites being damaged by human activities, for example setting protected boundaries of AMVF to avoid the destruction of volcanic landscape integrity caused by urban expansion.

Keywords: Geoheritage, Al-Medina volcanic field, Late Quaternary, Scientific value and aesthetic appeal, Multi-source remote sensing data

Introduction

Geological heritage or Geoheritage includes "pure" geological and geomorphological heritage, representing the entity of unique features of the Earth's crust that can be employed for the purposes of science, education and tourism [1]. Geoheritage has different types

(geomorphological, sedimentary, igneous, etc.) and forms (natural outcrops and landscapes, etc.), which is the subject of geoconservation.

Two main types of localities exhibiting geoheritage that are officially designated are geosites and geoparks. The former are relatively small objects or areas representing unique phenomena. Geoparks are areas specially designated for geoheritage exploitation for the purposes of tourism, education and science, as well as for their conservation [1]. Additionally, geoparks bring jobs to rural and indigenous people, in turn helping to protect sites of

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importance and promote geoheritage. UNESCO (United Nations Educational, Scientific and Cultural Organization) Global Geoparks are single, unified geographical areas where sites and landscapes of international geological significance are managed with a holistic concept of protection, education, and sustainable development. Their bottom-up approach of combining conservation with sustainable development while involving local communities is becoming increasingly popular. At present, there are 169 UNESCO Global Geoparks in 44 countries [2]. The distribution of UNESCO Global Geoparks around the world is presented in Fig. 1. It shows that current UNESCO Global Geoparks are mainly distributed in southwestern Europe and eastern Asia. Among them, the volcanic Global Geoparks are mainly distributed in China, Japan, Korea, Peru, and Turkey [2].

One of the geoheritage features, the volcanic fields, which are widespread on Earth, such as scoria cones, tuff rings, maars, lava flows and lava lakes, help to increase in interest and wealth of new science knowledge [4]. The establishment of volcanic geoparks and geoheritage sites is becoming increasingly popular worldwide. UNESCO Global Geoparks and the European Geopark Network have numerous geoparks which achieved their status due to their volcanic geoheritage [4].

The Saudi Arabia, with an area of 2,250,000 km², is ranking the 14th in the world. Induced by the expansion of the Red Sea, Saudi Arabia has developed at least nine Cenozoic basaltic volcanic fields in the western part, with a total area of 180,000 km² [4]. However, there is still no

geoheritage site in Saudi Arabia that has been inscribed on the UNESCO Global Geoparks.

The Al-Medina volcanic field (AMVF), part of the Har-rat Rahat in northwest of the Saudi Arabia, is the worth notable active volcanic field characterized by the occurrence of two historical eruptions approximately in 641 and 1256 AD. The evolution, lithology, geochronology, geochemistry and the hazard analysis on the region [5–9] have provided important information to the inventory of the volcanic heritage. Here, we identify significant volcanic features in AMVF by using multi-source satellite images, including Moderate-resolution Imaging Spectrometer (MODIS), Landsat-8 OLI (Operational Land Imager) and China Gaofen-2 (GF-2) data. The results of our studies indicates that the AMVF could be organized and promoted as the UNESCO Global Geopark in the Kingdom of Saudi Arabia.

Remote sensing data products (aerial photographs and satellite images) give direct information on the landscape-the surface features of the Earth, and therefore geomorphological investigations are most easy to carry out based on such data. Through different bands combinations, different lithology and eruption periods of lavas can be highlighted. Remote sensing investigations have a two-fold purpose: (a) to view the ground features in a different perspective, on a different scale, or in a different spectral region, and (b) to reduce the amount of field work involved in covering the entire study area, especially when the target in the region are far away and difficult and expensive to access.

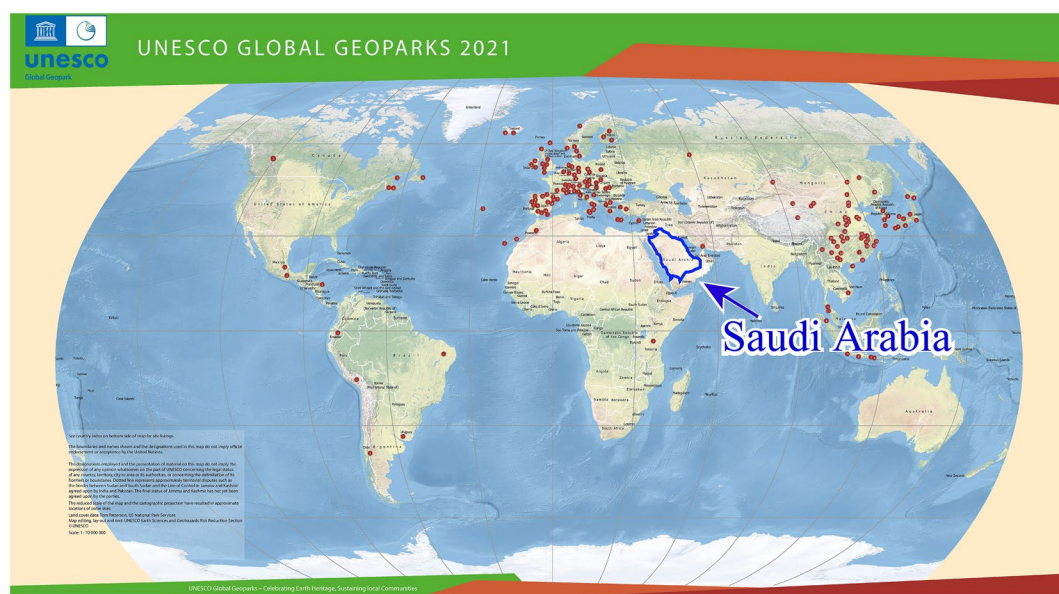


Fig. 1 The distribution of UNESCO designated Global Geoparks around the world [3]

Our approach focus on using remote sensing techniques, supplemented by a literature review and field studies. The approach applied in this study was as follows. Following the introduction, a detailed description of the study area in Saudi Arabia is presented in Sect. 2. In Sect. 3, the methodology to interpret the geological and geomorphological features of AMVF by using multi-source satellite images and the results are described in Sect. 4. In Sect. 5, we discuss AMVF fits the criteria for consideration as a potential volcanic Geopark Project. The conclusions are drawn in the last section.

Geological background

Kingdom of Saudi Arabia, referred to as Saudi Arabia, is located in the Arabian Peninsula in the western Asia. It borders the Persian Gulf in the east and the Red Sea in the west, with a 2,437 km-long coastline, as shown in Fig. 2.

Saudi Arabia occupies most of the Arabian Peninsula topographically higher in the west and lower in the east. Along the Red Sea, there is a “backbone” of the Arabian Peninsula, named “Tuwaiq Mountain chain”, extending in a north–south direction in general. In the east of the mountains, the terrain gradually declines towards the eastern plain, where a large portion is covered by sand dunes and rocky regolith [12].

The Red Sea Rift 2000 km-long striking NNW-SSE, forms a broad zone of active deformation between Africa and Arabia [6]. Rifting of the Red Sea began about 30 Ma ago, separating the western edge of the Arabian Plate from African Plate [13], as shown in Fig. 2. Following that, the late Cenozoic geodynamic

evolution of the Arabian Shield area was mainly controlled by (1) extensional processes as a consequence of the complex kinematic interactions that developed the Red Sea Basin [14–17], which are moving the Arabian Plate towards NE with a speed of 1.6–2 cm/yr. [18–20]; (2) continental collision between Arabia and Eurasia to the east since the middle Miocene [21–24].

In response to this complex tectonics of the Arabian Plate, a series of large Cenozoic volcanic fields and volcanic rocks mainly developed along its western margin by the rising mantle plume induced by expansion of the Red Sea after the continental plate collision between Arabian and Eurasian plates [5, 7, 26–31], as shown in Fig. 3. At least nine intracontinental Cenozoic basaltic lava fields parallel to the Red Sea Rift are developed in western Arabian Shield (Fig. 2), with a total area of 180,000 km². These volcanoes and lava fields form a 600 km-long unique volcano chain from north to south in western Arabian Shield, named “Mecca-Medina-Nafud Volcano Line (MMN Line)”. Among the volcanoes, the Al-Medina volcanic field (AMVF), part of the Harrat Rahat in northwest of the Arabian Plate, is the worth notable active volcanic field characterized by two historical eruptions approximately in 641 and 1256 AD [6]. AMVF is characterized by a central NNW-SSE volcanic chain that extends about 100 km to Medina city in the north. This volcanic chain consists of more than 500 scoria cones (up to 30–200 m high) surrounded by fields of coalescing low viscosity basaltic lava flows [6].



Fig. 2 A MODIS remote sensing image shows the distribution of Cenozoic volcanic fields in Saudi Arabia. Note that the schematic Cenozoic tectonic map of the Arabian and African plates also displayed that the northward subduction of Arabian plate toward the Eurasia plate has led to the extension of the Red Sea (modified after [10, 11])

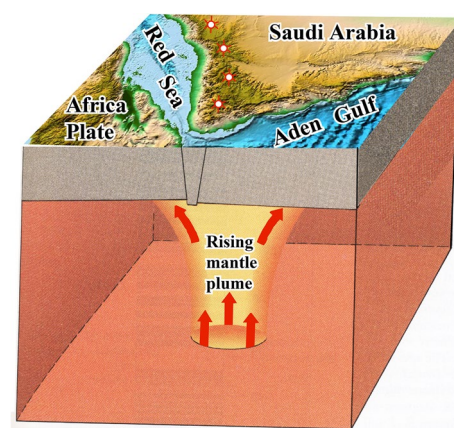


Fig. 3 The three-dimensional (3D) geodynamic concept diagram showing that the Cenozoic volcanoes in western Saudi Arabia are formed by the rising mantle plume induced by expansion of the Red Sea after the plate collision between Arabian and Eurasian plates (The figure is modified according to [25], the red stars mark the active volcanoes)

Methodology

Based on the geological background, the geological and geomorphological features of the AMVF in western Saudi Arabia are interpreted using Landsat-8 OLI and Gaofen-2 data, respectively.

Remote sensing data

Landsat-8 satellite

Landsat satellites came from the National Aeronautics and Space Administration (NASA). Landsat-8 satellite was successfully launched on February 11, 2013, carrying two sensors: OLI and TIRS (Thermal Infrared Sensor). The technical specifications of the Landsat-8 data are listed in Table 1.

The Landsat-8 image used in this study is the Level 1 T data product with spatial resolution of 30 m, which has undergone systematic radiometric calibration and geometric correction by the United States Geological Survey (USGS) (<https://www.usgs.gov/>). The investigated Landsat-8 image was acquired on September 24, 2018.

Gaofen-2 (GF-2) satellite

GF-2 satellite is the first civilian optical remote sensing satellite with spatial resolution up to 1 m developed by China. It was launched on August 19, 2014, carrying two cameras: 1 m panchromatic and 4 m multispectral cameras. The technical specifications of the GF-2 are listed in Table 2.

In this paper, we collected two Level 1-A GF-2 remote sensing images over the AMVF area which were acquired on February 10, 2018.

Interpretation of the Landsat-8 data over the AMVF

The spectral reflection characteristics of volcanic lavas (including pyroclasts, such as ash, lapilli, and scoria)

Table 1 The main technical specifications of the Landsat-8 data

No.	Band	Wavelength (μm)	Spatial resolution (m)
1	Coastal	0.43–0.45	30
2	Blue	0.45–0.51	30
3	Green	0.53–0.59	30
4	Red	0.64–0.67	30
5	NIR (near-infrared)	0.85–0.88	30
6	SWIR1 (short wave infrared)	1.57–1.65	30
7	SWIR2	2.11–2.29	30
8	PAN	0.50–0.68	15
9	Cirrus	1.36–1.38	30
10	TIR1 (thermal infrared)	10.60–11.19	100
11	TIR2	11.50–12.51	100

Table 2 The main technical specifications of GF-2 data

No.	Band	Wave length (μm)	Spatial resolution (m)
1	Pan	0.45–0.90	1
2	Blue	0.45–0.52	4
3	Green	0.52–0.59	4
4	Red	0.63–0.69	4
5	NIR (near infrared)	0.77–0.89	4

with different lithological components or eruption periods are different in the remote sensing image. According to [32], the spectral reflectance of different weathering degrees in basalt volcanic lavas has a noticeable distinction in thermal infrared bands [32]. Therefore, Band 10 or Band 11 of Landsat-8 can be used to distinguish the weathering degree of volcanic lava. In addition, considering that the volcanic lava after weathering may contain hematite and aluminum elements, the near-infrared band (Band 5) and short-wave infrared band (Band 6 or Band 7) are selected to identify hematite and aluminum in the weathered lavas. Finally, Band 11, Band 5 and Band 7 are arranged for Red, Green and Blue channels of the Landsat-8 remote sensing image, respectively, which is shown in Fig. 4.

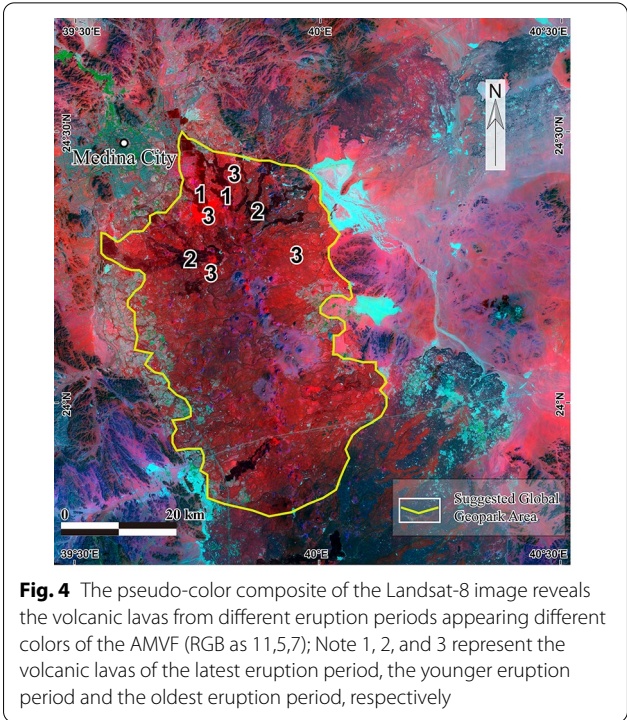


Fig. 4 The pseudo-color composite of the Landsat-8 image reveals the volcanic lavas from different eruption periods appearing different colors of the AMVF (RGB as 11,5,7); Note 1, 2, and 3 represent the volcanic lavas of the latest eruption period, the younger eruption period and the oldest eruption period, respectively

Interpretation of the GF-2 data of over the AMVF

In order to judge the eruption periods of the Medina volcanic lavas more clearly, we obtained the GF-2 data of the same area (Fig. 5).

The pseudo-color synthesis of the GF-2 data shows that volcanic landforms are widely distributed with different colors in the AMVF, and it is speculated that at least four eruption periods can be identified: (1) the purple part (numbered 1 in Fig. 5); (2) the dark green part (2 in Fig. 5); (3) the lighter green part (3 in Fig. 5) and (4) the off-white part (4 in Fig. 5). There are about 50 volcano craters with different landforms in the AMVF, and most of them are cinder cones, while some are shield-shaped volcanoes.

Geological interpretation and analyses of the GF-2 and Landsat-8 images of the AMVF generated a 1:50,000 volcanic geological interpretation map (Fig. 6), combining the results of previous research [5, 6, 8], suggest that there are at least four eruption periods as following.

- 1) The red pattern (numbered 1) in Fig. 6, corresponding to the purple part (1 in Fig. 5), belongs to the Qm7: ~1500 BP-1256 AD, which is the latest volcanic lavas. According to the existing geological data, the last eruption of this volcano occurred in AD 1256. The latest lava flows is quite close to Medina City;
- 2) The orange pattern (numbered 2) in Fig. 6, corresponding to the dark green part (2 in Fig. 5), belongs

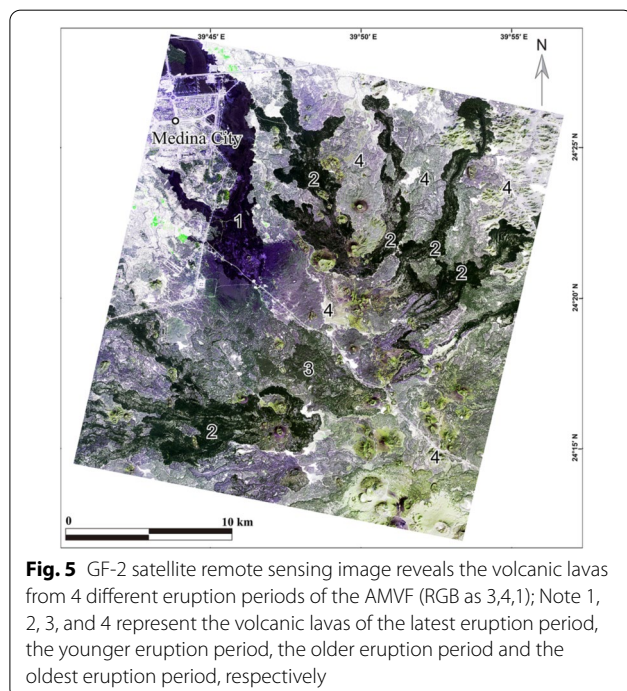


Fig. 5 GF-2 satellite remote sensing image reveals the volcanic lavas from 4 different eruption periods of the AMVF (RGB as 3,4,1); Note 1, 2, 3, and 4 represent the volcanic lavas of the latest eruption period, the younger eruption period, the older eruption period and the oldest eruption period, respectively

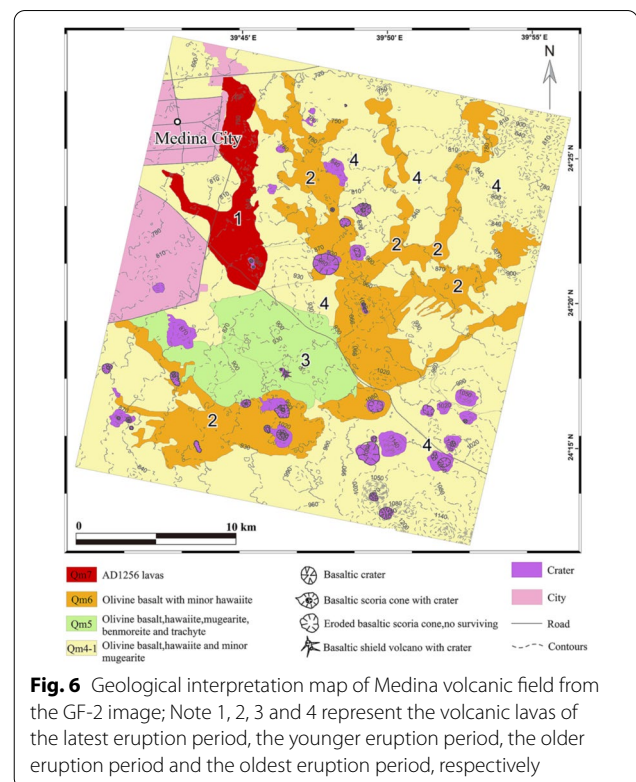


Fig. 6 Geological interpretation map of Medina volcanic field from the GF-2 image; Note 1, 2, 3 and 4 represent the volcanic lavas of the latest eruption period, the younger eruption period, the older eruption period and the oldest eruption period, respectively

to the Qm6: ~4500–1500 BP, which represents the younger volcanic lavas;

- 3) The bright green pattern (numbered 3) in Fig. 6, corresponding to the lighter green part (3 in Fig. 5), belongs to the Qm5: ~0.3 Ma-4500 BP, which represents the older volcanic lavas;
- 4) The bright yellow pattern (numbered 4) in Fig. 6, corresponding to the off-white part (4 in Fig. 5), belongs to the Qm1-4: ~1.7 Ma-0.3 Ma, which represents the oldest volcanic lavas.

Three-dimensional (3D) perspective view images of the AMVF

Two typical regions in north and south of the AMVF were selected to generate 3D perspective view images, as shown in Figs. 7, 8 and 9. These images were obtained by superimposing the GF-2 remote sensing image on the digital elevation model (DEM) data with stretching the elevation value at the same time. The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) data with a spatial resolution of 30 m were used here.

Two different volcanic lavas erupted in the north of the AMVF. The purple pattern is the latest volcano lavas from 1256 AD around Medina city. Partial of the city was built in this period of lava flows, for example the roads

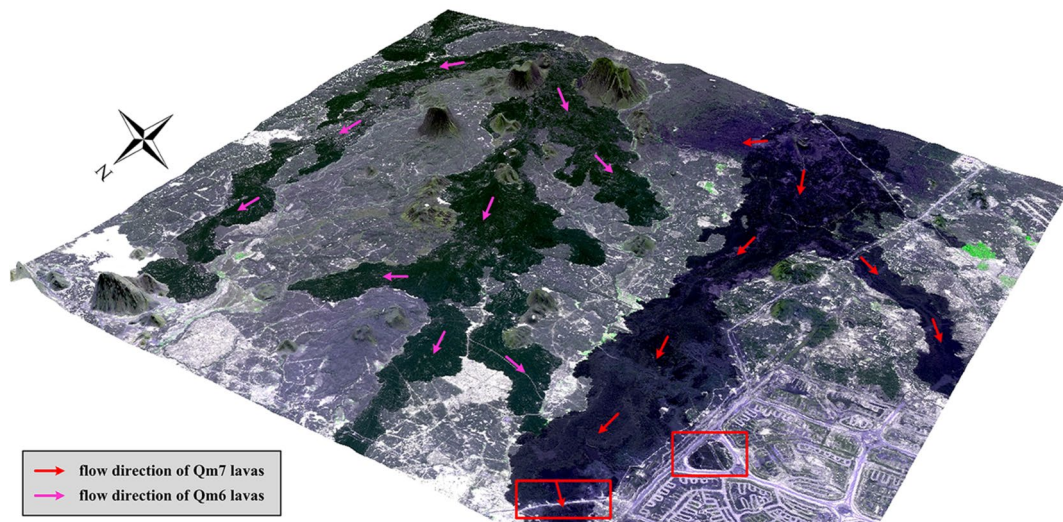


Fig. 7 3D perspective view image reveals the different eruption periods and the flows direction in the northwestern part of the AMVF (view: WN-ES)

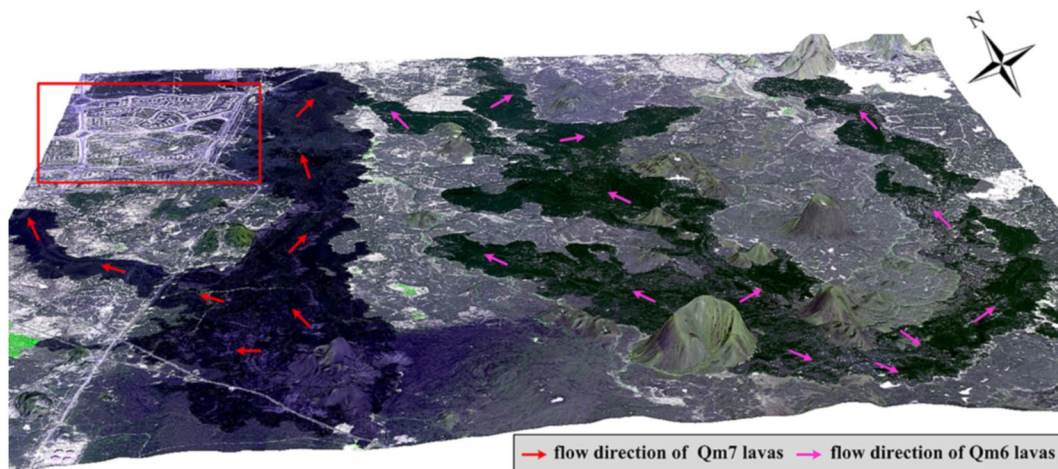


Fig. 8 3D perspective view image reveals the different eruption periods and the flows direction in the northwestern part of the AMVF (view: N-S)

are through these lava flows (as the red rectangles indicated in Figs. 7 and 8), indicating that human activities like urban expansion have caused damage and destruction to this volcanic geological site.

From the 3D perspective view image (Fig. 9), it can be observed that the multiple volcanic cones and multi-stage volcano lavas developed in the southern part of the AMVF. These different shaped volcanos are well-preserved. Moreover, because of the sparse vegetation, the coverage relationship among the volcano lavas generated in different eruption periods can be identified clearly, which is benefitting for future tourism viewing. Rare examples of white volcanoes comprised mainly of

the felsic rock commodity [9] can be seen clearly in some craters as shown in Fig. 9, which is a unique volcanic type among in the world.

Results

The pseudo-color synthesis of the Landsat-8 data shows that the volcanic lavas of AMVF can be divided into at least three periods: (1) the dark red part (marked by 1 in Fig. 4); (2) the black part (2 in Fig. 4) and (3) the lighter red part (3 in Fig. 4).

The geological interpretation map from the GF-2 image reveals that the AMVF had experienced multiple eruptions, and the exposed volcanic lavas appear in different

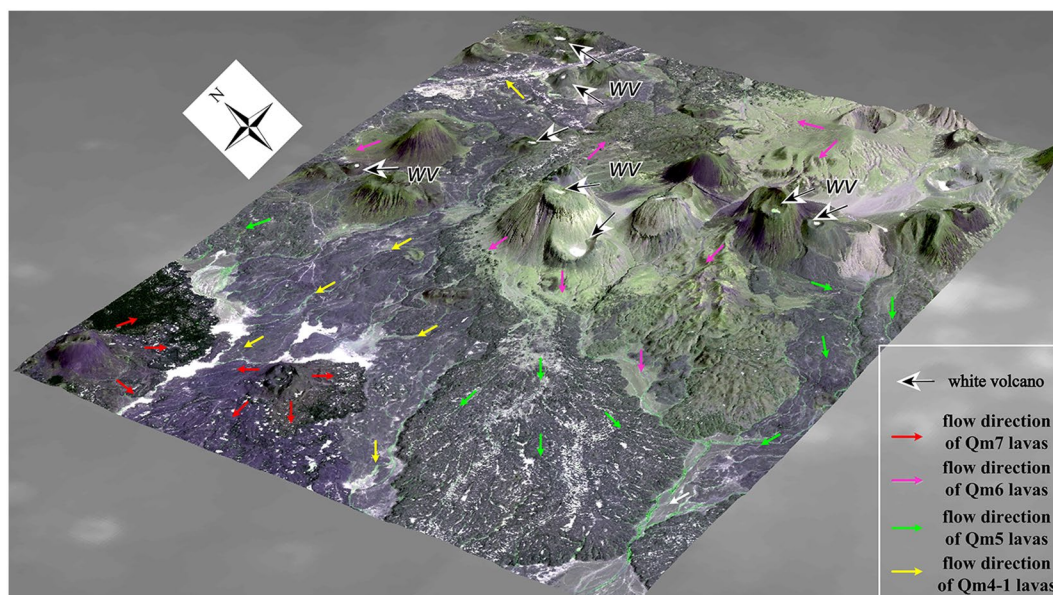


Fig. 9 3D perspective view image reveals the lava flows generated in different eruption periods and the flows direction in the southern part of AMVF (view: WS-EN); WV means white volcano

colors and forms after a long time of weathering. The lava flows produced from the latest eruption (Qm7) in the lava area are very close to Medina city, indicating that future volcanic eruption may have potential disaster risks to the city. In addition, partial Medina city located in this lava flows, also indicates that human activities like urban expansion had caused damage and destruction to this volcanic geological site. Therefore, the AMVF deserves more appropriate protection and management.

Discussion

The interpretation results of multi-source satellite images indicate that the AMVF in western Saudi Arabia has the potential and advantage to become a volcanic geopark for its uniqueness compared with other existing volcanic geoparks:

- 1) Tectonically, the Medina volcanic field is related to the hot rising mantle plume induced by the expansion of the Red Sea after the plate collision between Arabian and Eurasian Plates since the middle Miocene (Figs. 2, 3). Its geodynamic mechanism is entirely different from the back-arc volcanoes, such as the Japanese islands, and the intracontinental volcanoes, such as the Wudalianchi volcanoes in China [32]. The former is induced by the collision between oceanic and continental plates [25, 33], while the Wudalianchi volcanoes are formed by the deep subduction and dehydration of the west Pacific stagnant

slab, possibly through hot and wet upwelling in the big mantle wedge under the NE China [32, 34–37].

- 2) Concerning the volcanic landscape, the AMVF has developed abundant multi-phase volcano lava flows, including lave tubes, ropy pahoehoe lavas and aa-type lavas [38], as well as wholly preserved scoria cones and craters (as shown in Fig. 10a–d, respectively). Compared with the existing UNESCO's volcanic geoparks, such as Wudalianchi UNESCO Global Geopark [32] and Leiqiong UNESCO Global Geopark [39], the AMVF has not only kinds of well-conserved volcanic geological sites, but also striking volcanic landforms. Due to the sparse cover of vegetation, the lava flows from different eruption stages are well exposed on the surface, appearing in different colors and landforms. Moreover, the coverage relationship among the multi-stage volcanic lavas produced in different eruption periods is apparent, which makes AMVF a natural geological museum showing abundant volcanic landforms and aesthetic charm to the general public.
- 3) About the lithologic characteristics, there are rare and distinctive white volcanoes comprised mainly of the felsic rock commodity in AMVF, which is a unique volcanic type among the world and totally different from the existing volcanic geoparks. So it has international geological significance and unique scientific, aesthetic and tourism value.

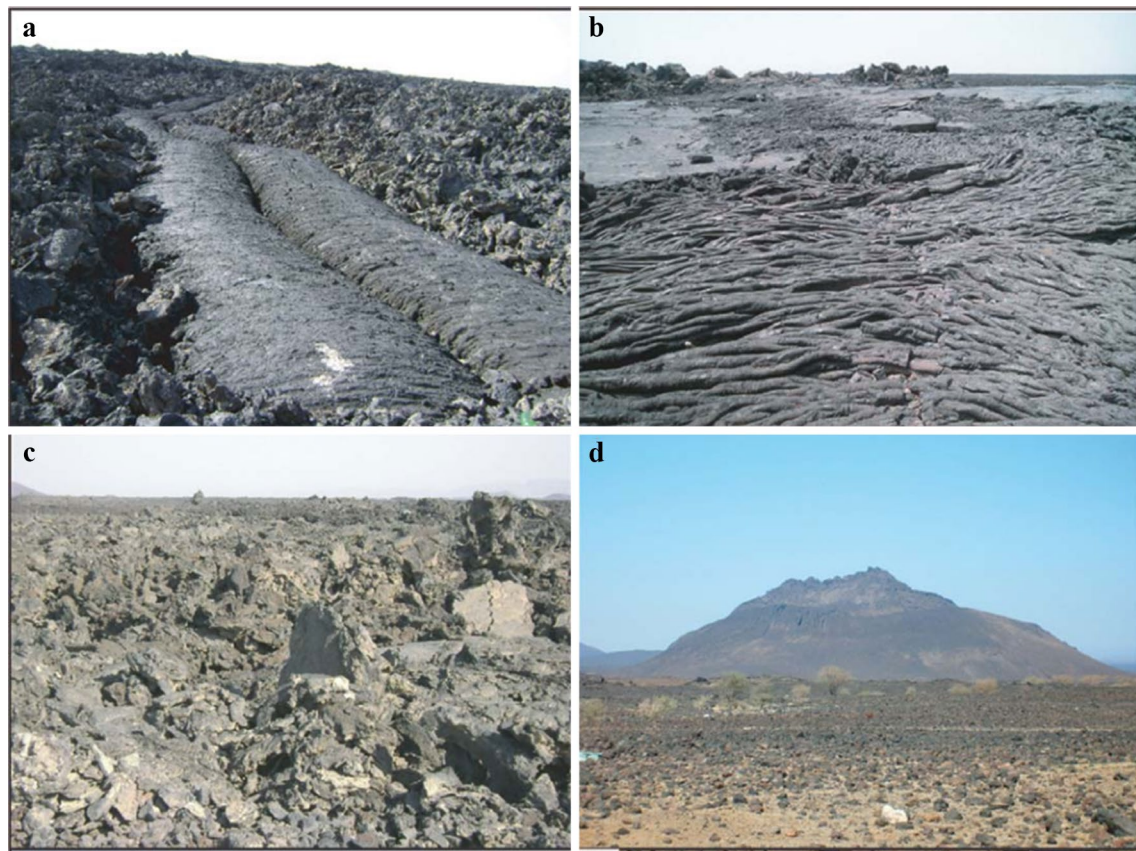


Fig. 10 Field photographs showing some volcanic landscapes of the AMVF: **a** lava tubes recorded within the eastern parts of Qm7; **b** ropy pahoehoe lava flows near the vent zone of the 1256 AD historic eruption; **c** aa-type lava flows of the 1256 AD historic eruption; **d** trachytic cone of Qm4. (The picture is from [6])

4) Concerning the volcanic hazard, AMVF is very close to the Medina city, the second holy city of Islam, which has convenient transportation and is suitable for the general public to visit and developing tourism, such as hiking trails, geotourism and volcano tourism, which is one of the sustainable human activities that the Global Geoparks Network is promoting. Moreover, the latest eruption of AMVF occurred in 1256 AD, ca. 765 years ago. Therefore, future possible volcano eruptions will have potential disaster risks to the urban development. Establishment of the UNESCO Global Geopark Project, for example setting protected boundaries (as suggested in Fig. 4), can not only prevent potential geological hazard risks to the people in Medina city from future volcanic eruptions, but also provide better protection and conservation to geoheritage sites from being damaged by urban expansion.

The comparative analysis of geological features between AMVF and other existing volcanic Global Geoparks are shown in Table 3.

To achieve a sustainable management and protection of AMVF, the local government and residents should exchange their opinions and experiences to create a protection regulation for this geoheritage. And then they are suggested to work together to have a comprehensive conservation status (such as establishment of National Park, Natural Park, Natural Monument or scenic area) and develop some tourism activities (such as hiking trails, geotourism, and volcano tourism) for the AMVF before the recognition by UNESCO as a Global Geopark.

Conclusions

The interpretations and analyses of geological and geomorphical features of volcanic fields based on multi-source remote sensing data can effectively identify the

Table 3 The comparative analysis of geological features between AMVF and other existing volcanic Global Geoparks

Volcanic geoparks	Tectonics	Landscape	Lithological characteristics
AMVF	The extension of the Rea Sea caused by the continental collision between the Arabian and Eurasian plates	Multi-stages lava flows with sparse vegetation	Basalt with rare white volcanos
Unzen volcanic area UGGP	The collision between oceanic and continental plates	Lava flows with sparse vegetation	Basalt
Wudalianchi UGGP	The deep subduction and dehydration of the west Pacific stagnant slab	Multi-stages lava flows with vegetation	Basalt
Leiqiong UGGP	The deep subduction and dehydration of the west Pacific stagnant slab	Multi-stages lava flows with vegetation	Basalt

scientific, aesthetic and tourism values of the potential volcanic Geopark. Furthermore, help to recognize the suitable location and boundary of the potential UNESCO Global Geopark Project. The results indicate that the AMVF in western Saudi Arabia has the potential and advantage to become a volcanic Geopark due to its unique international geo-scientific significance and rare natural value in geodynamic mechanism, volcanic landscape and lithological characteristics. Furthermore, the AMVF has great aesthetic appreciation to attract the general public and is suitable for developing tourism to promote the economic and social development. It is suggested that the Saudi Arabia government should formulate management measures to guarantee the geoheritage sites and landscapes will be managed with a holistic concept of conservation and sustainable development before declaring the AMVF as UNESCO Global Geopark Project.

Abbreviations

UNESCO: United Nations Educational, Scientific and Cultural Organization; MODIS: Moderate-resolution imaging spectroradiometer; OLI: Operational Land Imager; AMVF: Al-Medina volcanic field; MMN Line: Mecca-Medina-Nafud Volcano Line; NASA: National Aeronautics and Space Administration; TIRS: Thermal infrared sensor; NIR: Near infrared; SWIR: Short wave infrared; TIR: Thermal infrared; DEM: Digital elevation model; ASTER GDEM: Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model.

Acknowledgements

We appreciate editors and anonymous reviewers for their constructive suggestions and comments that help us significantly improve this paper's quality. Thanks Xiaochuan Qin, Jingxia Li and Jiaxin Du from the HIST natural heritage research group for their help to this study.

Authors' contributions

Conceptualization, B.F. and H.F.; methodology, H.F. and B.F.; formal analysis, H.F., P.S. and Y.Z.; resources, B.F.; data curation, H.F. and P.S.; writing-original draft preparation, H.F.; writing-review and editing, H.F. and B.F.; figures, H.F. and P.S.; visualization, H.F.; supervision, B.F.; funding acquisition, B.F. All authors read and approved the final manuscript.

Funding

This research was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (XDA051002) and the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (2019QZKK0901).

Availability of data and materials

The Landsat-8 remote sensing data used in this study are available in the <https://www.usgs.gov/>.

Declarations

Competing interests

The authors declare no conflict of interest.

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Received: 30 April 2021 Accepted: 7 October 2021

Published online: 10 November 2021

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