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Overview of the Cenozoic Geology of the Northern Harrat Rahat Volcanic Field, Kingdom of Saudi Arabia

Chapter R of
Active Volcanism on the Arabian Shield—Geology, Volcanology, and Geophysics of Northern Harrat Rahat and Vicinity, Kingdom of Saudi Arabia

U.S. Geological Survey Professional Paper 1862
Saudi Geological Survey Special Report SGS–SP–2021–1

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph to northwest, showing geologist conducting geologic mapping. Red, oxidized scoria in foreground was deposited from mafic vents just off image to right. Dark rocks in middle distance are blocky ʻaʻā lava flows of the basalt of Southern Fingers (unit bsof; 24.4±1.3 kilo-annum [ka]). Hills in center of image and to left along skyline are cluster of mafic vents of the undifferentiated vents (v) unit. Smooth, middle peak shows shallow-dipping layers of scoria and air-fall tephra. Craggy peaks to right make up one of series of vents that supplied lava to flows of the basalt of Southern Fingers (bsof). Photograph by Andrew Calvert, U.S. Geological Survey, 2014. Background image shows northern Harrat Rahat lava flows, maars, and lava domes. U.S. Geological Survey photograph by Andrew Calvert, January 25, 2012.

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Edited by Thomas W. Sisson, Andrew T. Calvert, and Walter D. Mooney

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Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

Abbreviations

$^{40}Ar/^{39}Ar$	argon-40/argon-39 method
A.H.	in the year of the Hijra
C.E.	Common Era
^{36}Cl	chlorine-36
GIS	geographic information system
ka	kilo-annum (or, thousand years ago)
K-Ar	potassium-argon
k.y.	thousand years
Ma	mega-annum (or, million years ago)
SGS	Saudi Geological Survey
USGS	U.S. Geological Survey

Chapter R

Overview of the Cenozoic Geology of the Northern Harrat Rahat Volcanic Field, Kingdom of Saudi Arabia

By Joel E. Robinson and Drew T. Downs

Introduction

The Harrat Rahat volcanic field, located in the west-central part of the Kingdom of Saudi Arabia, is one of the larger Cenozoic harrats (Arabic for "stony lava field") among the more than 17 harrats situated upon the Arabia Plate (Coleman and others, 1983). Harrat Rahat, which is a composite of four smaller, coalesced volcanic fields (Camp and Roobol, 1989), is about 50 to 75 kilometers (km) wide (east-west) and 300 km long (north-south), covering an area of about 20,000 square kilometers (km^2).

The map plate contained herein shows, at a scale of 1:100,000, the mapped volcanic geology of northern Harrat Rahat, which consists of the northernmost one-fifth of Harrat Rahat. Northern Harrat Rahat has an area of about 3,340 km^2, of which 2,567 km^2 is covered by Harrat Rahat volcanic rocks and deposits, and it encompasses more than 900 exposed vents (that is, craters, cryptodomes, maars, and scoria cones), 289 of which are isolated by younger volcanic deposits and have not been correlated with the 234 volcanic rock units distinguished by geologic mapping.

Northern Harrat Rahat is of special interest owing to its proximity to the city of Al Madinah al Munawwarah (hereafter, referred to as Al Madinah), which sits within, and is continuing to expand southward over, the north end of the volcanic field (Downs and others, 2018). Al Madinah is home to an expanding population, currently at more than 2 million residents, together with the intermittent addition of approximately 3 million pilgrims during Hajj and Umrah (religious visitations). The center of Al Madinah is less than 8 km from lava flows of the only confirmed historically documented eruption (unit bla; included in red-shaded area [eruptive stage 1] on plate), which occurred in 1256 C.E. (654 A.H.) (Al-Samhūdī, 1488; Camp and others, 1987; Camp and Roobol, 1991; Kereszturi and others, 2016; Murcia and others, 2017; Dietterich and others, 2018; Downs and others, 2018). Earlier prehistoric lava flows also encroached into the area of the present-day city limits, as demonstrated by volcanic rocks exposed widely throughout the city in roadcuts, parks, and excavations for new buildings, although no evidence has been found of any other than the 1256 C.E. lava having reached that area during times of human habitation.

Geologic mapping was undertaken by the U.S. Geological Survey (USGS) in collaboration with the Saudi Geological Survey (SGS) as part of a project entitled "An Agreement for Implementing a Volcano and Seismic Hazard Evaluation and Mitigation in the Al Madinah Region (Northern Harrat Rahat)." The features of primary interest within the map area are scoria cones, lava flows, lava domes, craters, and pyroclastic deposits from the Quaternary, which have compositions of basalt, hawaiite, mugearite, benmoreite, and trachyte (nomenclature from Cox and others, 1979). The geologic mapping was published by Downs and others (2019) on a single sheet at 1:75,000 scale and two detailed sheets at 1:25,000 scale, accompanied by detailed explanations of the geology. This report presents the geology on a single sheet (see plate) at 1:100,000 scale and provides condensed geologic explanations for the convenience of readers of this volume. Some minor errors of nomenclature and lava source regions that do not change fundamental interpretations have been corrected herein. Note that some geographic names used in this chapter (and on plate) may not exactly match those used elsewhere in this Professional Paper (specifically, some diacritical marks are omitted); however, they do match names used by Downs and others (2019), and they are internally consistent within this chapter and plate.

Physiography

Quaternary scoria cones, lava flows, lava domes, craters, and pyroclastic deposits in northern Harrat Rahat are concentrated along a main vent axis, a broad, north-northwest-trending ridge situated in the central part of the map area. This ridge, which marks the topographic crest of the volcanic field, stands about 300 meters (m) above its flanking valleys to the east, west, and north and was the locus of the most frequent eruptions of northern Harrat Rahat. A second subsidiary, more diffuse vent axis lies 5 to 10 km west of the main vent axis. Lavas flowed both eastward and westward from the main vent axis, as well as northward from its northern tip to form gentle slopes off the main vent axis.

The entire volcanic plain of northern Harrat Rahat has elevations of 700 to 900 m above sea level. Other scoria cones and lava domes are scattered throughout the map area, many of which rise more than 100 m above the main vent axis and its surrounding volcanic plain, reaching elevations as high as 1,400 m above sea level.

Access

In contrast to the densely urbanized city of Al Madinah, most of the map area is sparsely populated and contains few man-made structures. Farming communities and small towns are generally confined to valleys along the western and eastern margins of the volcanic field. Although access to most of the city is restricted to those of Muslim faith and appropriate permissions are required prior to traveling to, or sampling within, the city, access to the surrounding areas is relatively easy. Several major roadways run along the periphery of northern Harrat Rahat; one road cuts through and across the crest of the volcanic field, and a network of unpaved roads crosses the volcanic field. Most unpaved roads that cross the volcanic field are poorly maintained and require high-clearance 4-wheel drive vehicles; however, one well-maintained dirt road runs east-west near the southern border of the map area. The unvegetated nature of northern Harrat Rahat and its surrounding areas, coupled with the generally gentle topography, make hiking to areas of interest relatively easy. However, hiking on younger lava flows offers more of a challenge, as many of these retain the rubbly morphologies typical of ‘a‘ā lavas.

Previous Mapping

Reconnaissance mapping of Cenozoic volcanic fields of the Arabia Plate, including Harrat Rahat, was compiled by Coleman and others (1983) and Brown and others (1989). Harrat Rahat itself was mapped in stages during the 1980s as a series of eight 1:250,000-scale map sheets for the Saudi Arabian Deputy Ministry of Mineral Resources (Pellaton, 1981; Clark, 1981; Kemp and others, 1982; Camp, 1986; Ramsay, 1986; Sahl and Smith, 1986; Ziab and Ramsay, 1986; Moore and Al-Rehaili, 1989). Moufi (1985) mapped and described in detail the more evolved, silicic volcanic rocks of northern Harrat Rahat and presented many of the unit and place names used in this and other scientific reports. Camp and Roobol (1991) undertook new fieldwork, sample collection, and analyses, and they provided new interpretation of petrographic, geochemical, and geochronological data to create a 1:250,000-scale map that completely covered Harrat Rahat.

The Camp and Roobol (1991) geologic map subdivides Harrat Rahat into three formations; in order of emplacement, they are the Shawahit, Hammah, and Madinah basalts. The areal extents of these formations decrease with decreasing age, and the locus of volcanism generally shifts northward. Based on few radiometric age determinations, Camp and Roobol (1989, 1991) estimated the Shawahit basalt was emplaced from approximately 10 to 2.5 million years ago (Ma), the Hammah basalt from 2.5 to 1.7 Ma, and the Madinah basalt from 1.7 Ma to historical times. All of northern Harrat Rahat was assigned to the Madinah basalt except for scattered small shields that were interpreted to be exposures of the Hammah basalt, although the present study establishes those exposures as younger than 1.7 Ma.

Camp and Roobol (1989, 1991) compiled 25 potassium-argon (K-Ar) isotopic ages for Harrat Rahat, including 15 from Pellaton (1981) and Coleman and others (1983); in addition, Moufti and others (2013) presented 25 argon-argon ($^{40}Ar/^{39}Ar$) isotopic ages that redefined the basalts within northern Harrat Rahat. Notably, the number of $^{40}Ar/^{39}Ar$ ages has been greatly expanded by work of the current USGS–SGS effort, presented in this volume (Stelten and others, 2020, 2023; Stelten, 2021).

Methods

Fieldwork was conducted for a few weeks each year in 2014, 2015, 2016, and 2017, in the late fall or winter months. Probable contacts between volcanic rocks and deposits were identified in advance by examination of shaded relief images produced from digital elevations and from satellite photographic images in a geographic information system (GIS). The nature and veracity of contacts and their locations were then determined or verified in the field and, if necessary, modified using a mobile GIS system, along with sampling and identifying the volcanic products. Mapped units were then characterized, correlated, and distinguished by thin-section-petrographic, geochemical, paleomagnetic, and geochronologic studies. Downs and others (2018) and Stelten and others (2018) reported analytical methods for the geochemistry, paleomagnetism, and geochronology data collected. Paleomagnetic results are presented by Champion and others (2023). The entire whole-rock geochemical and geochronological datasets are available online (Downs, 2019; Stelten, 2021).

Geologic and Tectonic Setting

The Arabian Peninsula is on the Arabia Plate, which is bounded on the northeast by the Bitlis-Zagros suture zone, on the west and south by the Red Sea and Gulf of Aden spreading ridges, respectively, and on the northwest by the Aqaba–Dead Sea and East Anatolian transform boundaries. The eastern part of the Arabia Plate is covered by Phanerozoic platform sediments, whereas the western part is the exposed Proterozoic Arabian Shield (Camp, 1984; Stoeser and Camp, 1985; Gettings and others, 1986; Stern, 1994; Johnson and Stewart, 1995; Johnson, 2006; Stern and Johnson, 2010). The Arabia Plate began separating from the Africa Plate sometime between 30 and 25 Ma, although well-organized seafloor spreading magmatism commenced in the Gulf of Aden at only 10 Ma and in the Red Sea at 5 Ma (Calvert and Sisson, 2023).

Harrat Rahat is one of more than 17 large continental, intraplate volcanic fields hosted on the western part of the Arabia Plate (Coleman and others, 1983), with Cenozoic volcanism occurring during three general periods (summarized by Calvert and Sisson, 2023):

1. The oldest period is that of the Oligocene Yemen Traps, which are interpreted as partial-melting products from arrival of the Afar mantle plume that predated the onset of opening of the Red Sea and Gulf of Aden rift systems (Gass, 1970; Zumbo and others, 1995; Baker and others, 1996). The Yemen Traps correlate with the more voluminous and areally extensive traps of the Ethiopian highlands and parts of southeast Sudan.

2. The next period is that of a north-northwest-striking swarm of tholeiitic basalt dikes, gabbroic intrusions, and volcanic fields on the east side of, and parallel to, the Red Sea that were emplaced mainly in the latest Oligocene and earliest Miocene (Hughes and others, 1991; Bosworth and others, 2005). Emplacement of the dike swarm provides some of the evidence for the onset of extension that produced the Red Sea (Bosworth, 2015). Some early harrat volcanism took place during this period.

3. Finally, the last period is that of eruption of the dominantly alkali basaltic harrats, which commenced about 10 Ma, although their onset ages are not well documented. Onset of widespread late Cenozoic harrat volcanism coincided with, or shortly followed, uplift of the Hijaz–ʻAsir highlands along the east side of the Red Sea (Bohannon and others, 1989; Szymanski and others, 2016), development of seafloor spreading in the Gulf of Aden (Phillips, 1970; Cochran, 1983; Bosworth, 2015), and initiation of Aqaba–Dead Sea transform faulting (Bosworth and McClay, 2001; Bosworth and others, 2005). These were followed by development of seafloor-spreading magmatism in the central and southern Red Sea at about 5 Ma (Bosworth, 2015).

Volcanic-Rock Types

Eruptive products within northern Harrat Rahat encompass compositions that range from transitional and alkalic basalt to hawaiite, mugearite, benmoreite, and trachyte; the transitional basalts are distinguished from the alkalic basalts by a trace of normative hypersthene in the former and normative nepheline in the latter for analyses calculated with magmatically appropriate ferric iron concentrations (Sisson and others, 2023). These compositions, which are distinguishable by their K_2O versus SiO_2 contents (in weight percent) are determined herein (661 samples analyzed) to be transitional basalt (47.0–50.5% SiO_2; 0.2–1.1% K_2O), alkalic basalt (44.2–49.7% SiO_2; 0.2–1.7% K_2O), hawaiite (45.0–51.5% SiO_2; 1.3–2.0% K_2O), mugearite (48.0–55.5% SiO_2; 1.6–3.1% K_2O), benmoreite (54.8–59.9% SiO_2; 3.1–4.3% K_2O), and trachyte (59.9–65.4% SiO_2; 4.1–5.3% K_2O), for compositions normalized to 100 percent totals with ferric iron appropriate for the fayalite-quartz-magnetite oxidation state. By area, exposed rocks of northern Harrat Rahat are the following: basalts, 1,932 km^2 (75 percent of total area of volcanic rocks and deposits); hawaiites, 261 km^2 (10 percent); mugearites, 226 km^2 (9 percent); and benmoreites and trachytes, 123 km^2 (5 percent). Fewer than 5 percent of analyzed basalts from northern Harrat Rahat are transitional basalts, with the great majority classified as alkalic basalts. The absence of true tholeiites is a revision from Downs and others (2019). The pattern of alkalic basalt being more prevalent than transitional basalt also carries over into the nonbasalts, with nearly all the more evolved rocks being alkalic (Sisson and others, 2023). Basalts typically have phenocrysts of olivine and plagioclase. Hawaiites are usually distinguished by the additional presence of microphenocrysts of titanomagnetite; mugearites, by microphenocrysts of clinopyroxene and sporadic apatite joining the assemblage; and benmoreites and trachytes, by the presence of alkali feldspar phenocrysts and the loss of plagioclase.

Eruptive Styles

Eruptions of basalt, hawaiite, and mugearite were dominantly effusive, producing lava flows as long as or slightly longer than 20 km for basalts, but most of the basalt flows were 10 to 15 km long, and flows of the more evolved magma types were shorter still. Basalt and hawaiite flows consist of ʻaʻā and pāhoehoe lava about 10 to 15 m thick. Mugearite flows tend to be shorter (<10 km), broader, and thicker, and their surfaces can contain numerous hornitos or arcuate pressure ridges. Eruptions were of mainly Hawaiian and Strombolian styles, which resulted in scoria cones, spatter ramparts, and, for some transitional and alkalic basalts, small shield volcanoes. The numerous scoria cones are generally steep sided and can rise more than 100 m above the main vent axis and its surrounding, gently sloping volcanic field. Clusters and chains of cones result from fissure eruptions (for example, eruptions of units bcef and bla). Scoria cones generally are composed of scoria, vesicular and vitric bombs, lapilli, agglutinated spatter ramparts, and, locally, spindle bombs. Other than in the vicinity of scoria cones, tephra-fall deposits are rare. Less abundant shield volcanoes (for example, those of units bfa, bgh, bh89, and bhu) have gentle slopes of only a few degrees and can be as much as 4 km in diameter.

More silicic magmas (benmoreites and trachytes) commonly erupted in a Peléan manner, but sub-Plinian eruptions and cryptodomes are inferred to have occurred as well. These more silicic eruptions developed lava domes and spines that periodically collapsed and generated small-volume, juvenile-pumice- and lithic-rich pyroclastic deposits (for example, units trg, tg4, and tma). Sub-Plinian eruptions resulted in craters and moderately pumiceous pyroclastic deposits that are preserved as much as 9 km from their sources (for example, Moufti, 1985; Camp and Roobol, 1989; Stelten and others, 2018; Downs and others, 2019, 2023b). Cryptodomes, which are geomorphic features that have a lava dome-like morphology, can be more than 1 km in diameter and are uplifted more than 100 m high; they formed as evolved magma intruded into the near surface, where it spread beneath, and eventually uplifted, the older volcanic rocks. Four cryptodomes are recognized in the map area.

Eruptive History

The eruptive history of northern Harrat Rahat was interpreted in this study on the basis of geochronology, paleomagnetic analysis, and field mapping. Isotopic ages of eruption were determined for 115 volcanic units, of which 108 were dated by the $^{40}Ar/^{39}Ar$ method and 7 were dated by chlorine-36 (^{36}Cl) cosmogenic surface-exposure dating (Stelten and others, 2020, 2023; Stelten, 2021). Paleomagnetic field studies also were conducted on 173 sites in the volcanic field (Champion and others, 2023). Magnetic directions determined from these sites were used to correlate dated map units to geographically separate exposures or map units that have matching remanent-magnetic directions, thereby allowing eruptive ages to be assigned to disparate units that were not dated directy.

Dated and mapped volcanic deposits of northern Harrat Rahat have been assigned to 12 eruptive stages (1 being the youngest, and 12 being the oldest) (Downs and others, 2019). Resolution for the older stages is poor because of concealment by younger volcanic products and because erosion has obscured contacts between flows, so that some older map units are composites from multiple eruptions. Comparison of the total eruptive volume of northern Harrat Rahat—calculated on the basis of its volcanic relief, using the estimated volumes of volcanic products that were distinguished by mapping (Stelten and others, 2023)—indicates that, although perhaps as little as 20 percent of the eruptive products are accessible for study, the eruptive history of the last several hundred thousand years is exposed robustly.

The 12 eruptive stages, the boundaries of which have been placed at significant eruptive-frequency minimums, vary in duration and in numbers of assigned known eruptive events:

- Eruptive stage 12 consists of 6 recognized volcanic units erupted between 1,200 and 780 kilo-annum (ka). Eruptive stage 12 is the smallest eruptive stage by exposed areal extent, having only 47 km^2 of exposed volcanic rocks and deposits. It includes the oldest isotopically dated volcanic product in the volcanic field, an unnamed benmoreite lava, dated at 1,137.9±3.1 ka, that is too sparsely exposed to be mapped at publication scale.
- Eruptive stage 11 consists of 13 exposed and mapped volcanic units erupted between 780 and 570 ka, of which 12 are basalts and 1 is a mugearite. Eruptive stage 11 is the second smallest eruptive stage by exposed areal extent, having only 50 km^2 of exposed volcanic rocks and deposits.
- Eruptive stage 10 marks an increase in exposed units, having 33 mapped volcanic units erupted between 570 and 460 ka.
- Eruptive stage 9 suggests a significant increase in frequency of volcanism and area covered, having 51 mapped volcanic units erupted between 460 and 360 ka and making up 391 km^2 of exposed volcanic rocks and deposits.
- Eruptive stage 8 represents a relative lull in activity, having only 5 units erupted between 360 and 323 ka.
- Eruptive stage 7 consists of 16 units erupted between 323 and 260 ka, including 14 basalts, 1 benmoreite, and 1 trachyte.
- Eruptive stage 6 consists of at least 53 mapped units erupted between 260 and 180 ka, making this the stage that has the largest number of identified eruptions, as well as the largest exposed area, at 578 km^2.
- Eruptive stage 5, which consists of 36 units erupted between 180 and 100 ka, displays a distinctive spatial distribution when compared to previous eruptive stages, having had all mapped eruptions occurring along the main vent axis.
- Eruptive stage 4, which consists of 8 units erupted between 100 and 70 ka, was characterized by trachyte eruptions that were more frequent than in previous eruptive stages. No eruptions occurred in the volcanic field for 20 thousand years (k.y.) after this stage.
- Eruption stage 3 encompasses only 2 known eruptions between 70 and 45 ka.
- Eruptive stage 2 consists of 9 eruptions, 5 of which are basalt, 1 is hawaiite, and 3 are trachyte, that erupted between 45 and 11 ka. Within eruptive stage 2 is a cluster of small scoria cones and short lava flows dated at 13.3±1.9 ka that erupted geographically separate from the contiguous volcanic field, in what is now a western suburb of Al Madinah. Previous workers used historical records to interpret that these scoria cones (mapped as the basalt of Al Du’aythah, unit bdu) may have erupted in 641 C.E. (39 A.H.) (Camp and Roobol, 1989; Murcia and others, 2015), but this provisional age assignment is now known to be incorrect (Downs and others, 2018, 2023a; Stelten and others, 2020, 2023).
- Eruptive stage 1, which, at 11 to 0 ka, is the youngest eruptive stage, includes 2 units, (1) the trachyte spine and pyroclastic flows of the trachyte of Um Rgaibah (unit trg; fig. 1), dated at 8.19±2.25 ka (weighted mean of ^{36}Cl and $^{40}Ar/^{39}Ar$ ages) (Stelten and others, 2020, 2023; Downs and others, 2023b), and (2) the well-documented basaltic-lava-flow-and-vent complex of the basalt of Al Labah (unit bla), erupted in 1256 C.E. (654 A.H.).

Volcanic rocks from two older periods of volcanism also are shown on the map: these consist of Tertiary volcanic rocks (Miocene units Tbjj and Tbja), which cap mesas to the west and southwest of Al Madinah’s city center, and early Pleistocene volcanic rocks (units Qbra, Qbjs, and Qbhk) that flowed into the map area from neighboring Harrats Kurama and Khaybar (Harrat Kurama adjoins northern Harrat Rahat along its northeast side; the closest Harrat Khaybar vent is 30 km north-northeast of northern Harrat Rahat). Rocks from these older periods of volcanism were not examined in detail during this study.

Conclusions

Harrat Rahat, one of more than 17 harrats situated on the Arabia Plate, is a composite of four smaller, coalesced volcanic fields, and it is one of the larger Cenozoic harrats (Camp and Roobol, 1989). Geologic mapping, combined with isotopic dating, paleomagnetic investigations, and geochemistry, has resulted in identification of 234 volcanic units distinguishable at the scale of mapping, most of which are interpreted as the product of single eruptions. About 900 constructional vents (scoria cones and spatter ramparts) are exposed across northern Harrat Rahat, of which 289 have been surrounded by younger lava flows, isolating them

Figure 1. Photograph to southeast, showing lava dome and lava spine at peak of Um Rgaibah; dome, spine, and smooth slopes of peak are composed of the trachyte of Um Rgaibah (unit trg). Pyroclastic-flow deposits erupted from crater, now partly filled by lava dome and spine, blanket smooth slopes of peak; lava dome is 0.6 kilometers (km) wide and stands 65 meters (m) above slopes of peak, and lava spine towers more than 100 m above lava dome. Photograph by Andrew Calvert, U.S. Geological Survey, 2014.

from associated effusive products. The volcanic features of primary interest within northern Harrat Rahat include scoria cones, shield volcanoes, lava flows, lava domes, craters, and pyroclastic deposits from the Quaternary. These observable features, which cover an area of approximately 20,000 km^2, account for 20 percent of the total volume of this part of the harrat, the remaining volume being buried by these features visible at the surface. The volcanic products of the harrat range in composition from transitional basalt, alkalic basalt, hawaiite, mugearite, benmoreite, and trachyte (nomenclature from Cox and others, 1979). Isotopic ages of eruption were determined for 115 of the 234 volcanic units; 108 units were dated by the $^{40}Ar/^{39}Ar$ method, and 7 units were dated by ^{36}Cl cosmogenic surface-exposure dating (Stelten and others, 2023). The dated and mapped units within the volcanic field have been assigned to 12 eruptive stages (1 being the youngest, and 12 being the oldest), on the basis of periodicity of known eruptive events (Downs and others, 2019).

Northern Harrat Rahat is of notable interest because Al Madinah sits at the margin of, and is continuing to expand over, the north end of the volcanic field (Downs and others, 2018). Al Madinah is home to an expanding population, currently at more than 1.5 million residents, with the intermittent addition of approximately 3 million pilgrims. The center of Al Madinah is less than 8 km from lava flows of the only confirmed historically documented eruption, which occurred in 1256 C.E. (654 A.H.) (Al-Samhūdī, 1488; Camp and others, 1987; Camp and Roobol, 1991; Kereszturi and others, 2016; Murcia and others, 2017; Dietterich and others, 2018; Downs and others, 2018). However, the 1256 C.E. eruption is not the only eruption to produce lava flows that encroached on the city limits, as multiple prehistoric lava flows are exposed widely throughout the city in roadcuts, parks, and excavations for new buildings.

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DESCRIPTION OF MAP UNITS

[Surficial deposits are listed alphabetically by unit symbol. Quaternary volcanic rocks consist of undifferentiated vents (v), volcanic rocks of northern Harrat Rahat volcanic field, and volcanic rocks of Harrats Kurama and Khaybar (Harrat Kurama adjoins northern Harrat Rahat along its northeast side; the closest Harrat Khaybar vent is 30 kilometers (km) north-northeast of northern Harrat Rahat). Volcanic rocks of northern Harrat Rahat volcanic field are subdivided into 12 eruptive stages (stage 1, youngest; stage 12, oldest); within each eruptive stage, units are listed alphabetically by unit symbol; first letter of unit symbol indicates composition of unit (b, basalt; h, hawaiite; m, mugearite; o, benmoreite; t, trachyte). Volcanic rocks not associated with northern Harrat Rahat volcanism are subdivided into volcanic rocks of Harrats Kurama and Khaybar (units Qbhk, Qbjs, and Qbra) and Tertiary volcanic rocks (units Tbja and Tbjj); these units also are listed alphabetically by unit symbol. Undifferentiated Precambrian rocks are labeled as pЄ. Basalts that have chemical analyses are termed either “alkalic basalt” or “transitional basalt,” whereas those that lack chemical analyses are termed simply “basalt.” Unit descriptions that lack phenocryst information had no representative hand sample or thin sections. Unit names and ages are modified from Downs and others (2019); full unit descriptions are available in Downs and others (2019) and Robinson and others (2019), as are identifications of any tiny, unlabeled polygons. Note that some geographic names used in this chapter (and on plate) may not exactly match those used elsewhere in this Professional Paper (specifically, some diacritical marks are omitted); however, they do match names used in Downs and others (2019), and they are internally consistent within this chapter and plate. Other abbreviations: ^{40}Ar/^{39}Ar, argon-argon; ka, kilo-annum, or thousand years ago; m, meter]

SURFICIAL DEPOSITS

al — **Modern alluvium (Quaternary)**—Fine sand, cobbles, and boulders, in present-day drainages. Derived from surrounding volcanic and Precambrian rocks. Concentrated around periphery of northern Harrat Rahat

Qal — **Alluvium (Quaternary)**—Alluvium, colluvium, loess, and mud-flat and sabkha (Arabic for “salt flat”) deposits. Present as mud-flat and sabkha deposits around periphery of northern Harrat Rahat, as alluvial fans and colluvium, and as pockets of loess in low-lying areas

QUATERNARY VOLCANIC ROCKS

v — **Undifferentiated vents (Quaternary)**—Isolated, undifferentiated vents (scoria cones, spatter ramparts, and craters) of transitional and alkalic basalt, hawaiite, and mugearite. Vents, which are not associated with any mapped units, are scattered throughout northern Harrat Rahat. Aphyric or contains phenocrysts of plagioclase and olivine. One vent has ^{40}Ar/^{39}Ar age of 986.2±10.7 ka, but most could not be dated

VOLCANIC ROCKS OF NORTHERN HARRAT RAHAT

Eruptive Stage 1 (0 to 11 ka)

bla — **Basalt of Al Labah (Holocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very rough relief; pressure ridges, channels, levees, and inflated surfaces. Flows emanate from 2.2-km-long fissure vent composed of scoria cones, craters, and spatter ramparts. Contains phenocrysts of plagioclase and olivine. Youngest eruption in northern Harrat Rahat; erupted in 1256 C.E. (654 A.H.)

trg — **Trachyte of Um Rgaibah (Holocene)**—Trachyte lava dome and pyroclastic-flow deposits composed of abundant, poorly inflated juvenile clasts. Contains phenocrysts of potassium-rich feldspar and clinopyroxene. Lava dome (0.6 km in diameter) and summit lava spine fill eruption crater

Eruptive Stage 2 (11 to 45 ka)

bcef — **Basalt of Central Finger (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very rough relief; pressure ridges, channels, and levees. Flows emanate from 1.9-km-long fissure vent composed of craters that have spatter ramparts. Contains phenocrysts of plagioclase and olivine

bdu — **Basalt of Al Du’aythah (late Pleistocene)**—Two small-volume, ‘a‘ā alkalic basalt lava flows, subdued relief; pressure ridges; four scoria cones. Contains phenocrysts of plagioclase and olivine

bdw — **Basalt of Ad Duwaykhilah (late Pleistocene)**—‘A‘ā and minor pāhoehoe alkalic basalt lava flows, rough relief; pressure ridges, channels, and levees. Flows emanate from two scoria cones composed of nine craters. Contains phenocrysts of plagioclase and olivine bnof **Basalt of Northern Fingers (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, rough relief; pressure ridges, channels, levees, and inflated surfaces. Scoria-cone complex is 0.7 km long. Contains phenocrysts of plagioclase and olivine

bsof **Basalt of Southern Fingers (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very rough relief; pressure ridges, channels, and levees. Fissure vent extends 2.9 km and has multiple craters and spatter ramparts. Contains phenocrysts of plagioclase and olivine

hkh **Hawaiite of Khamisah (late Pleistocene)**—‘A‘ā and minor pāhoehoe hawaiite lava flows, rough to moderate relief; pressure ridges, channels, and levees; breached scoria cone. Aphyric

td1 **Trachyte of Dabaa 1 (late Pleistocene)**—Trachyte lava dome surrounded by block-and-ash-flow deposits and proximal air-fall-tephra deposits; pyroclastic deposits consist of abundant, dense juvenile clasts. Lava dome uplifted units bd1 and md1. Contains phenocrysts of potassium-rich feldspar

tmo **Trachyte of Mouteen (late Pleistocene)**—Trachyte lava dome and pyroclastic-flow deposits. Lava dome (0.8 km in diameter) and smaller crater near summit partly fill eruption crater. Lava dome uplifted unit hmo. Pyroclastic deposits consist of abundant, poorly inflated juvenile clasts. Contains phenocrysts of potassium-rich feldspar

twa **Trachyte of Al Wabarah (late Pleistocene)**—Trachyte pyroclastic-flow deposits consisting of abundant, poorly inflated juvenile clasts. Sourced from crater (0.4 km in diameter). Contains phenocrysts of potassium-rich feldspar and clinopyroxene

Eruptive Stage 3 (45 to 70 ka)

bms **Basalt of Musawda’ah (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt and hawaiite lava flows, very rough relief; pressure ridges, channels, and levees. Erupted from single scoria cone that has spatter ramparts. Contains phenocrysts of plagioclase and olivine

han3 **Hawaiite of Al Anahi 3 (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt and hawaiite lava flows, very rough relief. Scoria cone has two craters. Contains phenocrysts of plagioclase and olivine

Eruptive Stage 4 (70 to 100 ka)

bsk **Basalt of Sha’ib Al Khakh (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very rough relief; pressure ridges, channels, levees, and inflated surfaces. Two scoria cones are 0.2 and 0.6 km long. Contains phenocrysts of plagioclase and olivine

bsu **Basalt of As Suddiyah (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Scoria-cone complex (1.4 km long) has 14 craters. Contains phenocrysts of plagioclase and olivine

han2 **Hawaiite of Al Anahi 2 (late Pleistocene)**—‘A‘ā and minor pāhoehoe hawaiite lava flows, very rough relief; pressure ridges, channels, levees, and inflated surfaces. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine

mh11 **Mugearite of Hill 1125 (late Pleistocene)**—‘A‘ā and pāhoehoe hawaiite and mugearite lava flows, very rough relief; pressure ridges, channels, levees, and inflated surfaces. Erupted from single scoria cone. Contains olivine phenocrysts

tef **Trachyte of Al Efairia (late Pleistocene)**—Trachyte pyroclastic-flow and -surge deposits. Sourced from two craters (1.8 and 0.8 km in diameter). Contains phenocrysts of potassium-rich feldspar and clinopyroxene within abundant, poorly inflated juvenile clasts. Lithic clasts include previously erupted basalt, hawaiite, mugearite, and benmoreite lavas, as well as Precambrian rocks

tg2 **Trachyte of Gura 2 (late Pleistocene)**—Two trachyte pyroclastic-flow deposits. Sourced from two nested craters (0.6 and 0.8 km in diameter). Contains phenocrysts of potassium-rich feldspar and clinopyroxene within abundant, poorly inflated juvenile clasts

tg4 **Trachyte of Gura 4 (late Pleistocene)**—Trachyte pyroclastic-flow and air-fall-tephra deposits. Sourced from crater (0.5 km in diameter). Contains phenocrysts of potassium-rich feldspar and clinopyroxene within abundant, poorly to moderately inflated juvenile clasts. Lithic clasts include previously erupted basalt, hawaiite, mugearite, and benmoreite lavas

tg5 **Trachyte of Gura 5 (late Pleistocene)**—Trachyte pyroclastic-flow deposits. Sourced from crater (0.2 km in diameter). Cryptodome (0.3 km in diameter) uplifted part of unit. Contains phenocrysts of potassium-rich feldspar within abundant, poorly to moderately inflated juvenile clasts

Eruptive Stage 5 (100 to 180 ka)

bar **Basalt of Abu Rimthah (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief; breached scoria cone. Contains phenocrysts of plagioclase and olivine

bdy **Basalt of Ad Dubaysiyah (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic basalt lava flows, subdued relief; pressure ridges, channels, levees, and inflated surfaces. Vent complex (3.4 km long) has single scoria cone and 14 craters and spatter ramparts. Contains olivine phenocrysts

bh10 **Basalt of Hill 1066 (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, very rough relief; pressure ridges, channels, and levees. Vent complex has seven craters and spatter ramparts. Contains phenocrysts of plagioclase and olivine

bjb **Basalt of Al Janubi (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic basalt lava flows, subdued relief. Aphyric

bka **Basalt of Al Khanaq (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, subdued relief. Contains phenocrysts of plagioclase and olivine

bm2 **Basalt of Al Malsaa 2 (late or middle Pleistocene)**—Alkalic basalt lava flows. Source is scoria cone that has two craters. Aphyric

bmat **Basalt of Mahd Adh Thahab Road (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very rough relief; pressure ridges, channels, levees, and inflated surfaces. Flows emanate from substantially eroded scoria-cone complex. Contains phenocrysts of plagioclase and olivine

bmz **Basalt of Al Muzayyin (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief; inflated surfaces. Flows emanate from cluster of scoria cones and spatter ramparts. Contains phenocrysts of plagioclase and olivine

bna **Basalt of Nabta (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief. Scoria-cone complex (0.8 km long) has five craters. Contains phenocrysts of plagioclase and olivine

bnar **Basalt north of Abu Rimthah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, rough relief; pressure ridges and inflated surfaces. Flows emanate from cluster of scoria cones

bns **Basalt of Nashbah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, moderately rough relief. Flows emanate from breached cluster of scoria cones

bnu **Basalt of Nubala (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately subdued relief. Contains phenocrysts of plagioclase and olivine

bra **Basalt of Al Rafi’ah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt, very subdued relief. Cluster of scoria cones (0.8 km long) has four craters. Contains phenocrysts of plagioclase and olivine

brt **Basalt of Radio Tower (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued and heavily eroded relief. Flows emanate from cluster of scoria cones. Contains phenocrysts of plagioclase and olivine

bsas **Basalt of Shai’ab Abu Sikhbir (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, rough to moderately rough relief; channels, levees, and inflated surfaces. Vent destroyed during uplift of lava dome of unit td1. Contains phenocrysts of plagioclase and olivine

bsb **Basalt of Sha’ib Banthane (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief. Contains phenocrysts of plagioclase and olivine

bsi **Basalt of Sha’ib Iskabah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine. Ground cracks that break lava-flow surface are interpreted to have formed during eruption of unit bsof

bsq **Basalt of Ash Suqayyiqah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately subdued relief. Scoria-cone complex (0.8 km long) has four craters. Aphyric

bun **Basalt of Umm Nathilah (late Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately subdued relief. Scoria-cone cluster (0.9 km long) has four craters. Contains phenocrysts of plagioclase and olivine

bwar **Basalt west of Abu Rimthah (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic basalt lava flows, very subdued relief. Flows emanate from eroded scoria cone. Contains olivine phenocrysts

bwm **Basalt west of Matan (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief. Contains phenocrysts of plagioclase and olivine

bza **Basalt of Az Zanat (late Pleistocene)**—‘A‘ā and pāhoehoe basalt, rough relief. Erupted from single scoria cone

han1 **Hawaiite of Al Anahi 1 (middle Pleistocene)**—Pāhoehoe hawaiite lava flows, subdued relief. Scoria cone has two craters. Contains phenocrysts of plagioclase and olivine har **Hawaiite of Abu Rimthah (middle Pleistocene)**—‘Aʻā and pāhoehoe hawaiite lava flows, subdued relief. Flows emanate from two scoria cones. Contains plagioclase phenocrysts

hd2 **Hawaiite of Dabaa 2 (late or middle Pleistocene)**—‘Aʻā and minor pāhoehoe hawaiite lava flows, rough relief; pressure ridges; breached scoria cone. Covers cryptodome (0.8 km in diameter) that uplifted younger flows of this unit. Contains phenocrysts of plagioclase and olivine

hlh **Hawaiite of Al Lihyan (middle Pleistocene)**—‘Aʻā and pāhoehoe hawaiite and alkalic basalt lava flows, very rough relief; pressure ridges, channels, and levees. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine

hm3 **Hawaiite of Al Malsaa 3 (middle Pleistocene)**—Pāhoehoe and ‘aʻā hawaiite and alkalic basalt lava flows, subdued relief. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine

md1 **Mugearite of Dabaa 1 (late Pleistocene)**—‘Aʻā and pāhoehoe alkalic basalt, hawaiite, mugearite, and benmoreite lava flows, very rough relief. Vent disturbed when it was partly uplifted by domes of units td1 and tg2. Contains phenocrysts of plagioclase, olivine, and clinopyroxene

mma **Mugearite of Matan (middle Pleistocene)**—‘Aʻā and pāhoehoe mugearite and hawaiite lava flows, very rough relief; channels and levees; breached scoria cone. Contains phenocrysts of plagioclase, olivine, and clinopyroxene

mmk **Mugearite of Mukhayar (late Pleistocene)**—‘Aʻā and pāhoehoe mugearite lava flows, very rough relief; channels, levees, and inflated surfaces. Scoria-cone complex has three craters. Aphyric

og2 **Benmoreite of Gura 2 (late Pleistocene)**—‘Aʻā and pāhoehoe benmoreite lava flows, subdued relief. Contains phenocrysts of plagioclase, potassium-rich feldspar, olivine, and clinopyroxene

oqa **Benmoreite of Al Qara'in (middle Pleistocene)**—Benmoreite lava dome. Contains phenocrysts of plagioclase and potassium-rich feldspar

ort **Benmoreite of Radio Tower (middle Pleistocene)**—Benmoreite and mugearite lava dome and block-and-ash-flow deposits. Contains phenocrysts of plagioclase, potassium-rich feldspar, olivine, and amphibole

tg3 **Trachyte of Gura 3 (middle Pleistocene)**—Trachyte pyroclastic-flow deposits. Sourced from crater (0.6 km in diameter). Contains phenocrysts of potassium-rich feldspar and clinopyroxene within abundant, poorly inflated juvenile clasts. Lithic clasts include previously erupted basaltic lavas

tma **Trachyte of Matan (late Pleistocene)**—Trachyte lava dome and pyroclastic-flow deposits. Pyroclastic deposits erupted from crater (0.4 km in diameter) that was partly filled by lava dome (1.6 km in diameter) that has small crater near summit. Dome uplifted units bmt, hmo, and mma. Contains phenocrysts of potassium-rich feldspar and clinopyroxene within dome rocks and abundant, poorly inflated juvenile clasts

tz2 **Trachyte of Um Znabah 2 (late Pleistocene)**—Trachyte lava dome (0.9 km in diameter) and minor pyroclastic-flow deposits. Lava-dome extrusion uplifted unit mz2. Contains phenocrysts of potassium-rich feldspar

Eruptive Stage 6 (180 to 260 ka)

badb **Basalt of Al Adhbah (middle Pleistocene)**—Pāhoehoe and ‘aʻā basalt lava flows, subdued relief

badh **Basalt of Adh Dhiyabah (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows, moderate relief. Erupted from single scoria cone. Contains olivine phenocrysts

bag **Basalt of Abu Ghuwayshiyah (middle Pleistocene)**—Pāhoehoe and ‘aʻā alkalic basalt lava flows, very rough relief; pressure-ridges, levees, and channels. Scoria-cone complex (2.5 km long) has six craters. Contains phenocrysts of plagioclase and olivine

bahu **Basalt of Al Hulays (middle Pleistocene)**—Pāhoehoe and ‘aʻā basalt lava flows, moderate relief. Flows emanate from scoria-cone complex (2 km long)

bam1 **Basalt of Amlit 1 (middle Pleistocene)**—Pāhoehoe and ‘aʻā alkalic basalt lava flows, rough relief; pressure ridges. Scoria cone (0.9 km long) has three craters. Contains phenocrysts of plagioclase and olivine

bam2 **Basalt of Amlit 2 (middle Pleistocene)**—Pāhoehoe and ‘aʻā alkalic basalt lava flows, moderately rough relief. Scoria cone (0.3 km long) has two craters. Contains phenocrysts of plagioclase and olivine

bam3 **Basalt of Amlit 3 (middle Pleistocene)**—Pāhoehoe basalt lava flows, very subdued relief. Erupted from single scoria cone

bam4 **Basalt of Amlit 4 (middle Pleistocene)**—‘Aʻā basalt lava flows, rough, hummocky relief. Erupted from single scoria cone

bawa	**Basalt of Al Wabarah (middle Pleistocene)**—Pāhoehoe basalt lava flows, subdued relief. Scoria cone (0.7 km long) has three craters
bbd	**Basalt of Banthane Dam (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, subdued relief. Contains phenocrysts of plagioclase and olivine
bbr	**Basalt of Al Buraysha (middle Pleistocene)**—Pāhoehoe basalt lava flows, subdued relief
bda	**Basalt of Ad Darah (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic and transitional basalt lava flows, subdued relief. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine
bdr	**Basalt of Dab Al Harus (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, moderately rough relief; breached scoria cone. Contains olivine phenocrysts
besa	**Basalt east of Al Shathaa (middle Pleistocene)—**Pāhoehoe and ‘a‘ā basalt lava flows, moderately subdued relief. Vent (0.6 km long), which has two craters and spatter ramparts, is offset 10 m by normal fault
bh81	**Basalt of Hill 810 (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, moderate to subdued relief. Flows emanate from three scoria cones. Contains phenocrysts of plagioclase and olivine
bhb	**Basalt of Hamra Al Bidun (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, rough relief; pressure ridges, channels, and levees. Contains phenocrysts of plagioclase and olivine
bhy	**Basalt of Sha’ib Hayaya (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, hawaiite, and mugearite, rough to moderately rough relief; breached scoria cone. Contains phenocrysts of plagioclase and olivine
bjr	**Basalt of Umm Jurmat (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, moderate relief. Scoria cone (0.6 km long) has three craters. Contains phenocrysts of plagioclase and olivine
bjs	**Basalt of Al Jassah (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, very subdued relief. Aphyric
bli	**Basalt of Al Billa’ah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, moderately rough relief. Cluster of scoria cones has two craters and spatter ramparts
blqa	**Basalt of Lower Qa Al Aqul (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief. Contains phenocrysts of plagioclase and olivine
blqh	**Basalt of Lower Qa Hadawda (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic basalt lava flows, subdued relief. Contains phenocrysts of plagioclase and olivine
blsl	**Basalt of Lower Sha’ib Lihyan (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief. Contains phenocrysts of plagioclase and olivine
bm1	**Basalt of Al Malsaa 1 (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic basalt lava flows, subdued relief. Shield volcano has spatter ramparts. Contains phenocrysts of plagioclase and olivine
bmd	**Basalt of Al Madba’ah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, rough relief. Cluster of eroded scoria cones is 1.1 km long. Contains olivine phenocrysts
bme	**Basalt of Al Mesba’ah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, moderate relief
bml	**Basalt of Al Mulaysa (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately subdued relief. Two scoria cones are 0.8 km long. Contains olivine phenocrysts
bmt	**Basalt of Matan (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderate to subdued relief. Scoria cone is partly exposed. Unit uplifted by lava dome of unit tma. Contains phenocrysts of plagioclase and olivine
bqar	**Basalt of Al Qara’in (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief. Scoria-cone complex (2.0 km long) has four craters. Contains phenocrysts of plagioclase and olivine
bqg	**Basalt of Qa Al Ghusun (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt and hawaiite lava flows, very rough relief; pressure ridges, channels, and levees. Contains phenocrysts of plagioclase and olivine
bru	**Basalt of Ar Rummanah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief. Contains phenocrysts of plagioclase and olivine

bsf	**Basalt of Umm Sufar (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, rough relief; pressure ridges, channels, and levees. Scoria-cone complex is 0.9 km long. Contains phenocrysts of plagioclase and olivine
bsh	**Basalt of Shuran (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief; eroded scoria cone. Contains phenocrysts of plagioclase and olivine
bso	**Basalt of South (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderate relief. Flows emanate from two clusters of scoria cones. Contains phenocrysts of plagioclase and olivine
bsy	**Basalt of Abu Siyilah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderate relief. Flows emanate from two scoria cones. Contains olivine phenocrysts
buaa	**Basalt of Umm Al Awshaz (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, moderately rough relief. Erupted from single scoria cone
buak	**Basalt of Umm Arakah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief; pressure ridges, channels, and levees. Scoria cone (0.6 km long) has three craters. Contains phenocrysts of plagioclase and olivine
bups	**Basalt of Upper Sahab (middle Pleistocene)**—Pāhoehoe basalt lava flows, subdued relief. Scoria cone (0.5 km long) has two craters
buqh	**Basalt of Upper Qa Hadawda (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderate relief; pressure ridges. Contains phenocrysts of plagioclase and olivine
buri	**Basalt of Upper Ar Ritajah (middle Pleistocene)**—Pāhoehoe basalt lava flows, very subdued relief. Erupted from single scoria cone
buru	**Basalt of Umm Rutaj (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderate relief. Scoria-cone complex (1.3 km long) has five craters. Contains phenocrysts of plagioclase and olivine
busi	**Basalt of Upper Sha’ib Iskabah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief. Flows emanate from scoria-cone cluster
bwh8	**Basalt west of Hill 870 (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, moderate relief; breached scoria cone
hma	**Hawaiite of Al Malsa (middle Pleistocene)**—‘A‘ā and pāhoehoe hawaiite lava flows, moderate to rough relief; pressure ridges, channels, and levees. Two scoria cones span 3.8 km. Contains phenocrysts of plagioclase
hmk	**Hawaiite of Mukhayar (middle Pleistocene)**—Pāhoehoe and ‘a‘ā hawaiite lava flows, moderate to subdued relief. Vent destroyed by eruption of unit tef. Contains phenocrysts of plagioclase and olivine
hmo	**Hawaiite of Mouteen (middle Pleistocene)**—‘A‘ā and pāhoehoe hawaiite and mugearite lava flows, moderately subdued relief; partly exposed scoria cone. Unit uplifted by lava domes of units tma and tmo. Contains phenocrysts of plagioclase and olivine
masu	**Mugearite of As Sumak (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, moderately rough relief. Vent zone (1.4 km long) has two scoria cones. Contains phenocrysts of plagioclase and olivine
mmu	**Mugearite of Al Mulaysa (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, very rough relief; pressure ridges, channels, and levees. Erupted from single scoria cone. Contains phenocrysts of plagioclase, olivine, and clinopyroxene
mmy	**Mugearite of Murayyikh (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, rough relief. Flows emanate from elongate scoria cone (0.5 km long)
murr	**Mugearite of Umm Ar Rish (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, rough relief; pressure ridges, channels, and levees; breached scoria cone. Contains phenocrysts of plagioclase and olivine
mz2	**Mugearite of Um Znabah 2 (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite and benmoreite lava flows, rough relief; pressure ridges, channels, and levees. Erupted from single scoria cone. Unit uplifted by lava dome of unit tz2. Contains phenocrysts of plagioclase and olivine
oba	**Benmoreite of Al Bayadah (middle Pleistocene)**—Hummocky debris-avalanche deposit composed of poorly sorted benmoreite lava and ash. Vent inferred to be where unit bm2 is now. Contains clinopyroxene phenocrysts
oma	**Benmoreite of Al Malsaa (middle Pleistocene)**—Block-and-ash-flow deposits of benmoreite and trachyte juvenile clasts, subdued relief. Aphyric

Eruptive Stage 7 (260 to 323 ka)

bash **Basalt of Ash Shamali (middle Pleistocene)**—Pāhoehoe basalt lava flows, subdued relief

bau **Basalt of An Nughayr (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, moderately rough relief; pressure ridges. Eroded cluster of scoria cones is 1.0 km long. Contains phenocrysts of plagioclase and olivine

bd3 **Basalt of Dabaa 3 (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderate to rough relief. Erupted from single scoria cone. Cryptodome (0.8 km in diameter) uplifted juvenile lava flows of this unit and unit muq. Contains phenocrysts of plagioclase and olivine

bh86 **Basalt of Hill 865 (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, rough relief; pressure ridges, channels, and levees. Scoria cone (0.6 km long) has three craters. Contains phenocrysts of plagioclase and olivine

bhag **Basalt of Hilayyat Ghuwayshiyah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, rough relief; pressure ridges, channels, and levees. Flows emanate from scoria-cone complex (0.6 km long). Contains phenocrysts of plagioclase and olivine

bhm **Basalt of Al Humayra (middle Pleistocene)**—Pāhoehoe and ‘a‘ā basalt lava flows, moderate to rough relief; breached scoria cone

bhu **Basalt of Al Huzaym (middle Pleistocene)**—Pāhoehoe alkalic and transitional basalt lava flows, very subdued relief. Shield volcano has summit vent. Contains phenocrysts of plagioclase and olivine

bmk **Basalt of Mukhayar (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately subdued relief. Contains phenocrysts of plagioclase and olivine

bqaq **Basalt of Qa Al Qina’ah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, subdued relief. Erupted from single scoria cone

bsa **Basalt of Al Shathaa (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief. Eroded scoria-cone complex (0.7 km long) has spatter ramparts. Displaced 10 m by normal fault. Contains olivine phenocrysts

bssu **Basalt south of As Sumak (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief; breached scoria cone. Contains phenocrysts of plagioclase and olivine

bsuy **Basalt of Umm Suyuf (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately subdued relief; breached scoria cone. Contains phenocrysts of plagioclase and olivine

busb **Basalt of Al Usbu’ah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt and hawaiite lava flows, rough relief; channels and levees; breached scoria cone. Contains phenocrysts of plagioclase and olivine

bya **Basalt of Yalla (middle Pleistocene)**—Alkalic basalt lava flows. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine

og4 **Benmoreite of Gura 4 (middle Pleistocene)**—Benmoreite lava flows, exposed in crater wall of unit tg4. Contains phenocrysts of plagioclase, potassium-rich feldspar, olivine, and clinopyroxene

tz1 **Trachyte of Um Znabah 1 (middle Pleistocene)**—Trachyte lava dome (0.8 km in diameter). Aphyric

Eruptive Stage 8 (323 to 360 ka)

bjab **Basalt of Jabal (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, subdued relief. Flows emanate from scoria-cone complex (0.7 km long). Contains phenocrysts of plagioclase and olivine

blsa **Basalt of Lower Sahab (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, moderately subdued relief; pressure ridges. Vent complex (1.4 km long) has four scoria cones. Contains phenocrysts of plagioclase and olivine

bmu **Basalt of Al Mustarah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Scoria cone (0.6 km long) has two craters. Contains phenocrysts of plagioclase and olivine

bsj **Basalt south of Al Jufdirah (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic and transitional basalt lava flows, very subdued relief. Contains phenocrysts of plagioclase, olivine, and clinopyroxene

bsm **Basalt of Sha’ib Murayyikh (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief. Contains olivine phenocrysts

Eruptive Stage 9 (360 to 460 ka)

baaj **Basalt of Abar Al Julud (middle Pleistocene)**—Pāhoehoe and ‘a‘ā basalt lava flows, very subdued relief. Erupted from single scoria cone baq **Basalt of Al Qurdi (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, subdued relief. Scoria cone has five craters. Contains phenocrysts of plagioclase and olivine

basu **Basalt of As Sumak (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic basalt lava flows, moderately rough relief. Scoria-cone cluster is heavily eroded. Contains phenocrysts of plagioclase and olivine

bay **Basalt of Atiyah (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows, subdued relief. Aphyric

bdg **Basalt of Duwayghir (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, subdued relief. Scoria cone (0.9 km long) has three craters. Aphyric

bduw **Basalt of Ad Duwayfi’ah (middle Pleistocene)**—Pāhoehoe basalt lava flows, very subdued relief

bh87 **Basalt of Hill 870 (middle Pleistocene)**—Pāhoehoe basalt lava flows, subdued relief. Erupted from single scoria cone

bhg **Basalt of Al Harrah Al Gharbiyah (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic basalt lava flows, subdued relief. Contains phenocrysts of plagioclase and olivine

bju **Basalt of Al Jurb (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, moderate relief. Erupted from single scoria cone

bmuf **Basalt of Al Mufayriq (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderate relief. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine

bmus **Basalt of Muslimah (middle Pleistocene)**—Pāhoehoe basalt lava flows, very subdued relief. Erupted from single scoria cone

bnh **Basalt of Al Negea’ah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt, subdued relief. Scoria-cone complex (2.2 km long) consists of multiple cones and craters

bni **Basalt north of Iskabah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Scoria-cone complex (0.8 km long) has four craters. Contains olivine phenocrysts. Ground cracks that break lava-flow surface are interpreted to have formed during eruption of unit bsof

bnj **Basalt north of Al Jufdirah (middle Pleistocene)**—Alkalic basalt lava flows, exposed in crater wall of unit twa. Contains phenocrysts of plagioclase and olivine

bpr **Basalt of Powerline Road (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately subdued relief. Erupted from single scoria cone. Aphyric

bqi **Basalt of Al Qirayy (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, subdued relief. Erupted from single scoria cone

bqr **Basalt of Quraydah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Contains phenocrysts of plagioclase and olivine

brb **Basalt of Rawd Al Baham (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Erupted from single scoria cone. Aphyric

brh **Basalt of Rahat (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief. Contains phenocrysts of plagioclase and olivine

bri **Basalt of Ar Ritajah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief. Contains phenocrysts of plagioclase and olivine

brum **Basalt of Ar Rumahiyah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, moderate relief. Erupted from single scoria cone

brw **Basalt of Ruwawah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief; breached scoria cone

bsah **Basalt of Shi’ban Al Hulaysiwat (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief. Scoria-cone complex is 1.1 km long. Contains phenocrysts of plagioclase and olivine

bsam **Basalt of Sha’ib Al Maqrin (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief. Erupted from single scoria cone

bsaw **Basalt of Sha’ib Al Wuqayt (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief. Erupted from single scoria cone

bsou **Basalt of Southwest (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately rough relief. Contains olivine phenocrysts

bswu **Basalt of Sha’ib Al Wuqayyit (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief

bte **Basalt of Abu Tunaydibah East (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Scoria-cone cluster is heavily eroded. Contains olivine phenocrysts buh **Basalt of Umm Hamd (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows. Scoria-cone cluster is heavily eroded. Aphyric

buj **Basalt of Umm Ja’adat (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, subdued relief

bur **Basalt of Al Urayd (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Contains plagioclase phenocrysts

burr **Basalt of Upper Abu Rimthah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic and transitional basalt lava flows, moderately rough relief. Shield volcano has two nested craters. Contains phenocrysts of plagioclase and olivine

busa **Basalt of Al Ushayrah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief

busq **Basalt of Usquf (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief

hsb **Hawaiite of As Sabah (middle Pleistocene)**—‘A‘ā and pāhoehoe hawaiite lava flows, moderate relief; eroded scoria cone. Contains phenocrysts of plagioclase and olivine

mha **Mugearite of Al Harara (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, very subdued relief. Scoria cone is partly eroded. Aphyric

mns **Mugearite northwest of Al Shathaa (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, very subdued relief. Scoria-cone complex (1.4 km long) is substantially eroded. Contains plagioclase phenocrysts

mnzy **Mugearite north of As Zayinah (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, subdued relief. Scoria cone is partly eroded. Cryptodome uplifts part of unit. Aphyric

msi **Mugearite of Sha’ib Abu Sidrah (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, very subdued relief. Aphyric

msr **Mugearite of Sha’ib Rushayyah (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, moderate relief. Erupted from single scoria cone. Contains olivine phenocrysts

muq **Mugearite of Umm Qurah (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, rough relief. Scoria cone has spatter ramparts. Part of unit is uplifted by cryptodome (0.7 km in diameter). Contains phenocrysts of plagioclase and olivine

mz3 **Mugearite of Um Znabah 3 (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, rough relief; pressure ridges. Scoria cone is partly destroyed. Contains phenocrysts of plagioclase and olivine

mz6 **Mugearite of Um Znabah 6 (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, very subdued relief. Scoria cone is partly eroded. Contains phenocrysts of plagioclase and olivine

mzy **Mugearite of As Zayinah (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite and hawaiite lava flows, rough relief; inflated surfaces. Erupted from single scoria cone. Unit uplifted by cryptodome (1.4 km in diameter). Contains plagioclase and olivine

oju **Benmoreite of Um Junb (middle Pleistocene)**—Benmoreite lava domes and trachyte pyroclastic-flow deposits. Benmoreite lava domes contain phenocrysts of plagioclase, potassium-rich feldspar, olivine, and clinopyroxene. Trachyte pyroclastic-flow deposits are aphyric

osa **Benmoreite of Al Shathaa (middle Pleistocene)**—Benmoreite and trachyte block-and-ash-flow deposits and pyroclastic-flow deposits. Sourced from crater (0.5 km in diameter). Contains phenocrysts of plagioclase, potassium-rich feldspar, and clinopyroxene

oz4 **Benmoreite of Um Znabah 4 (middle Pleistocene)**—Benmoreite lava domes and flows. Contains plagioclase, potassium-rich feldspar, olivine, and clinopyroxene

oz5 **Benmoreite of Um Znabah 5 (middle Pleistocene)**—Benmoreite lava flows. Contains phenocrysts of plagioclase and potassium-rich feldspar

ozy **Benmoreite of As Zayinah (middle Pleistocene)**—Benmoreite lava flows. Contains phenocrysts of plagioclase, potassium-rich feldspar, and olivine

tqa **Trachyte of Al Qayf (middle Pleistocene)**—Trachyte pyroclastic-flow deposits. Contains abundant aphyric, moderately inflated juvenile clasts

tz6 **Trachyte of Um Znabah 6 (middle Pleistocene)**—Trachyte lava dome. Aphyric

Eruptive Stage 10 (460 to 570 ka)

bada **Basalt of Ad Dayyir (middle Pleistocene)**—Pāhoehoe and ‘a‘ā basalt lava flows, subdued relief

bai **Basalt of Al Ihn (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine bara **Basalt of Ar Ra (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief. Erupted from single scoria cone

bbsh **Basalt below Ash Shamali (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows, subdued relief. Aphyric

bedh **Basalt east of Dab Al Harus (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief

bef **Basalt of Al Efairia (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows, very subdued relief. Contains phenocrysts of plagioclase and olivine

bfa **Basalt of Al Farash (middle Pleistocene)**—Pāhoehoe alkalic and transitional basalt lava flows, very subdued and eroded relief. Shield volcano has summit crater. Contains olivine phenocrysts

bh82 **Basalt of Hill 821 (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, moderate to subdued relief; channels and levees. Two scoria cones (1.1 km long) have five craters. Contains phenocrysts of plagioclase and olivine

bh83 **Basalt of Hill 838 (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows, subdued relief. Scoria cone (0.6 km long) has two craters. Contains plagioclase phenocrysts

bha **Basalt of Hathm (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows, very subdued relief. Contains olivine phenocrysts

bhc **Basalt of Half Cone (middle Pleistocene)**—Pāhoehoe basalt lava flows, very subdued relief; substantially eroded scoria cone

bhin **Basalt of Al Hinu (middle Pleistocene)**—Pāhoehoe basalt lava flows, subdued relief. Scoria-cone complex (2.4 km long) has 10 craters

bhq **Basalt of Sha’ib Huquf (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows. Scoria cone is partly eroded. Contains plagioclase phenocrysts

bis **Basalt of Al Iskan (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, very subdued relief. Contains phenocrysts of plagioclase and olivine

bjg **Basalt of Al Jaga (middle Pleistocene)**—Pāhoehoe basalt lava flows, very subdued relief

bjn **Basalt of Al Jan (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, moderately subdued relief. Contains phenocrysts of plagioclase and olivine

bkf **Basalt of Al Khafaq (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, subdued relief. Scoria cone (0.8 km long) has five craters. Aphyric

bmg **Basalt of Al Mughatiyah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, moderately subdued relief; pressure ridges; breached scoria cone. Aphyric

bmh **Basalt of Al Muq’iyah (middle Pleistocene)**—‘A‘ā and minor pāhoehoe alkalic basalt lava flows, moderately rough relief. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine

bmsm **Basalt of Al Musamma (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows, very subdued relief

bqu **Basalt of Quba (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic basalt lava flows, very subdued relief. Contains phenocrysts of plagioclase and olivine

brag **Basalt of Ar Raghibah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief

brg **Basalt of Um Rgaibah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic and transitional basalt lava flows, moderately subdued relief. Contains olivine phenocrysts

bss **Basalt of Sha’ib Si’ayd (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Contains phenocrysts of plagioclase and olivine

btw **Basalt of Abu Tunaydibah West (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Flows emanate from 0.7-km-long scoria-cone complex. Contains phenocrysts of plagioclase and olivine

buph **Basalt of Upper Sha’ib Huquf (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief. Flows emanate from 0.8-km-long scoria-cone complex

busm **Basalt of Upper Sha’ib Murayyikh (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief. Scoria cone is heavily eroded

bwhu **Basalt west of Al Hurus (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief

byid **Basalt of Yidum (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, subdued relief. Erupted from single scoria cone bzi **Basalt of Az Zinitah (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief. Vent zone (1.1 km long) has two scoria-cone complexes and four craters

hhil **Hawaiite of Hilayyat (middle Pleistocene)**—Pāhoehoe and ‘a‘ā hawaiite lava flows, moderate to subdued relief. Contains plagioclase phenocrysts

og3 **Benmoreite of Gura 3 (middle Pleistocene)**—Benmoreite lava flows, exposed in crater wall of unit tg3. Contains olivine phenocrysts

osb **Benmoreite of As Sabah (middle Pleistocene)**—‘A‘ā and pāhoehoe benmoreite lava flows, moderate relief; pressure ridges. Vent destroyed by eruption of unit oju. Contains phenocrysts of plagioclase, potassium-rich feldspar, and olivine

Eruptive Stage 11 (570 to 780 ka)

bas **Basalt of Abu Sidrah (middle Pleistocene)**—Pāhoehoe and minor ‘a‘ā basalt lava flows, subdued relief. Erupted from single scoria cone

bat **Basalt of Atiq (middle Pleistocene)**—Pāhoehoe basalt lava flows, very subdued relief. Erupted from single scoria cone

bba **Basalt of Al Bayadah (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows, subdued relief. Erupted from single scoria cone. Aphyric

bd1 **Basalt of Dabaa 1 (middle Pleistocene)**—Pāhoehoe alkalic basalt lava flows, subdued relief. Erupted from single scoria cone. Lava flows uplifted by unit td1. Contains phenocrysts of plagioclase and olivine

bg1 **Basalt of Gura 1 (middle Pleistocene)**—Alkalic basalt lava flows; scoria cone, uplifted lava flows along margin of lava dome, crater cluster, and maar crater. Contains phenocrysts of plagioclase and olivine

bja **Basalt of Al Jar’ah (middle Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, moderate relief. Scoria-cone complex (1.1 km long) has four craters. Contains olivine phenocrysts

bmy **Basalt of Al Matyan (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Contains phenocrysts of plagioclase and olivine

bsd **Basalt of Sha’ib Ad Dirwah (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Erupted from single scoria cone. Contains phenocrysts of plagioclase and olivine

bsl **Basalt of Sha’ib Luwa (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Contains phenocrysts of plagioclase and olivine

bsw **Basalt of Umm Suwasi (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief. Erupted from single scoria cone

buq **Basalt of Umm Qubayr (middle Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief. Erupted from single scoria cone. Aphyric

bush **Basalt of Al Ushu’a (middle Pleistocene)**—‘A‘ā and pāhoehoe basalt lava flows, very subdued relief. Scoria-cone cluster is heavily eroded

mss **Mugearite southwest of Al Shathaa (middle Pleistocene)**—‘A‘ā and pāhoehoe mugearite lava flows, very subdued relief. Aphyric

Eruptive Stage 12 (780 to 1,200 ka)

bg3 **Basalt of Gura 3 (early Pleistocene)**—Alkalic basalt lava flows, present in crater of unit tg3. Contains olivine phenocrysts

bgh **Basalt of Ghadwar (early Pleistocene)**—Pāhoehoe transitional and alkalic basalt lava flows, heavily eroded relief. Shield volcano has 0.8-km-long crater. Contains phenocrysts of plagioclase and olivine

bgo **Basalt of Gorab (early Pleistocene)**—Pāhoehoe and ‘a‘ā alkalic basalt lava flows, subdued relief. Contains phenocrysts of plagioclase and olivine

bh89 **Basalt of Hill 892 (early Pleistocene)**—Pāhoehoe and minor ‘a‘ā alkalic basalt lava flows, very subdued relief. Shield volcano has central crater (0.2 km in diameter). Aphyric

bqa **Basalt of Al Qafif (early Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, very subdued relief. Only very small part of unit is present in map area. Aphyric

buqa **Basalt of Upper Qa Al Aqul (early Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows, subdued relief. Contains phenocrysts of plagioclase and olivine

VOLCANIC ROCKS OF HARRATS KURAMA AND KHAYBAR

Qbhk **Basalt of Harrat Kurama (early Pleistocene)**—Undifferentiated basalt lava flows from Harrats Kurama or Khaybar. Harrats Kurama and Khaybar are situated northeast of northern Harrat Rahat

Qbjs **Basalt of Jabal Umm Suhaylah (early Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows from Harrats Kurama or Khaybar, very subdued relief. Contains olivine phenocrysts. Overlies Precambrian rocks

Qbra **Basalt of Ar Ramram (early Pleistocene)**—‘A‘ā and pāhoehoe alkalic basalt lava flows from Harrats Kurama or Khaybar, very subdued relief. Several normal faults offset these lava flows by as much as 20 m. Contains olivine phenocrysts

TERTIARY VOLCANIC ROCKS

Tbja **Basalt of Jabal Ayr (Miocene)**—Alkalic basalt lava flows. Very flat topography, covers top of hill that consists of Precambrian rocks. Contains phenocrysts of plagioclase and olivine

Tbjj **Basalt of Jabal Jammah (Miocene)**—Alkalic basalt, basanite, and hawaiite lava flows. Very flat topography, covers tops of six hills that consist of Precambrian rocks. Contains phenocrysts of plagioclase, olivine, and clinopyroxene

PRECAMBRIAN ROCKS

p€ **Precambrian rocks (Precambrian)**—Undifferentiated metamorphosed sedimentary rocks sutured together with intrusive and extrusive igneous rocks from island-arc and back-arc terranes

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