



Geomorphology of the Al Wahbah crater at Harrat Kishb west of the Kingdom of Saudi Arabia

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Abstract

The main objective of this research is to conduct a geomorphic study of the Al Wahbah crater located in Harrat Kishb, west of Saudi Arabia. The crater is considered as one of the well-known national tourist places, which attracted many visitors a year. This study handles the geomorphic framework of the crater to draw a digital elevation model. It is a step to designate slopes of the crater and its surroundings, as well as other morphometric characteristics. The lithologic units of the crater and its surroundings have been updated using geologic maps and SPOT 5 (2.5 m) satellite image. The research aims also at analyzing the deposits of the crater floor through mechanical analysis of the field-collected samples. In this process, the circular floor of the crater had been classified into two halves. Then, field samples were collected from the radius of the crater at three places apart from each other. The lab analyses include porosity and hydraulic conductivity. The results of analyzing these samples disclosed high percentages of porosity. The porosity of all samples is homogeneous as well in the samples collected from the three profiles of different depths. As well the mechanical analysis indicates a regular and homogeneous grain size distribution. The current study elucidates the impact of the mutual interaction between the natural variable forming the Al Wahbah crater geomorphic system. The interaction resulted in a dynamic and complex geomorphic system along with distinctive associations of landforms and surficial deposits. The study is considered among the pioneer research efforts that tackled the Al Wahbah crater from different scientific and applications perspectives.

Keywords Al Wahbah crater · Harrat Kishb · Caldera geomorphology · Sediments

Introduction

The Calderas are salient geomorphic landforms associated with the areas of volcanic landforms. The caldera represents not only a geomorphic landform of scientific importance but also attractive tourist places. Numerous calderas have been developed along the Arabian shield in the west of Saudi Arabia in response to the tectonic activities since early Tertiary times until the early Quaternary (Brown et al. 1989; Alwelaie 1996). One of these Calderas is the Al Wahbah crater, which is a circular volcanic cone with a 2-km diameter and 220-m depth. The crater is one of the most active 150 volcanic cones that form lava flows and deposits of Harrat Kishb (Fig. 1). The volcanic

flows in the west of Saudi Arabia are considered one of the largest volcanic fields in the world (Brown et al. 1989; Mirza 2008). They comprise alkaline olivine basalts, which vary in composition from acidic, intermediate, basic, to ultra-basic igneous rocks, as indicated from the spectral signatures of the various lava flows. These basaltic lava flows vary as well in their thicknesses, viscosities, and flow velocities (Camp et al. 1987). In response to their high resistance to erosional forces relative to the surroundings, the volcanic flows developed inverted topographic features in the Harrat regions of Saudi Arabia (Mirza, 2008). Except for the study that has been carried out by Mirza (2008), no other geomorphic studies have been conducted on the Al Wahbah crater. On the other hand, a good number of geologic studies were carried out on the Al Wahbah crater (Abdel Wahab et al. 2014; Moufti et al. 2013; Roobol et al. 2002; Camp et al. 1992; Brown et al. 1989; Roobol and Camp 1991a, b). These studies handled various geologic aspects, such as structural and tectonic settings, rock formations, and stratigraphy. None of these studies paid attention to the geomorphic aspects of the Al Wahbah crater. The principal

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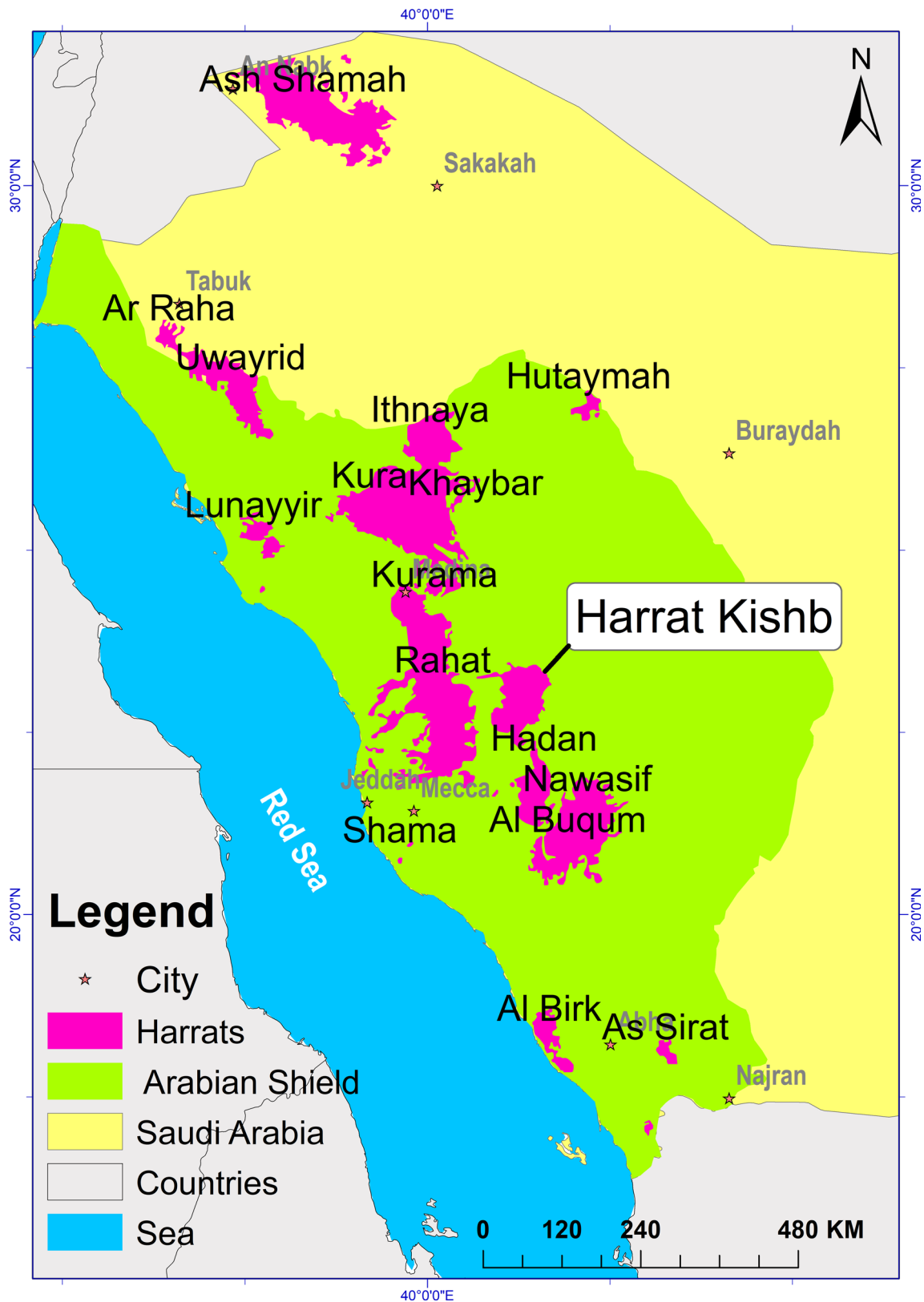


Fig. 1 Map showing the Cenozoic lava fields of Saudi Arabia (Roobol et al. 2002)

objective of this research is to investigate the geomorphic formation of the Al Wahbah crater using remote sensing,

topographic, geologic maps, and sedimentary lab analysis along with field investigations.



Fig. 2 Study area

Study area

The Al Wahbah crater is located in the west of Harrat (lava flow) Kishb northeast of the Al-Taif Governorate on a distance of 350 km (Fig. 2). The location of the Al Wahbah crater is normally accessed from the Umm Al-Dom district that is away from Al-Taif-Riyadh highway by ~ 50 km. The geographic location of Al Wahbah place is $41^{\circ} 09' E$ and $22^{\circ} 54' N$. The Al Wahbah crater is locally called the Tamiyya crater. Stratigraphically, the Al Wahbah crater belongs to Al-Hail mountain basalt which is the principal component of all the geomorphic features of Harrat Kishb. However, the crater can be categorized as recent sediments in the floor of the crater and old plutonic igneous rocks (granites), along the walls that surrounds the floor of the crater. The recent sedimentary rocks comprise loam, clay, and gypsum. On the other hand, the plutonic igneous rocks belong to the pre-Cambrian rocks along with quartz diorite and monzodiorite. The crater is surrounded by quaternary formations in form of volcanic eruptions mixed with volcanic lava, volcanic ash, and rock fragments with different shapes and sizes along with recent basaltic flows intervened with cracks that trend in various directions (Fig. 3).

The chemical analysis indicates that the majority of lava of the Harrat are the white and black lava whereas

the volcanic flows tends to be dark gray to glassy in their physical characteristics (Brown et al. 1989). The latter is younger than the former. However, the climatic conditions of the Pleistocene had influenced the geomorphic characteristics of the Al Wahbah crater area and all the western areas of Saudi Arabia as a whole (Abdel Wahab et al. 2014).

Hydrologically, the Al Wahbah crater is considered a local base level for all the hydrographic networks which are generally oriented from the northeast regions into the southwest. This is enhanced by the regional slopes and structural settings associated with the development of the Great African Rift.

Regarding the natural vegetation, the study area is one of the seventh plant regions that characterize the landscape of Saudi Arabia. Its distribution is greatly affected by the rainfall distribution in the Al Muwayh region as a whole. However, at the foot of the crater walls, collections of palm trees and other plants exist. The growth and existence of this vegetation assemblage is highly controlled by the hydrological potentials in the area. In addition, along the surroundings of the crater floor, many acacia species and different herbs flourish immediately after each rainfall event (Brown et al. 1989). On the eastern sides of the crater floor, many desert herbs and Arak (*Salvadora persica*) trees have grown while they disappear in the middle of the crater floor (Fig. 4).

Fig. 4 Some of plant species that characterize the Al Wahbah crater region (from the fieldwork on November 09, 2013)



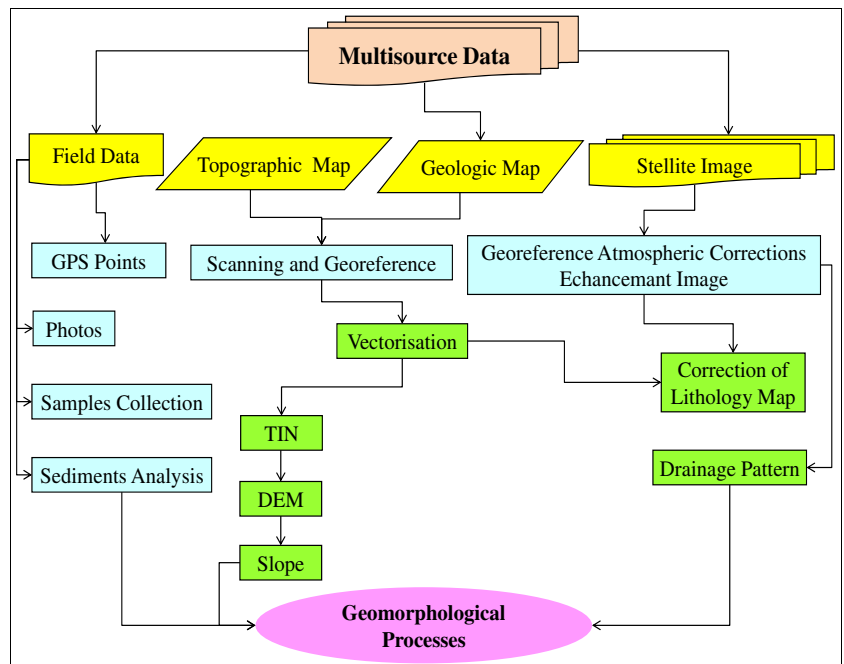
Materials and methods

The flow chart (Fig. 5) summarizes the overall methodology followed in this research.

Data and equipment

Data and equipment used in this research are presented in Tables 1 and 2.

Fig. 5 Flow chart of the study methodology



Production of a digital elevation model for the study area

The digital elevation model used in this study has been designed from the contour lines. The contour lines were digitized from the 1:50000 topographic maps. The elevation value of each contour line was entered in the feature attribute table. Finally, the GIS layer of the contour line had been georeferenced using ground control points with a

Table 1 The research data sources

No.	Type	Description	Notes
1	Data from Spot 5 Satellite	Higher resolution of 2.5	4 Band
2	Geologic Map of the Al Muwayh Quadrangle, Sheet 22E, the Kingdom of Saudi Arabia	Compiled by Mohammed Sahl and John W. Smith A.H. 1406, A.D. 1986	Scale 1:250000
3	Hafir Kishb Map Compiled from aerial photography dated 1973. First edition 1980. Field identification and completion 1979. Map produced by Clyde Surveys Ltd., under supervision of A.S.D	Executing Agency, Kingdom of Saudi Arabia, Ministry of Petroleum and Mineral Resources Aerial Survey Department (A.S.D.), Ar Riyad	Scale 1:50000
4	Aerial photo	No. 5990 – W3A -39	From 3.18.1956
5	GPS - 45 point	From Trimble	

georeferenced SPOT 5 image and spatial resolution of 2.5 m. The 3D analysis was then used to create the digital elevation model in the form of Triangulated Irregular Network (TIN). The created digital elevation model has been used to extract slope and topographic profiles for analyzing the topographic characteristics of Al Wahbah crater.

Digitizing the geologic map

Geologic formations were digitized from the geologic quarter million map to produce a GIS layer of geologic units. Some of such units were updated using visual interpretation of SPOT 5 satellite image. Table 3 presents the principal geologic formations that were identified from the available geologic map of the study area. A primary investigation of the geologic information implies a diversity of rock units in the study area that extend in age from Pre-Cambria to recent. However, the spatial extension of all rock units varies throughout the study area. Table 3 presents the spatial extent of each rock unit in the study area. Table 3 presents the various rock units in the study area and their spatial extension. As indicated, Hil formation nepheline hawaiite has the largest spatial extent in the order of ~41 km² accounting 29% of the study area. Wahbah formation, Young flows, and Olivine basalt rocks are considerably represented as well in the

Table 2 Equipment and software used in the study

No.	Description	Type	Notes
1	Erdas Imagine 2014	Software	Intergraph
2	ArcGIS 10	Software	Esri
3	GPS Pathfinder Office version 5.30	Software	Trimble
4	Graphics and Shapes Tools version 2.1.85	Software	Jeff Jenness
5	DEM Surface Tools version 2.1.399	Software	Jeff Jenness
6	Trimble GPS	Hardware	Trimble
7	A0 Scanner	Hardware	

order of 24.7, 20, and 19% respectively. All other rock formation and rock types have limited aerial representations.

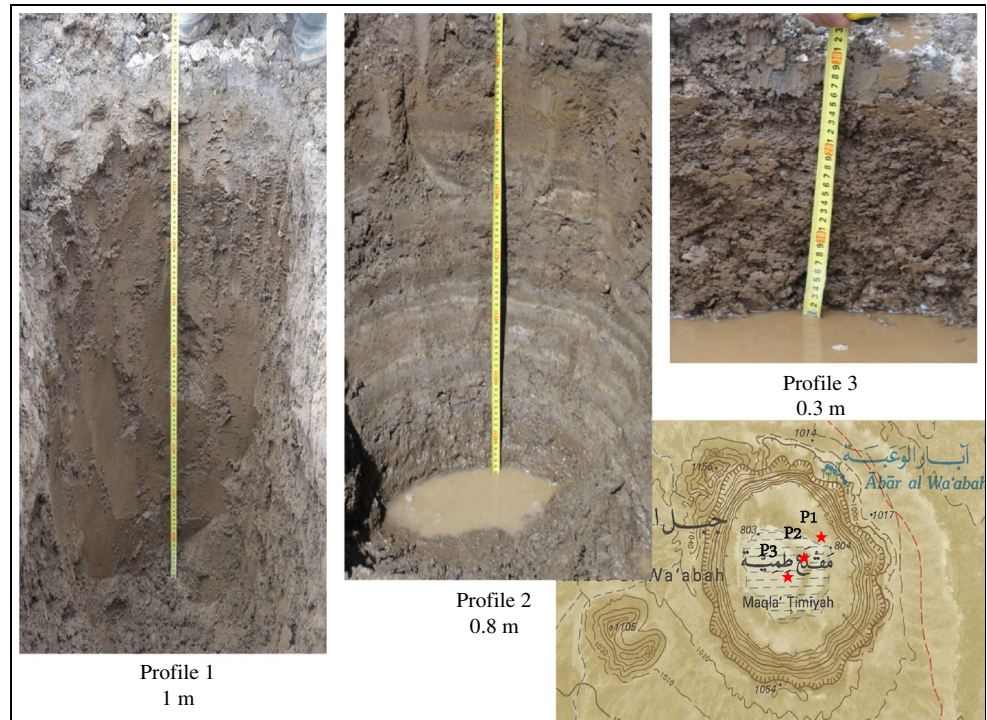
Field sampling

Field samples of sedimentary samples were collected from three selected profiles at depths 0.3, 0.8 and 1.0 m under the salty surficial layer. The profiles were located along the radius of the crater toward the center (Fig. 6). Various physical analyses were carried out such as porosity, hydrologic conductivity, and mechanical characteristics. Such analyses help in the determination of the nature of sedimentary components of the crater along with their textural and physical characteristics, as well as their relations to the geologic settings of the area for determining the geomorphological evolution.

Table 3 Lithologic units and rock formations of the study area along with their areas and percentages (based on Al Muwayh geologic map of scale 1:250000)

Description	Area/ km ²	%
Qu-Older sand and gravel deposits	0,267	0,188
QTku2 Old flowsbasanite and nepheline hawaiite	6066	4280
QTku1 earlier flows, basanite and nepheline hawaiite	2808	1981
Qsb Sabkha deposits Silt, clay and gypsum	4874	3439
Qm-Olivine basalt with minor hawaiite	19,338	19,647
Qkwe-Wahbah formation Pyroclastic rocks and minor lava	35,011	24,708
Qkuc-Cinder related to young flows	1813	1279
Qkub-Young flows, basanite and nepheline hawaiite	22,933	2008
Qkhh-Hil formation Nepheline hawaiite	40,974	28,916
Mir-Intermediate and minor mafic volcanic and volcaniclastic rocks	4142	2923
Dm-(+ mir Quartz) monzodiorite and quartz diorite	3470	2448

Fig. 6 Sedimentary profiles of the middle layer under the salty surficial crust



Results and discussion

It is deemed appropriate to handle the various morphometric characteristics, slope categories, dynamic aspects of geomorphic settings, and sedimentary composition.

Morphometric characteristics

The morphometric analysis of the Al Wahbah crater allows defining its shape through the determination of its dimensions,

perimeter, depth, and slopes (Srivastava and Varatharajan 2016; Degeai and Peulvast 2006). Analyzing both the external and internal edges in the north-south and east-west directions indicate that their dimensions are different. Elevation differences are in the order of 181 m in the north-south direction and 274 m in the east-west direction with a difference of 93 m. At the floor of the crater, the elevation difference between them

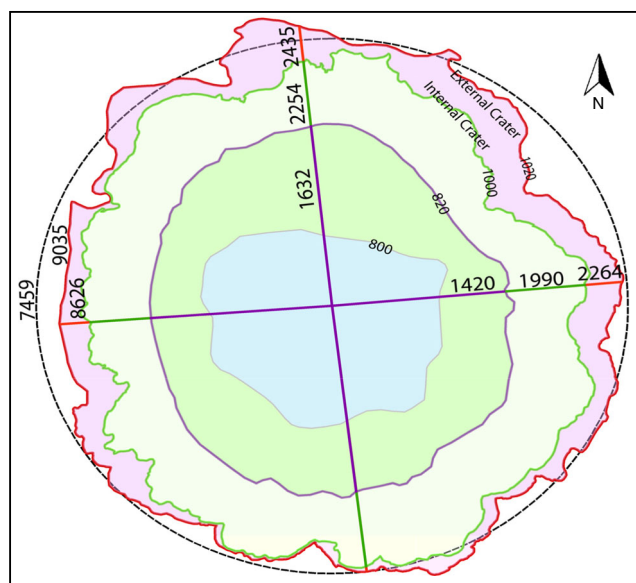


Fig. 7 Dimension and perimeter of the Al Wahbah crater

Table 4 The morphometric variables of Al Wahbah crater

Dimensions (meter)	North-south external edge of the crater	2435
	North-south internal edge of the crater	2254
Perimeter (meter)	External edge	9035
	Internal edge	8626
Area (km ²)	At elevation 800	0.669
	At elevation 820	1.823
	At elevation 1000	3.419
	At elevation 1020	4.122
Depth (meter) from previous studies	Topographic map of Harrat Kishb (1973)	220
	Brown et al. (1989)	270
	Mirza (2008)	> 270
	Saudi Geologic Survey	220
	Moufti et al. (2013)	~ 250
	Abdel Wahab et al. (2014)	250

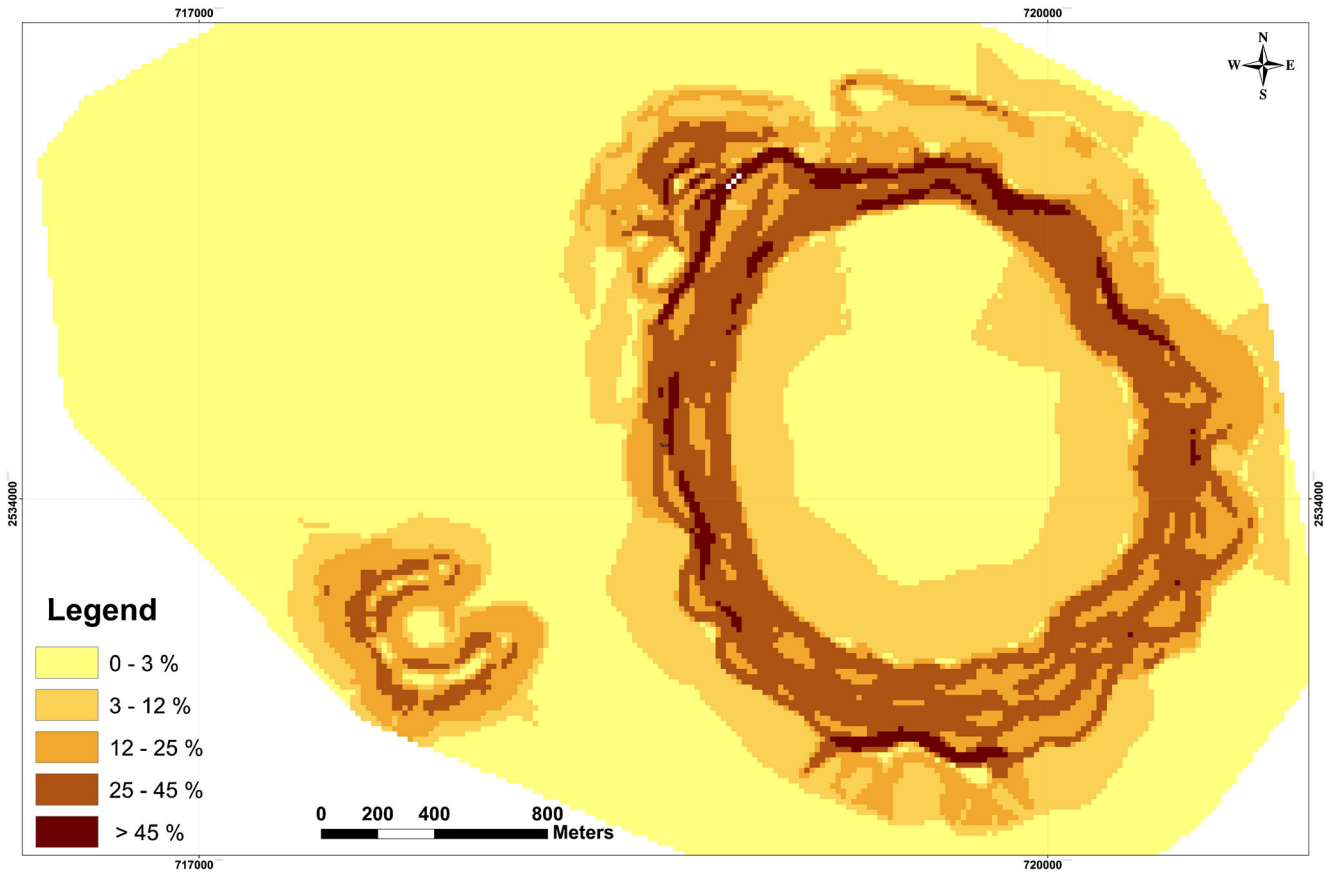


Fig. 8 Slopes of the Al Wahbah crater area

recorded 210 m. The perimeters vary also in the order of 408 m (Fig. 7). Regarding the area of the crater, it has been calculated at four levels from the floor to the summit peak of the crater. At the floor of the crater at an elevation of 800 m, the area of the crater is 0.67 km² with a low slope of 3%. A 20-m elevation (820 m) from the floor of the crater, the area enlarged triple times to become 1.8 km² with slopes ranging from 3 to 12%. At 200-m elevation from the floor of the crater at the internal edge, where the slope became steep in the order

of 25%, the area of the crater increased to be 3.42 km². At the external edge of the crater that is located at a 220-m elevation from the crater floor, the total area is 4.12 km².

Finally, the depth of the crater was 220 m based on the topographic maps of Harrat Kishb of scale 1:50000. Brown et al. (1989) recorded a 270-m depth of the Al Wahbah crater. Mirza (2008) states that the depth was higher than 270 m. However, the Saudi Geologic Survey Authority (2012) states that the depth of the Al Wahbah crater is 220 m. The last study on the Al Wahbah

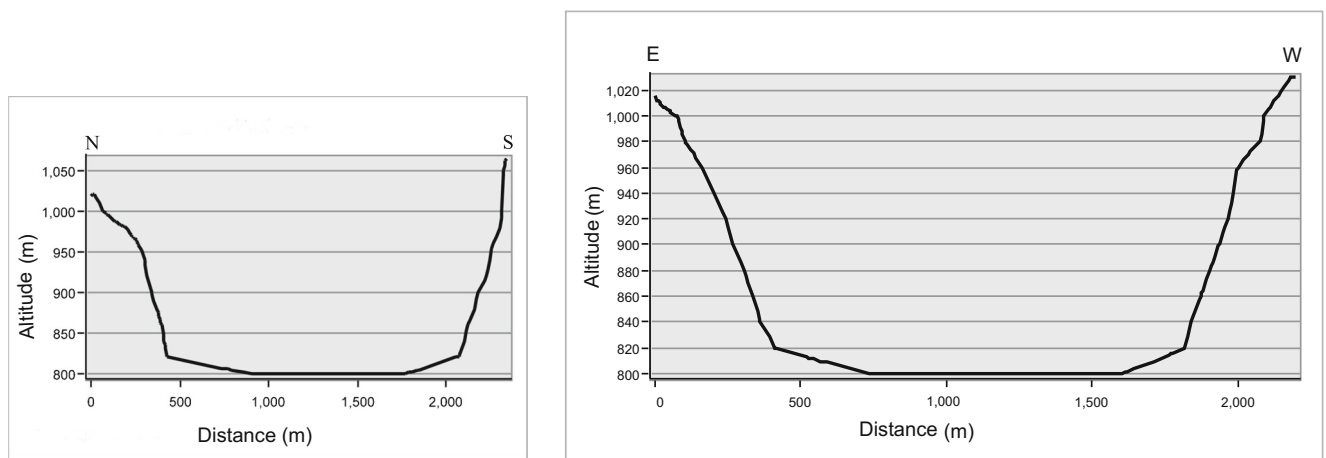


Fig. 9 Topographic profiles of the Al Wahbah crater: E-W to the right; N-S to the left



Fig. 10 Traces of the geomorphic dynamic aspects through weathering processes. **a** Chemical and biological weathering. **b** Mechanical fractures of basaltic rocks

crater that carried out by Abdel Wahab et al. (2014) estimated the depth of the Al Wahbah crater in the order of 250 m (Table 4). In attempt try to use google earth to explore the depth of the crater, it is found that the depth is in the order of 215 m.

Slopes

Slope is a principal variable that reflect highly the structure and evolution of the landscape. It controls surface runoff and dynamic nature of a given landscape. Mapping landscape slopes of a geographic area is considered a critical pre-requisite to secure the landscape from environmental hazards (Tricart 1965). The slope is an essential index that determines the dynamic and evolution of a landscape (Radoane et al. 1995; Kirkby and Bull 2000;

Vandekerckhove et al. 2000; Bou Kheir et al. 2001; Vanwalleghem et al. 2003, 2005; Valentin et al. 2005; Ionita 2006). According to Roose (1994), the length of the slope is less important than its shape and degree of inclination. When the degree of slope increases, the potential energy of running water remains stable but the sediment transfer is moving downwards. In the arid zones, the slope is positively associated with the surface coverage through mechanical fractures of rocks that leads to a decrease in the flow and a loss of surficial formations (Bou Keir et al., 2001). According to many scientific works, defining slope classes depends on the thresholds of geomorphic dynamic nature of the landscapes, from one hand, and on the geometry of landforms and landuse characteristics as well (Tricart 1965, 1978; Sari 1977; Gomer 1994; Roose 1994; Chaatal 1996;

Fig. 11 Erosional traces of the fossilized tufa layer and transportation of the erosional materials toward the floor of the crater

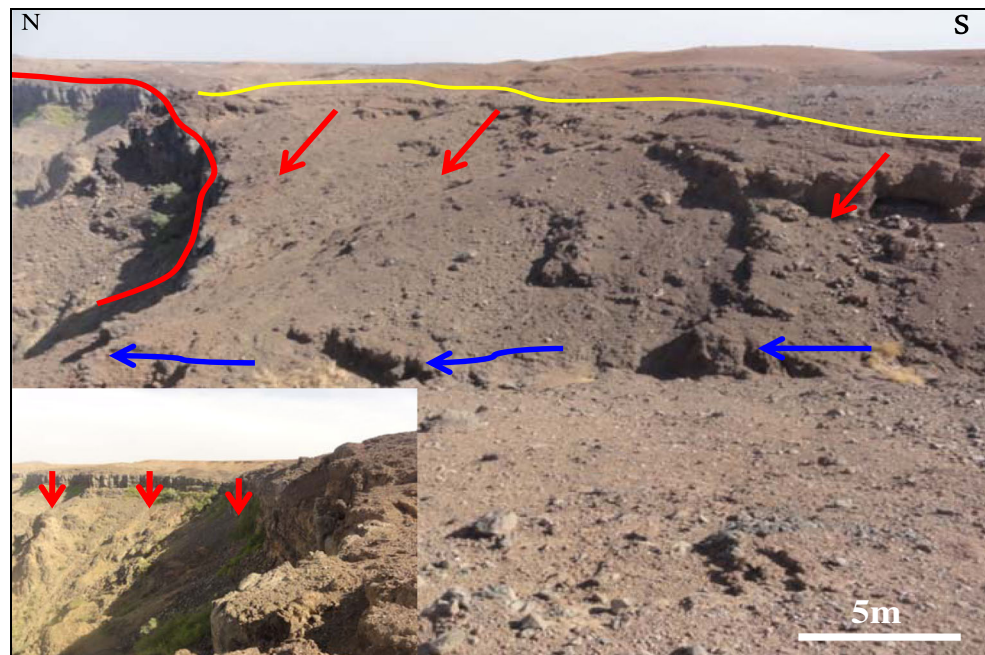
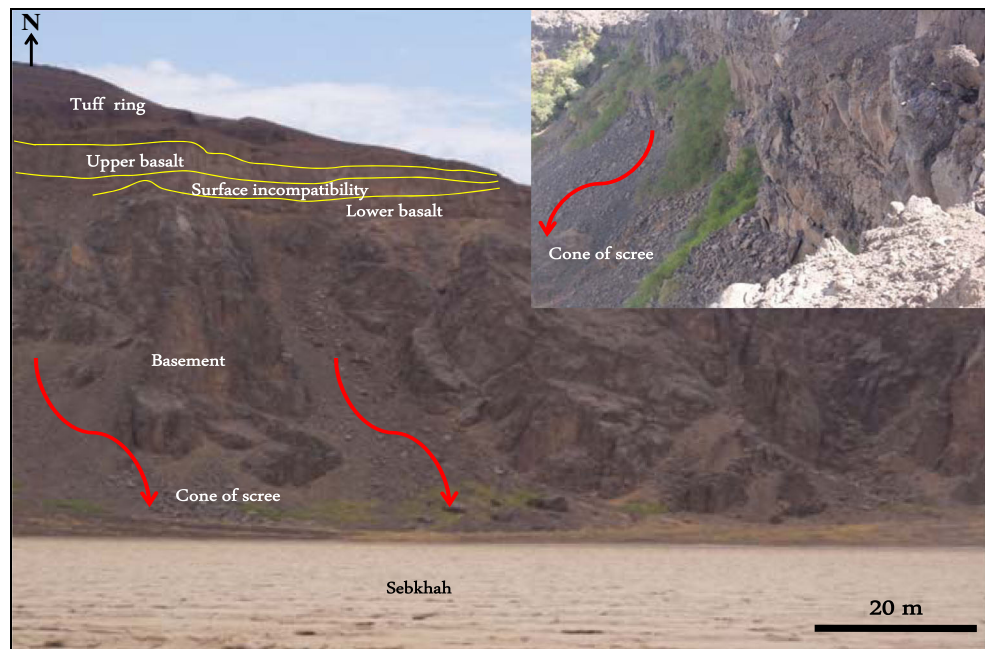


Fig. 12 Geologic profile of the volcanic eruptions overlain the edges of the Al Wahbah crater along with volcanic cones and slope talus



Bou Kheir et al. 2008; Daoudi 2008). In this research, the slopes of the Al Wahbah crater can be categorized into five classes (Fig. 8) which are:

- 0–3%

This category extends over 59% of the whole study area. It includes the floor of the crater, as well the areas outside the external edges.

- 3–12%

This category covers 18% of the whole study area. It occupies the initiation of the foot slope of the internal and external edges of the crater.

- 12–25%

This category covers 10% of the whole study area. It occurs as a transition area between the footslopes of the crater and its top areas. It narrows in the internal sides of the crater, whereas widen toward the external area of the crater, particularly in the western parts of the crater.

- 25–45%

This category covers 12% of the study area. This category comprises the footslope area and occupies the major parts of the internal edges and limited parts of the external northeast-ern areas of the crater.

- > 45%

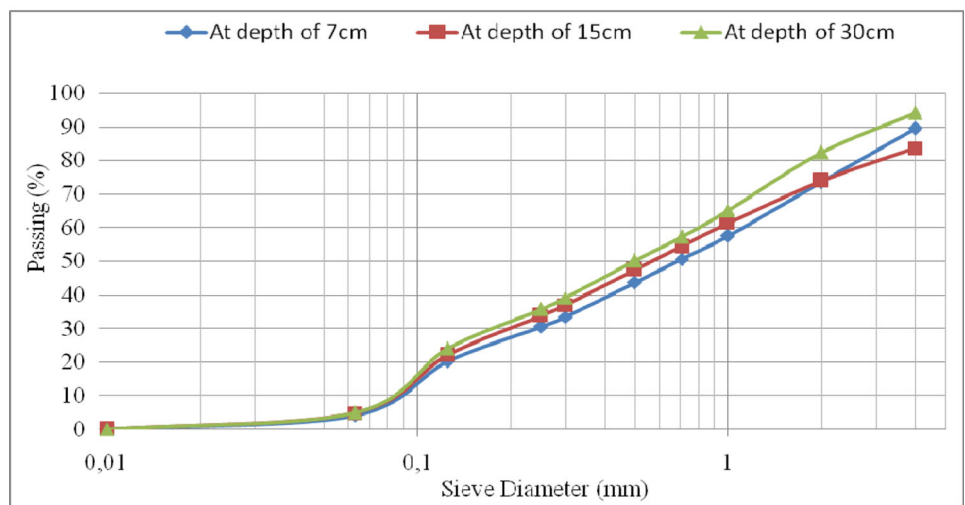
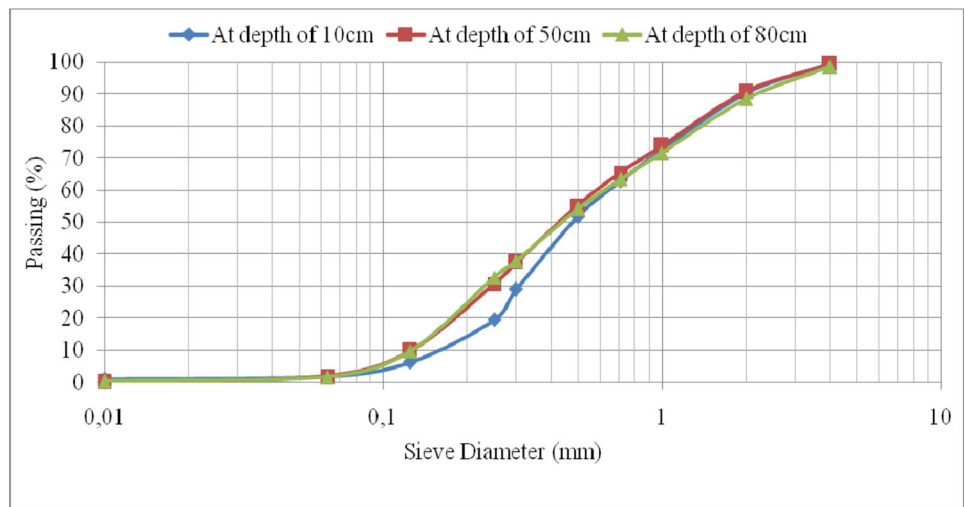
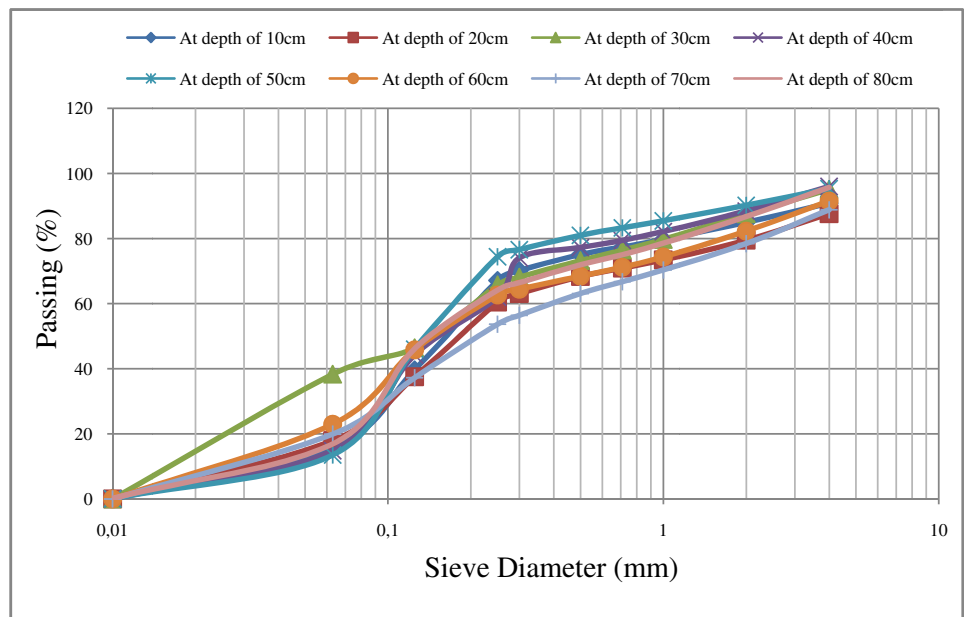
This category covers 1% of the study area. It includes the topographically rigid areas and cliffs along with scattered parts of the crater that is immediately located at the bottom, or at the external edges of the crater, in particular those located in the northeast and south of the crater.

It is also noticed that in the west of the main crater there is a small crater with a horseshoe shape. It is covered by the slopes of the first four categories. The external slopes of the Al Wahbah crater comprise the first two slope categories that range from 3 to 12%. These slope categories occupy extensive

Table 5 Variables of hydraulic conductivity and porosity of the three studied profiles

Profile No.	Sample depth (cm)	Porosity η (%)	Hydraulic conductivity (K) (cm/s)	Hydraulic conductivity (K) (m/day)
1	10	49.70727183	0.000443155	0.382886347
	20	51.54073677	0.004131576	3.569681565
	30	55.00394834	0.002445507	2.112917966
	40	52.55932841	0.007044397	6.086359052
	50	46.44777859	1.15741E-11	0.00000001
	60	46.95707441	0.144759162	125.0719155
	70	44.44059532	0.09466465	81.79025776
	80	46.44777859	0.060985164	52.69118183
2	10	52.8649059	1.15741E-11	0.00000001
	50	44.30873616	1.15741E-11	0.00000001
	80	50.11470848	1.15741E-11	0.00000001
3	7	49.09611685	1.15741E-11	0.00000001
	15	49.5035535	1.15741E-11	0.00000001
	30	49.40169434	0.024723898	21.36144795

Fig. 13 Grain size distribution analysis of mechanical deposits of the crater floor



areas around the Al Wahbah crater from all sides. Along with this, the slope category ranging from 12 to 25% are represented as well. This gradual change in the slope occurs outside the Al Wahbah crater except limited areas in the southwestern parts of the crater. On the other hand, this category occupies larger areas in the north, east, and south Al Wahbah crater.

Geomorphic dynamic aspects of the study area

Al Wahbah area consists of a group of stratigraphic units that comprise basically olivine basalt with a thickness of ~ 50 m. This olivine basalt belongs to Cenozoic times. It is overlain by the fossilized tufa deposits. Between both the olivine basalt and the tufa deposits, an erosional unconformable surface occurs. These stratigraphic units are underlain by the diorite and granite rocks that are of Pre-Cambrian origin (Mirza 2008; Abdel Wahab et al. 2014). These lithologic characteristics make the Al Wahbah crater qualified to be a dynamic geomorphically landscape through the geologic times and old climatic conditions that influenced Saudi Arabia (Sanlaville 1992; Thomas et al. 1998; Abdel Wahab et al. 2014). Reviewing multiple scientific sources indicates that the Al Wahbah crater has been evolving from the geomorphic perspectives. This is asserted by the piles of talus cones and rockfalls at the footslopes of the crater (Figs. 10 and 11). The amounts of detrital materials of the rockfalls referred to the strong erosional processes that act on the old weak rocks of the crater. It is possible that the geomorphic evolution is faster on the eastern and western sides located on the northern and southern areas of the crater. The variation in the values of the morphometric parameters could be attributed to the different scales of the geomorphic evolution as well. It is clear from Figs. 9, 10, and 11 that there are three slope forms which are regular slope, convex slope, and concave slope. In addition, the variability in the lithologic characteristics along with the slope values and shape has resulted in the dominance of the differential erosion in the Al Wahbah crater. In this process, the fossilized tufa rings and the mechanically fractured basaltic rocks have been strongly weathered through the geomorphic evolution of Al Wahbah crater.

In addition to the factors that control the dynamic nature of the Al Wahbah crater, the drainage systems played an essential role the geomorphic evolution of the Al Wahbah crater. There are two patterns of the drainage network, which are the centripetal and dendritic drainage networks. In the centripetal drainage ones, mass of water and sediments run toward the center of the crater floor from the surrounding high sides. The dendritic drainage networks occur in the drainage basins surrounding the Al Wahbah crater. However, the Al Wahbah crater is considered a local base level of a number of these surrounding drainage basins. Surface runoff of these drainage basins erodes and wastes the surficial deposits of tufa rings resulting in poor soil (Figs. 11 and 12).

Sedimentary analysis

The sedimentary processes in the Al Wahbah crater area is related with the dynamic of the geomorphic processes. The sediments of the floor of the Al Wahbah crater are the result of the various erosional processes that transported into the crater by both the fluvial and Eolian processes (Abdel Wahab et al. 2014). Table 5 presents the physical characteristics of the transported sediments into the Al Wahbah crater. The table shows the high porosity and homogeneity of sizes. These characteristics imply that these sediments have small sizes and high sorting of values and tend to have clayey texture.

The hydraulic conductivity analysis (Table 5) indicates that the samples from profile 1 ranged in their values from sand to loam with the exception of only one sample that belongs to clay range. On the other hand, all the samples from profile 2 belong to clay range only. Except of one sandy sample, all the samples from profile 3 belong to clay range as well. The hydraulic conductivity recorded a considerable increase as the depositional process increases by rate of 125.07 per day at the depth of 50 cm for the first profile. Samples from profile 2 and 3 have no hydraulic conductivity, except one sample on a depth of 30 cm from profile 3 which recorded a high value of the hydraulic conductivity. This high value is attributed to the homogeneity (sorting) and cube packing of the detrital grains. The mechanical analysis of grain size distribution using the hydrometer produces a regular S curve. This implies that the grain sizes of all samples are homogenous indicating a normal depositional process in the research area (Fig. 13).

Conclusion

The Al Wahbah crater is considered a salient geomorphic feature with a distinctive geologic structure and remarkable morphometric characteristics. The study asserted the interaction between the natural variables forming this geomorphic system and the driving forces that control the geomorphic processes. This interaction resulted in a dynamic geomorphic setting of the Al Wahbah crater, distinguished landforms and detrital sediments. This research activity could represent an outset for further geomorphic and geologic ones of Al Wahbah crater. Such studies will help enhancing the economic values of such sites in the west regions of Saudi Arabia for the purpose of initiating sustainable developments.

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