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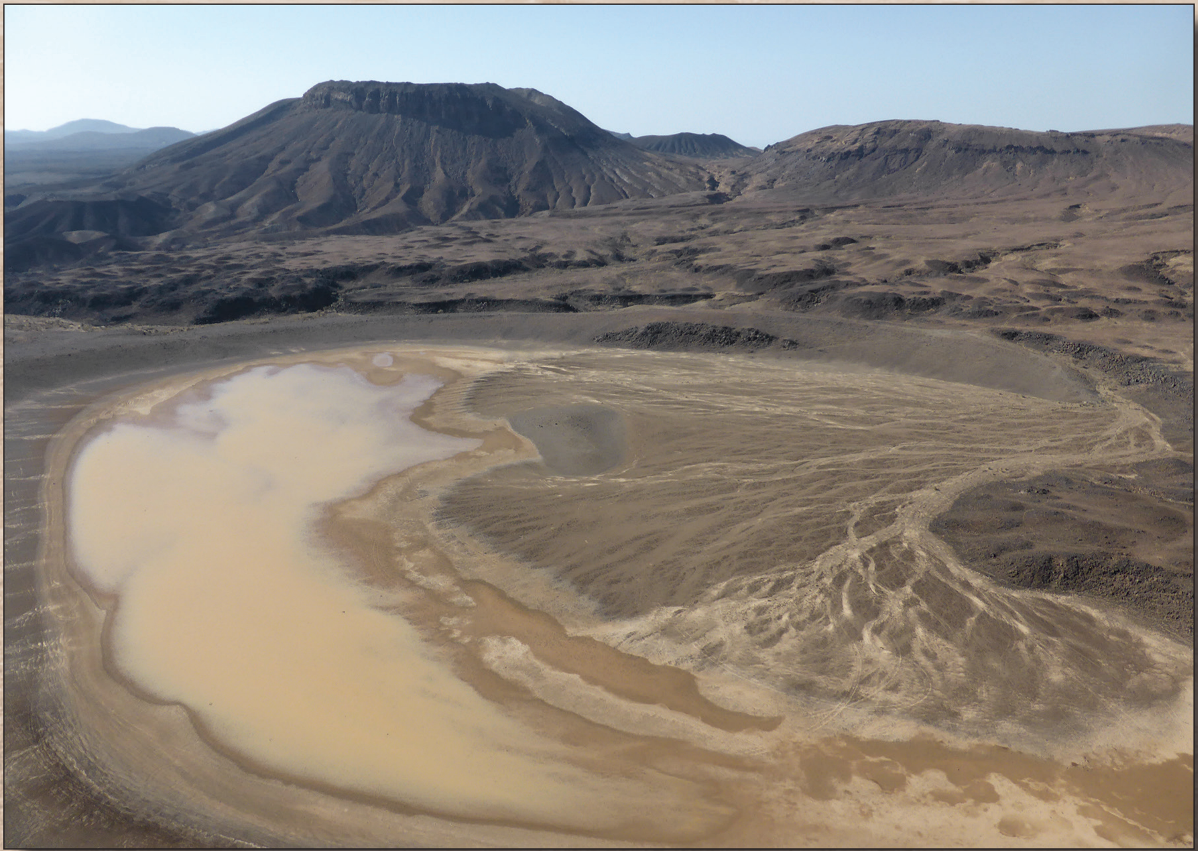
SAUDI GEOLOGICAL SURVEY

The Saudi Geological Survey-U.S. Geological Survey Northern Harrat Rahat Project—Styles, Rates, Causes, and Hazards of Volcanism Near Al Madīnah al Munawwarah, Kingdom of Saudi Arabia

Chapter A of

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



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Cover. View south-southwest across maar crater of Gura 1 toward benmoreite lava dome and flow of Um Junb. Trachytic pyroclastic flow deposits of Gura 2 enter from upper right, mantling mugearite lava flow of Dabaa 1. Maar crater is about 0.7 kilometers across, and Um Junb stands about 250 meters above surroundings. U.S. Geological Survey photograph by Andrew Calvert, February 12, 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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هيئة المساحة الجيولوجية السعودية
SAUDI GEOLOGICAL SURVEY

Ministry of Industry and Mineral Resources
BANDAR BIN IBRAHIM BIN ABDULLAH AL-KHORAYEF, Minister and SGS Chairman

Saudi Geological Survey
Abdullah bin Mufter Al-Shamrani, Chief Executive Officer

Saudi Geological Survey, Jiddah, Kingdom of Saudi Arabia: 2023

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meter (m)	0.6214	yard (yd)
kilometer (km)	0.5400	mile (mi)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow rate	
centimeter per second (cm/s)	0.3937	inch per second (in/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Abbreviations

A.H.	in the year of the Hijra
C.E.	Common Era
g	gravitational acceleration
ka	kilo-annum
Ma	mega-annum
MORB	midocean ridge basalt
SGS	Saudi Geological Survey
USGS	U.S. Geological Survey

Summary

To broaden the understanding and use of this work, the Saudi Geological Survey has prepared an Arabic-language summary of the contents of this chapter.

ملخص

تعتبر حرة رهاط، الواقعة في وسط الجزء الغربي من المملكة العربية السعودية هي الأكبر من بين عدد 15 حرة من حقبة الحياة الحديثة، والتي تسمى باللغة العربية "الحقول البركانية" والموزعة على الصفيحة العربية بمنطقة الدرع العربي، وتمتد حرة رهاط لأكثر من 300كيلومتر من الشمال الى الجنوب ومن 50 إلى 75 كيلومترًا من الشرق إلى الغرب، وتغطي مساحة تبلغ حوالي 20000 كيلومتر مربع، ويبلغ حجمها حوالي 2000 كيلومتر مكعب، كما أنها تشمل أكثر من 900 فوهة بركانية، يمكن معاينتها على الطبيعة. وبدأ النشاط البركاني بحرة رهاط منذ حوالي 10مليون سنة واستمر على مر التاريخ الجيولوجي، حيث حدث أخر ثوران بركاني بها في عام 1256م، ويمَثّل البازلت القلوي أكثر منتجات الثوران البركاني مع تدفقات الحمم البركانية الهاوية، وكذلك تدفقات الحمم البركانية الثانوية، بالإضافة إلى تدفقات الصخور البركانية المكونة من الميجوريت (صخرة بازلتية حاملة للزبرجد الزيتوني)، والبنموريت (صخرة بركانية مكونة من السيليكا)، والقباب، وتدفقات من الغازات والرماد البركاني.

وتوضح الخريطة الجيولوجية لمنطقة حرة رهاط وجود عدد 239 فوهة بركانية، تغطي مساحة 3340 كم2، واقعة بشمال حرة رهاط المجاورة للمدينة المنورة، وتم عرض النتائج من خلال خريطة جيولوجية لمنطقة الدراسة بمقياس 1:75000، وخريطة اخرى بمقياس 1:25000 لمناطق أصغر ذات أهمية خاصة، مع تفسير نصي لهذه النتائج. واتضح أن معظم المناطق البركانية عبارة عن تدفقات من الحمم البازلتية والتي تدفقت خلال المحور الرئيسي المتسع في اتجاه شمال-شمال غرب، والذي كون القمة الطبوغرافية للحقل البركاني بالمنطقة، حيث يقع هذا المحور في الثلث الشرقي من شمال حرة رهاط، ويتراوح ارتفاعه بين 300 و400 متر وعرضه من 6 إلى 10 كيلومترات. ومن الممكن أن تمتد تدفقات الحمم البازلتية والهاوية لمسافة يصل طولها إلى 27 كم من الفوهات البركانية، ولكن معظمها يتراوح طول المسافة من 10 إلى 15 كم، كما ينتشر نتاج الثوران البركاني المتطور، مثل الميجوريت ، والبنموريت ، والتراكيت (صخرة بركانية مكونة من الفلسبار) بشكل أقل انتشارًا، وتمتد تدفقات الحمم البركانية الفتاتية (بيروكلاستك) لمسافة تصل إلى 9 كيلومترات من موقع الفوهات البركانية، برغم أن معظمها غالباً ما يصل إلى مسافة من 4 إلى 6 كيلومترات فقط.

وأثبتت النتائج عدم وجود صخور بركانية بحرة رهاط يزيد عمرها عن 1.2 مليون سنة، وتَكون حوالي 90 في المائة من الصخور البركانية المكشوفة خلال الـ 570 ألف سنة الماضية، كما وضحت الخرائط الجيولوجية أوقات الثوران البركاني خلال الإثنى عشر مرحلة لشمال حرة رهاط والذي حدث على مدى 1.2 مليون سنة ماضية، وتوصلت النتائج الى اكتشافات جيولوجية زمنية هامة أخرى، مثل؛ (1) أن تدفق العديد من الحمم البركانية بالقرب من المدينة المنورة تم في أخر عصر البليستوسين ، والتي تم تفسيرها خطئاً في السابق من خلال الأدلة الأثرية على أنها من عصر الهولوسين؛ (2) عُمر ثوران مجموعة البراكين ذات الفوهات المخروطية الشكل وكذلك الحمم الصغيرة المتدفقة في الضواحي الغربية من المدينة المنورة هو في الواقع 13.3±1.9 الف سنة، أي بالقرب من حدود العصر الجليدي-الهولوسيني، والتي نُسبت بالخطأ سابقًا إلى الثوران البركاني عام 641 م؛ (3) حددت الخريطة الجيولوجية بحرة رهاط حدوث عدد إثنين ثوران بركاني فقط حدثا في عصر الهولوسين، وهما البازلت الموصوف تاريخيًا ببازلت اللابة في عام 1256م، والقبة البركانية وكذلك البيروكلاستك والتراكيت في أم رقيبة منذ 4.2±5.2 الف سنة.

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Chapter A

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Abstract

Active volcanic systems pose serious hazards to people and property including inundation and incineration by lava, blanketing by tephra (volcanic ash), exposure to noxious volcanic gases, and damage from shallow earthquakes triggered by ascending molten material (magma). To improve understanding of volcanism and associated seismicity on the western Arabia Plate, the Saudi Geological Survey and the U.S. Geological Survey conducted a multi-year investigation of the northern Harrat Rahat volcanic field adjacent to the city of Al Madīnah al Munawwarah, Kingdom of Saudi Arabia. Project components included creation of a high-resolution digital topographic base; interpretation of eruptive history supported by detailed geologic mapping, paleomagnetism, and abundant high-precision geochronology of volcanic deposits; assessments of eruptive styles and volcanic hazards by physical volcanology; investigation of the origins of magmas in the mantle and of their differentiation in the crust revealed by chemical and isotopic petrology; gravity and magnetotelluric surveys to reveal crustal structures and to search for magma reservoirs; and regional and local seismic tomography and analyses of seismic hazards. Project results are presented in this Professional Paper as chapters written for technical scientific audiences. This initial chapter introduces the project and briefly summarizes results in plain language for readers who have more general backgrounds.

Introduction

Volcanoes are spread widely across the western Arabian Peninsula, some with historically described eruptions, and most including lava flows so little eroded or weathered that their youth is apparent despite a lack of eyewitness accounts or laboratory measurements to confirm their recent eruptions. The volcanoes chiefly erupt basaltic lavas similar to those of Hawai‘i, with lava flows extending from a few kilometers to several tens of kilometers from their vents. Over spans of as long as perhaps 10–15 million years (Coleman and others, 1983; Camp and Roobol, 1991; Bosworth, 2005; Bosworth and others, 2015), myriad eruptions of basaltic lava and cinders from closely spaced vents formed broad expanses of dark, stony, low-relief volcanic rocks studded with cinder cones, with each volcanic field known in Arabic as a harrat. The Arabian harrats form a belt spanning more than 2,000 kilometers (km) from Yemen into southern Syria, and if broadly similar volcanic fields in southern Turkey are included, the belt is nearly 3,000 km long (fig. 1). The Arabian volcanic province is one of the largest regions known where basalts that have relatively high concentrations of alkali elements (chiefly sodium and potassium) erupted on the continents (Coleman and others, 1983). Despite the province's great areal extent, the general public has little awareness of even the presence of volcanoes in Arabia, and study by the scientific community has been similarly limited.

The largest volcanic field entirely within the Kingdom of Saudi Arabia is Harrat Rahat, which spans about 310 km from near Makkah al Mukarramah in the south to Al Madīnah al Munawwarah (hereafter, Al Madīnah) in the north (figs. 1, 2). Harrat Rahat has an average width of 50–60 km, although some of its older large lava flows extended as much as 100 km west through gaps in the rugged Ḩijāz highlands, locally descending to the Red Sea (Camp and Roobol, 1991). Greater Harrat Rahat is the coalesced product of eruptions from four regions of concentrated vents collectively aligned north-south parallel to, and just east of, the crest of the Ḩijāz highlands. The constituent sub-harrats have local names (fig. 2), although scientific publications have not employed those commonly or consistently. Harrat Rahat's most recent eruption was in 1256 C.E., or 654 in the year of the Hijra (A.H.), when 0.5 cubic kilometers (km^3) of basalt effused from vents near the north end of the volcanic field. This eruption fed a lava flow system that eventually attained a length of 22–23 km (fig. 3), reaching to within 8 km of the city center of Al Madīnah (Camp and others, 1987). That historical eruption and other geologic evidence (Camp and Roobol, 1989, 1991) indicate that the youngest eruptions of Harrat Rahat were concentrated toward its north end in the vicinity of Al Madīnah. Future eruptions are also most likely to be from that region.

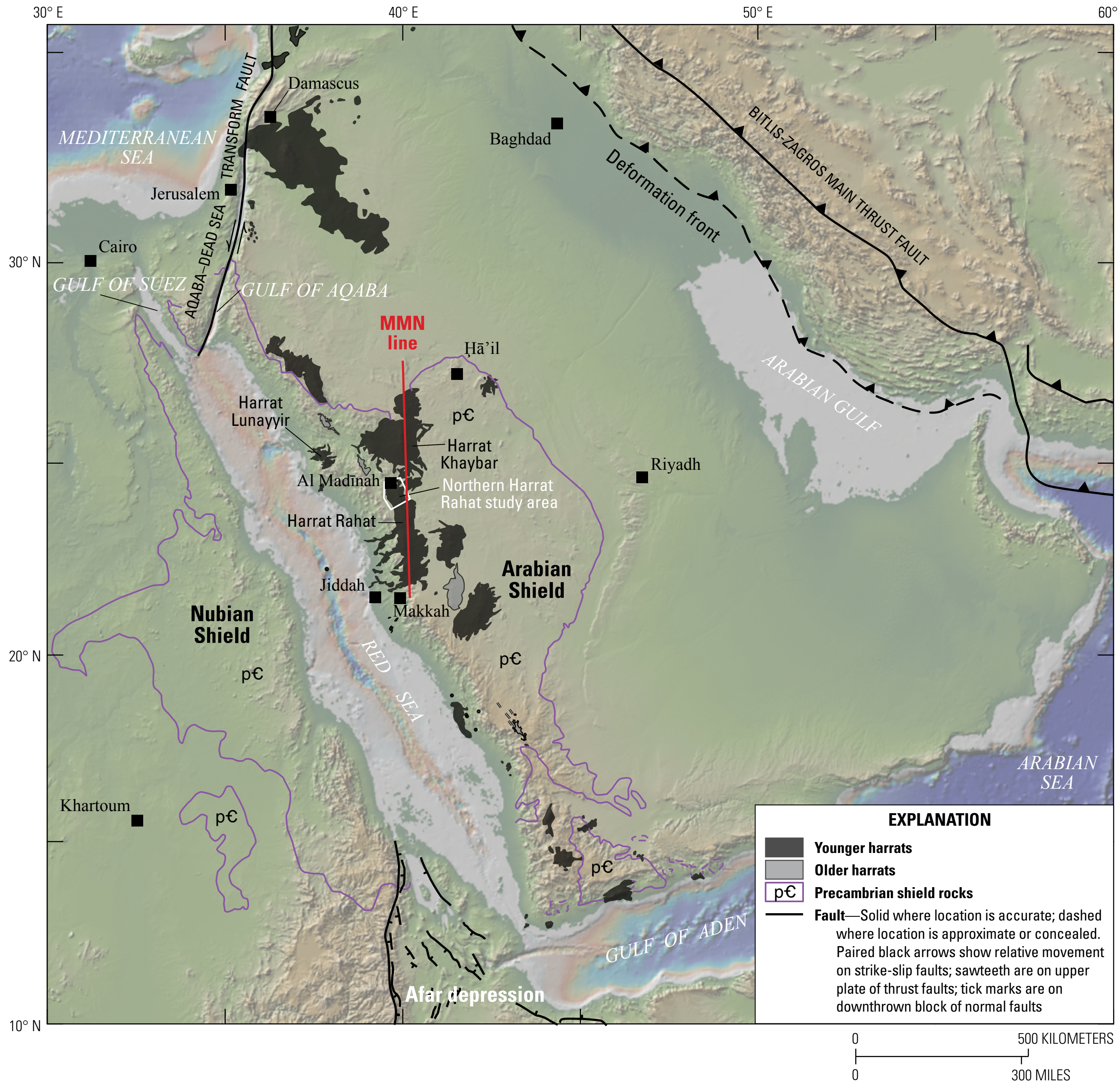

Figure 1. Colored shaded-relief map showing the locations of selected late Cenozoic volcanic rocks of the Arabia Plate (younger harrats in dark grey, older harrats in light gray), limits of Precambrian (pЄ) rock exposure on the Arabia and Africa Plates (outlined in purple), and selected tectonic and geographic features. Red line shows the Makkah-Madīnah-Nafud (MMN) volcanic line along the axis of the largest harrats. Omitted are young lavas of the Afar depression and Oligocene flood basalts that cap highlands to their west, northwest, and northeast. Locations of Arabian and Nubian Shields, plate-bounding structures, and faults modified from U.S. Geological Survey and Arabian American Oil Company (1963), Coleman and others (1983), Bosworth and others (2005), and Stern and Johnson (2010). Shaded-relief base map generated with GeoMapApp (www.geomapapp.org) using global multiresolution topography and bathymetry (Ryan and others, 2009). Vertical exaggeration is 8×; map uses Mercator projection.

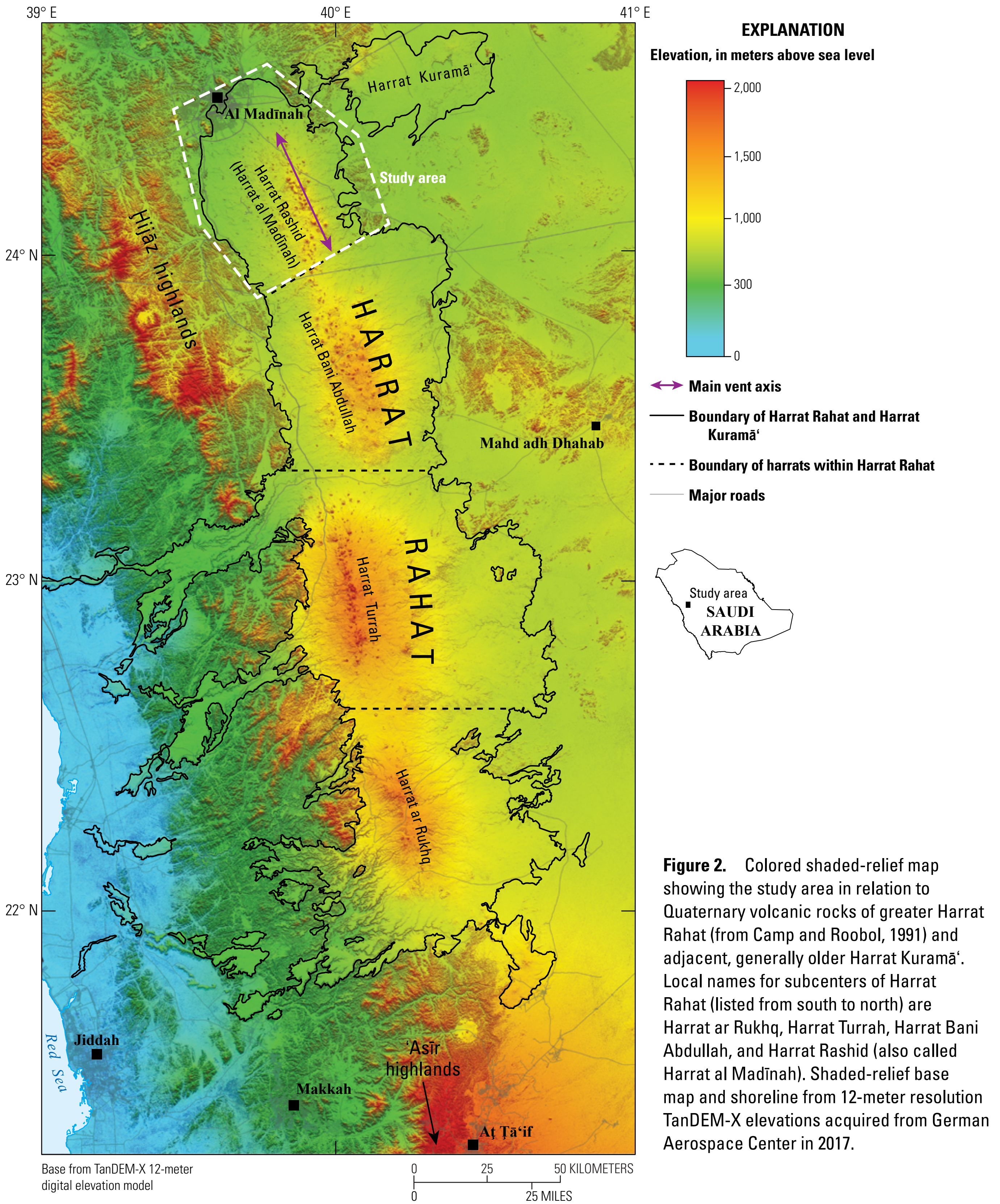

Figure 2. Colored shaded-relief map showing the study area in relation to Quaternary volcanic rocks of greater Harrat Rahat (from Camp and Roobol, 1991) and adjacent, generally older Harrat Kuramā‘. Local names for subcenters of Harrat Rahat (listed from south to north) are Harrat ar Rukhq, Harrat Turrah, Harrat Bani Abdullah, and Harrat Rashid (also called Harrat al Madīnah). Shaded-relief base map and shoreline from 12-meter resolution TanDEM-X elevations acquired from German Aerospace Center in 2017.

Geological and volcanological investigations in the 1970s and 1980s C.E. preceded current high-precision methods for measuring the eruption ages of volcanic rocks, so it was not then possible to assess eruption frequency quantitatively. Methods were also in their infancy, or did not exist, to evaluate where, how fast, and in what abundances lava and ash might travel during eruptions, or to use geophysical and geodetic signals to detect the presence or absence of magma stored in the crust. Subsequent great advances in those and other scientific methods have enabled much more accurate and useful assessments of volcanic hazards at sites around the world.

Al Madīnah and other cities in the Kingdom of Saudi Arabia are expanding rapidly, along with their supporting infrastructure, such as highways, high-speed rail, water pipelines, and electrical transmission systems (fig. 3). Informed decisions must be made on where to develop and to what standards, and plans must be made to safeguard the public when volcanic unrest next commences. A comprehensive and modern understanding of volcanic and associated seismic (earthquake) processes is therefore needed to make these decisions prudently. The need for such advance planning was highlighted by the sudden swarm of earthquakes and accompanied ground cracking in 2009 C.E. at the Harrat Lunayyir volcanic field (fig. 1) caused by the approach of magma (molten rock) so close to the surface (Pallister and others, 2010) that the event is referred to informally as a failed

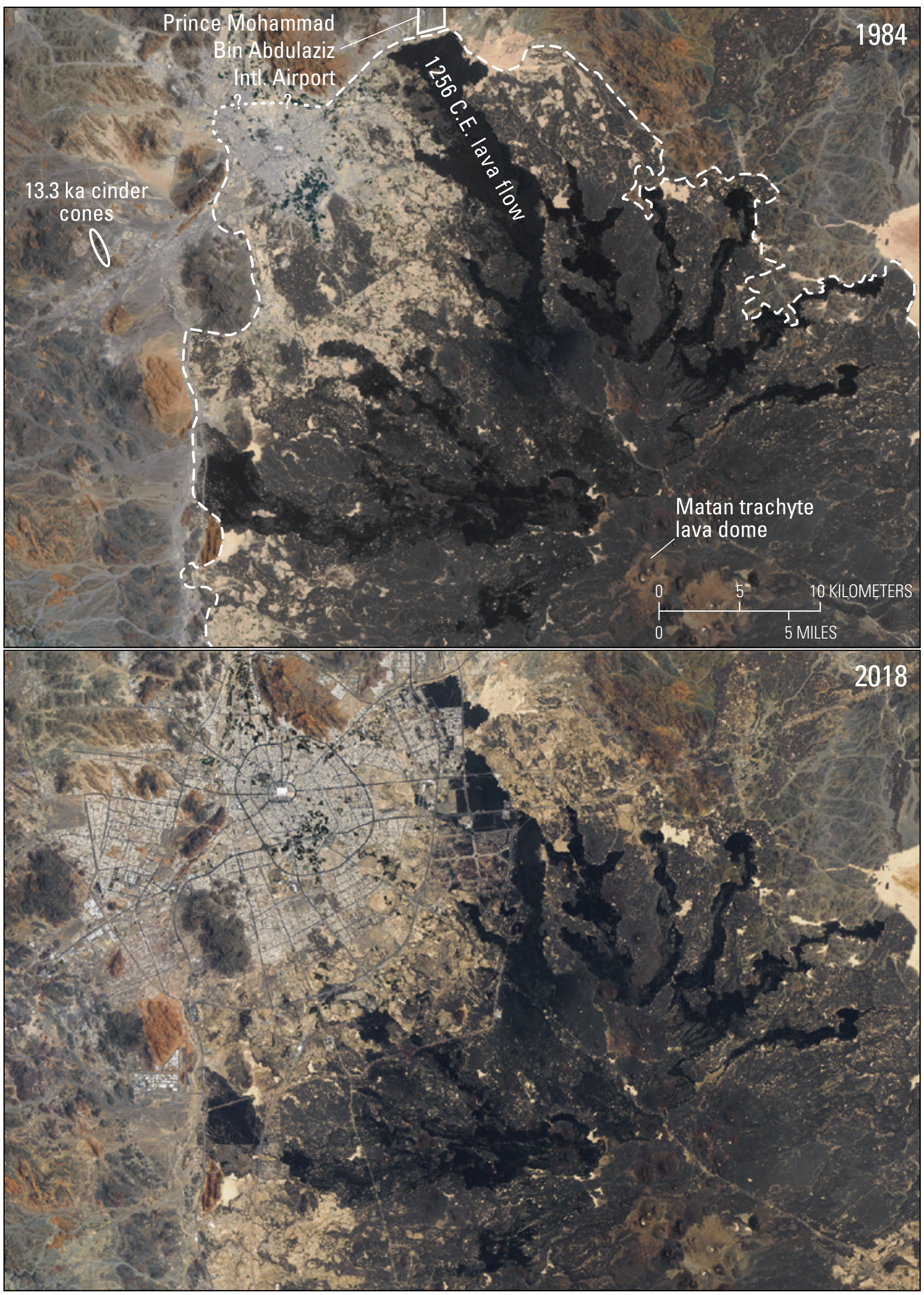

Figure 3. Satellite photographs showing Al Madīnah and the north end of Harrat Rahat in 1984 (top) and 2018. (bottom). Labeled are the 1256 C.E. lava flow, 13.3-thousand-year-old (ka) cinder cones in the western suburbs, the Matan trachyte lava dome, and the Prince Mohammad Bin Abdulaziz International Airport. The white dashed line shows the approximate perimeter of Quaternary volcanic rocks (queried where concealed in Al Madīnah) of Harrat Rahat. Prior studies interpreted distinctly dark-colored lava flows as Holocene, but all in the image except the 1256 C.E. flow proved to be latest Pleistocene (60–20 ka) as dated by the ^{36}Cl exposure-age method. Upper image was taken by the Landsat 5 thematic mapper on June 22, 1984 C.E.; lower image by the Landsat 8 operational land image on July 22, 2018 C.E.

eruption. A similar event, or an eruption, at northern Harrat Rahat would threaten large numbers of people and sites of international cultural importance. To allow for appropriate advance planning and to improve scientific understanding of this enigmatic continental volcanism, the Saudi Geological Survey (SGS) and the U.S. Geological Survey (USGS) embarked in 2013 C.E. on an intensive, multidisciplinary geological and geophysical investigation of northern Harrat Rahat. The study area extends for some 70 km south from Al Madīnah to near latitude 24° N., encompassing the entirety of what is known locally as Harrat Rashid or Harrat al Madīnah (fig. 2). Many of the findings of this effort have been published in peer-reviewed scientific journals as they were concluded. To present and highlight the results of the SGS-USGS project, this volume assembles generally expanded versions of most of those reports, as well as some wholly new findings, as a series of chapters. These chapters are somewhat technical scientifically, so the present chapter introduces the project and summarizes major results for readers who are non-specialists.

Geologic and Tectonic Setting

The Arabian harrats are the most recent of three peak periods of basaltic volcanism on the Arabia Plate over the last approximately 30 million years (Bosworth, 2015). The first period, at 31–30 million years ago (Ma) (during the Oligocene geologic epoch), preceded opening of the Red Sea and was part of the volcanic event that covered portions of present-day Ethiopia, Sudan, Eritrea, and southwest Yemen with floods of basaltic lava. This so-called trap volcanism has been interpreted as a consequence of the arrival beneath what is now the Afar depression of a major plume of material ascending from deep in the mantle that partly melted as the confining pressure diminished (Gass, 1970); these melts then segregated and rose to the surface, erupting as floods of basaltic lava. Modest uplifts locally preceded the volcanic outpourings, so the first indications of the arriving plume were prior to 31–30 Ma, but are not well dated (Gass, 1970; Sembroni and others, 2016, and references therein). The second period at 24–21 Ma (overlapping the transition from the Oligocene to the Miocene geologic epochs) marked the earliest known widespread magmatism associated with the initial opening of the Red Sea and is mainly recorded by swarms of basaltic dikes (planar cracks filled with magma that then solidify as hard rock) and small gabbroic intrusions flanking the Red Sea margins, although some deeply dissected volcanic fields are also preserved from that period (Camp and Roobol, 1992; Coleman, 1993; Bosworth, 2015). The dikes and intrusions undoubtedly fed volcanic fields, but subsequent erosion has stripped away most of those volcanic rocks. Various lines of geologic evidence indicate there were low elevations at that time near and along what is now the Red Sea, possibly similar to parts of the African rift valleys (Coleman, 1993), and that marine conditions had developed along the Red Sea by the middle Miocene (by about 16 Ma). The third period of volcanism constructed the late Cenozoic harrats, including Harrat Rahat. Onset ages of the harrats differ from one area to another, are not closely defined by direct dating, and in some localities overlap the prior volcanic events (Bohannon and others, 1989; Camp and Roobol, 1992; Coleman, 1993), but harrat volcanism mostly post-dated both the uplift of the Ḩijāz-ʻAsīr highlands along the east side of the Red Sea and the onset of the Aqaba-Dead Sea-Levant transform fault system (figs. 1, 2) at around 14–11 Ma during the Miocene geologic epoch (Bohannon and others, 1989; Reilinger and others, 2015). This time of mountain uplift and the initiation of transform faulting corresponded with the final phase of opening along the Gulf of Aden and establishment of its organized magmatic seafloor spreading (Bosworth, 2015). The tectonic rearrangements at that time may have been accompanied by a change in stress in the Arabia Plate, facilitating ascent of magmas and accounting for enhanced volcanism.

In most areas, the Saudi Arabian harrats directly overlie intrusive and low-grade metamorphic rocks of the Precambrian Arabian Shield, showing that the shield was uplifted and erosionally unroofed of nearly all covering younger (Paleozoic and Mesozoic) sedimentary rocks prior to harrat volcanism. Changes in the types of Arabian Platform sedimentary rocks across the Ḩāʼil arch (north of Ḩāʼil; fig. 1; Powers and others, 1966, p. D104) indicate that gentle uplift of the shield may have commenced as early as near the end of the Mesozoic (Campanian Stage of the Late Cretaceous Period, or around 80–70 Ma). Fault-bounded basins (grabens) along the east side of the Red Sea locally contain and expose rocks as old as Late Cretaceous, but widespread rift faulting and associated sediment in-filling commenced much later near the Oligocene to Miocene transition, around 23 Ma, about the time of widespread basaltic diking (Bosworth and others, 2005).

Camp and others (1991) and Camp and Roobol (1992) proposed that the largest harrats, including Harrat Rahat, define a central, north-trending belt that they refer to as the Makkah-Madīnah-Nafud, or MMN, line that coincides approximately with the crest of basement uplift (fig. 1). Harrats to the east and west of the MMN line are smaller, include lavas that are more alkaline and lower in silica, and locally contain fragments of rock carried up from the upper mantle that are nearly unknown from harrats along the MMN line. These differences in effusive flux and magma composition are consistent with greater extents of melting, and perhaps melting to shallower depths, beneath the MMN line than beneath its margins. Regional seismic tomography shows a substantial shallowing (to 60–80 km) of the base of the lithosphere[1] within the upper mantle beneath the MMN line (Chang and others, 2011; Yao and others, 2017), consistent with higher temperatures and enhanced partial melting beneath that region. Speculatively, enhanced volcanism along the MMN line may result from a prior localized region of thin lithosphere that focused subsequent Cenozoic upwelling and partial melting through a feedback process (Sisson and others, 2023).

[1]The lithosphere is the part of Earth's crust and upper mantle that is sufficiently cool to behave rigidly and to deform with some elasticity. The plates that move on Earth's surface, form at the midocean ridges, and in places subduct, compose the lithosphere.

Geology, Eruptive History, and Volcanic Hazards of Northern Harrat Rahat

Camp and Roobol (1991) produced a geologic map of the entirety of Harrat Rahat, and Moufti (1985) documented the detailed geology of the northernmost portion encompassing the majority of its young, explosive, and silicic products. Those studies accurately distinguished the spatial distribution and types of most volcanic deposits but lacked access to abundant high-precision eruption-age determinations, so interpretations about eruptive history and frequency were provisional. Camp and Roobol (1991) subdivided the volcanic field into three successively younger formations: the Miocene Shawahit basalt, the Pliocene Hammah basalt, and the Quaternary Madinah basalt. Each formation consists chiefly of basalt and subordinate hawaiite,[2] but the Madinah basalt, in particular, includes appreciable mugearite, benmoreite, and trachyte[3] that are clustered along the field's topographically highest and volcanically most productive vent axis. All Harrat Rahat rocks north of about latitude 24° N. were assigned to the Quaternary Madinah basalt except for scattered small shields interpreted as windows exposing the underlying Pliocene Hammah basalt.

Camp and Roobol (1991) further subdivided the Quaternary Madinah basalt into seven units, each interpreted as encompassing broadly similar eruption ages, designated from oldest to youngest as units Qm_1 to Qm_7. Deposits interpreted as Holocene (younger than 11,700 years old) were distinguished as units Qm_5 through Qm_7, with units Qm_5 and Qm_6 pre- and post-dating a Neolithic pluvial period during which widespread manmade stone rings, mounds, and other structures were constructed (fig. 4), and unit Qm_7 being products of the historical eruption of 1256 C.E. (654 A.H.) and possibly a cluster of four small cinder cones in the present western suburbs of Al Madīnah (fig. 3), which were speculatively assigned to an eruption in 641 C.E. (20 A.H.) recounted briefly in a written record as having taken place somewhere in the region. Within about 70 km of Al Madīnah, the map of Camp and Roobol (1991) designates two volcanic deposits as members of unit Qm_7, six as members of unit Qm_6, and eight as members of unit Qm_5, although for the latter, some separate mapped exposures may be of the same lava flows partly overlapped and subdivided by younger eruption products. If correct, these assignments would indicate more than 10 sizeable eruptions of mainly basaltic lavas close to Al Madīnah during the Holocene (the past 11,700 years), raising the strong possibility of similar eruptions in the near future that would pose a substantial hazard to the city and its servicing infrastructure.

The SGS-USGS project undertook detailed geologic re-mapping of the northern portion of Harrat Rahat, producing and employing a new high-resolution digital topographic base, with delineation of volcanic deposits aided by abundant high-precision $^{40}Ar/^{39}Ar$ and ^{36}Cl age determinations, whole-rock major and trace element geochemistry, and paleomagnetic measurements (Downs, 2019; Downs and others, 2018, 2019, 2023a,b; Stelten and others, 2020, 2023a,b; Champion and others, 2023; Robinson and Downs, 2023). Important revisions to the eruptive history include that only two deposits are identified as Holocene, these being the aforementioned lava flow and vent complex of the 1256 C.E. (654 A.H.) eruption and a trachyte dome and surrounding apron of pyroclastic flow deposits of Um Rgaibah located 55 km south-southeast of Al Madīnah's center. The cluster of four cinder cones in Al Madīnah's western suburb (fig. 3) proved to be latest Pleistocene (13,300 years old) based on a direct ^{36}Cl exposure-age measurement and supported by their paleomagnetic direction, which is also inconsistent with eruption at 641 C.E. (20 A.H.). Paleomagnetic directions and ^{36}Cl exposure ages from the large basaltic lava flows of Jabal Qidr and Habir at Harrat Khaybar, 130–160 km to the north-northeast of Al Madīnah (fig. 1), allow for their eruption at 641 C.E. (20 A.H.), potentially locating that eruption and reconciling the historical account. Other deposits of northern Harrat Rahat previously interpreted as Holocene proved to have erupted 60,000 to 20,000 years ago (at 60–20 kilo-annums [ka]) based on ^{36}Cl exposure ages. Potentially, the absence of manmade structures on Harrat Rahat lava flows previously classified as post-Neolithic (unit Qm_6) results from their rugged, uninviting surfaces that contrast starkly with nearby smoother, older lava flows that provided more comfortable sites for Neolithic inhabitants to live and work.

Another important finding is that the overall eruptive history of northern Harrat Rahat can be described as an exponential, or Poisson, frequency distribution with an average eruption frequency of about 3,000 years (Stelten and others, 2023a). A characteristic of exponential frequency distributions is that their standard deviation equals their average recurrence, so the times between eruptions have varied widely. A more detailed analysis of eruption ages treats these as following two superposed exponential probability distributions, one with repose periods averaging about 4,000 years and the other averaging about 200 years, although the latter is not narrowly defined. That analysis indicates about a 1.4 percent chance of an eruption of northern Harrat Rahat over the next 50 years, 2.8 percent for the next century, and 23 percent for the next millennium. There are no indications that volcanism has ended at northern Harrat Rahat, so despite Holocene eruptions being fewer than prior studies inferred, the eruption recurrence rates are similar to estimates from other intracontinental basaltic volcanic fields and are sufficiently high that future eruptions can be expected and should be planned for close to Al Madīnah.

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[2]Hawaiite is volcanic rock similar to basalt but with higher concentrations of alkali elements and typically lower concentrations of magnesia; most hawaiites form as melts segregated from alkali-rich basaltic magmas solidifying underground to modest extents.

[3]Mugearites, benmoreites, and trachytes are volcanic rocks with progressively higher concentrations of silica and alkali elements than basalts and hawaiites; they commonly form as the segregated residual melts produced at greater extents of underground crystallization of alkali-rich basaltic magmas than those that produce hawaiites.

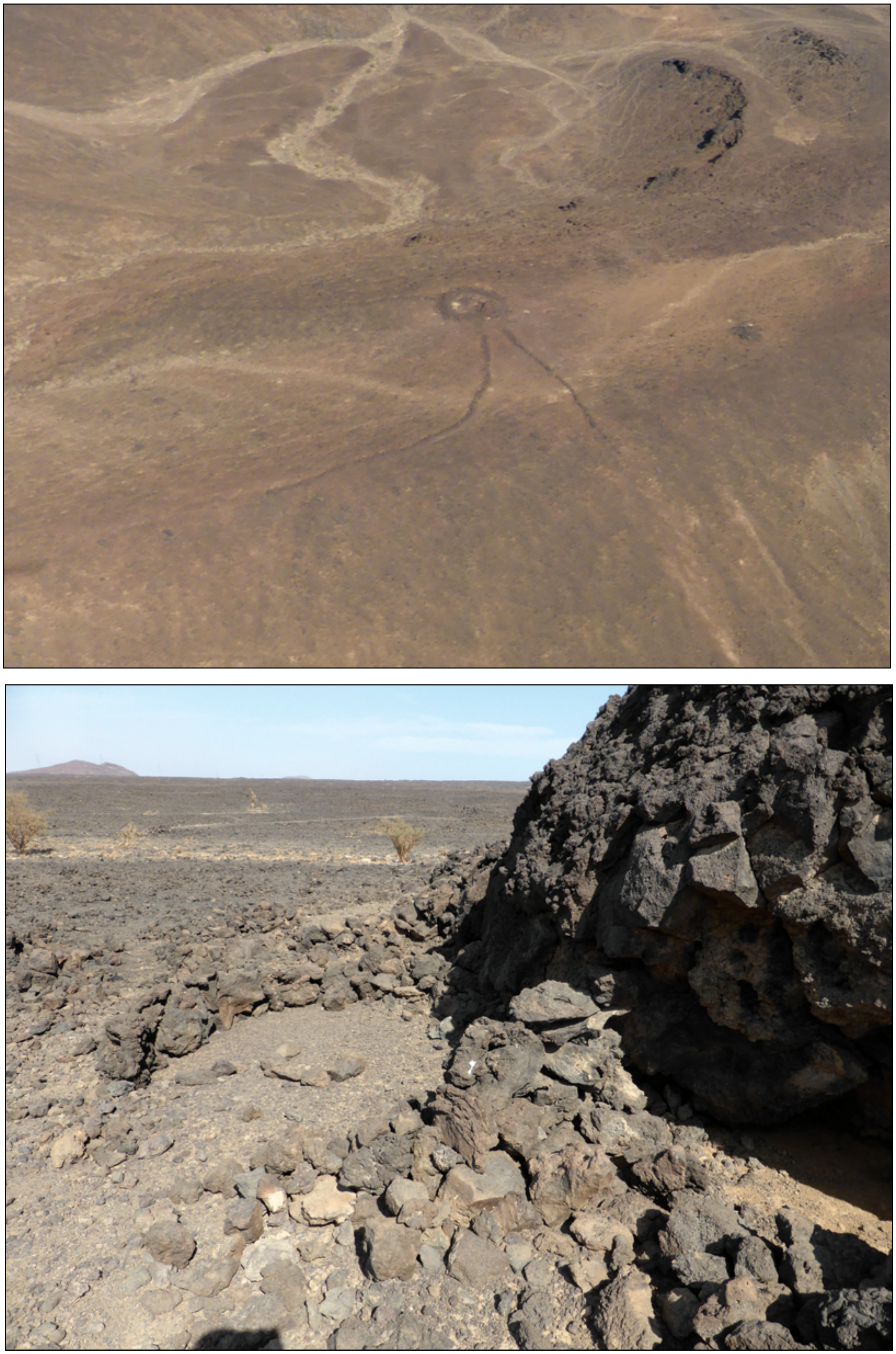

Figure 4. Photographs of representative Neolithic structures in northern Harrat Rahat. Upper photograph shows probable animal trap on the crest of an eroded cinder cone 3 kilometers (km) east of the Matan lava dome (U.S. Geological Survey [USGS] photograph taken from helicopter; ring diameter approximately 7 meters). Lower photograph shows low, ring-shaped stone walls built against the steep edge of a younger lava flow (at right) that probably served as the edges of shelters (USGS photograph taken about 18 km west-northwest of the Matan lava dome along the north margin of the hawaiite of Al Anahi 3; ring diameter approximately 2.5 meters).

The most likely site for the next eruption is toward the north end of the topographically highest and volcanically most productive eastern vent axis in the general area of the 1256 C.E. (654 A.H.) eruption site, although small eruptions venting elsewhere cannot be ruled out. Lava effusing from the vent will flow down shallow valleys, and if the vent is on the east side of the topographic crest of the harrat, lava would flow away from Al Madīnah, but if the vent is on the west side of the crest or its north end, lava would approach and potentially reach densely developed areas. Noxious fumes, ash and cinders, and shallow earthquakes could also harm any people, buildings, or equipment close to the vent site.

Highly explosive eruptions within Harrat Rahat were restricted to relatively uncommon trachyte and some benmoreite magmas that spread pyroclastic flows[4] across adjacent areas. Such pyroclastic deposits, consisting mainly of sheets of lightly indurated fragmental volcanic rocks (lapilli tuff and tuff breccia), each typically a few meters to about ten meters thick, that are preserved continuously as far as 5 km from their source vents but are likely to have extended as far as 10 km as thin, unconsolidated volcanic ash and sands that were readily eroded away. Trachyte and benmoreite eruptions have been restricted to the topographically highest, volcanically most productive parts of the harrat, and the closest trachytic vent, Matan, is about 35 km south-southeast from the center of Al Madīnah (fig. 3). Trachyte eruptions in the Matan area consistently followed nearby eruptions of mugearite or benmoreite by 7–23 thousand years (Stelten and others, 2018, 2023b). Since mugearites and benmoreites have not erupted close to Al Madīnah, explosive trachyte eruptions are not expected in the vicinity of currently developed areas. Even at distances of 35 km or more, such an explosive eruption would be highly visible to and alarming for residents of the city, would severely restrict flight operations at Prince Mohammad Bin Abdulaziz International Airport, threaten the high-speed rail line on the west slope of the volcanic field, close the road crossing the crest of the volcanic field from Al Madīnah south to Mahd adh Dhahab, and would potentially destroy an area of small farms along that road.

Dietterich and others (2018, 2023) used the shapes, slopes, and compositions of basalt and hawaiite lava flows of northern Harrat Rahat to calculate precisely their volumes, speeds of advance, and other eruption characteristics. Those authors find that the young, well-preserved lavas erupted in volumes of 0.1–0.4 km^3. During effusion, the lavas cooled at rates of 2–7 degrees Celsius (°C) per kilometer of flowage distance from their vents, and accordingly, their viscosities increased by about seven orders of magnitude (from 10^2 to 10^9 pascal seconds) from the vent to the flow terminus. Together, these results indicate effusion rates in the range of ten to several hundred cubic meters per second and durations of lava effusion of 1 to 15 weeks. Total eruption durations would have been longer, with unrest developing before and then following periods of lava effusion. Similar durations, volumes, and other properties are expected for future eruptions from northern Harrat Rahat.

[4]Pyroclastic flows are fast moving mixtures of hot rocks, volcanic ash, and volcanic gases that spread by gravity over the landscape. Commonly, pyroclastic flows arrive with sufficient heat, force, and thickness to destroy buildings and kill living creatures. The Roman cities of Pompeii and Herculaneum were destroyed by pyroclastic flows from Mount Vesuvius.

Geophysical Studies and Seismic Hazards

Rifting and separation of Arabia from Africa created extensional faults within the western Arabia Plate that trend approximately parallel to the Red Sea shoreline. Uplift and exposure by erosion of the Arabian Shield may have taken place as early as the Late Cretaceous, but rift faulting associated with plate separation commenced at about the Oligocene-Miocene transition, as shown by an unconformity of that age in grabens containing marine sedimentary rocks along the east margin of the Red Sea (Bosworth and others, 2005). Red Sea basaltic magmatism initiated concurrent with rift faulting at about 24–23 Ma, marking the first definitive and voluminous melting in the mantle along the length of the separating plates. Most prominent among the extensional faults is the system along the steep Great Escarpment along the west flank of the Ḩijāz and ‘Asīr highlands (fig. 2) with its approximately 2,000 meters of relief. Just east of the Ḩijāz highland crest, as well as to its north, is a complex system of broad, shallow, north through northwest trending valleys within which volcanic rocks of the major harrats accumulated. The locations and trends of volcanic vents are controlled by underlying faults or fractures, as shown by the strong clustering and alignment of vents similar to or slightly more northerly than the valleys, the Ḩijāz highland crest, and the Red Sea margin (figs. 1, 2). The harrats just east and north of the uplifted Ḩijāz highland crest probably thinly fill a network of shallow grabens. Continued extensional faulting could produce earthquakes strong enough to damage property and injure residents, so understanding structure and active tectonics was an important aspect of the SGS-USGS project.

Evidence for continued modest extensional faulting in the region of northern Harrat Rahat consists of (1) small-displacement normal faults that cut approximately 2 Ma volcanic rocks about 3–5 km east-southeast of Prince Mohammad Bin Abdulaziz International Airport (those lava flows probably erupted from the south end of Harrat Khaybar), (2) a north-striking, down-to-the-west fault on the east flank of the lava field, (3) north-northwest-striking open fissures along the crest of the volcanic field 5–10 km south-southeast of the vent system for some sizeable lava eruptions at about 20 ka, and (4) the north-northwest alignment of the 13.3 ka cinder cones in the Al Madīnah western suburb (Camp and Roobol, 1991; Downs and others, 2019; Robinson and Downs, 2023). Evidence for longer term extensional faulting includes the location of 13.6 Ma lava flows atop mesas to the west and southwest of Al Madīnah, such as on Jabal ‘Ayr and Jabal

Jimmah, which are substantially out of grade with the present topography (Downs and others, 2019; Stelten and others, 2020, 2023a; Calvert and Sisson, 2023; Robinson and Downs, 2023).

The SGS-USGS project conducted a gravity survey to investigate the possibility of a fault-bounded basin beneath northern Harrat Rahat (Langenheim and others, 2019, 2023). Young volcanic rocks typically have low densities resulting from abundant fractures and open former bubbles, and unconsolidated sediments and weakly consolidated sedimentary rocks have similarly low densities, so gravity measurements can be used to calculate the thicknesses of low-density volcanic rocks, and possibly underlying young sedimentary rocks, atop higher density rocks of the Arabian Shield. The gravity survey shows that low density rocks are thickest (500–600 meters) beneath the topographically highest, dominant vent axis, and that the thickness of low-density rocks approximately matches the constructional volcanic relief. Interpretation of the gravity measurements allows for basins under parts of the volcanic field as much as approximately 300 meters deeper than the flanking Precambrian exposures, but most of the field appears to be underlain by a relatively flat surface at about the elevation of the surroundings. Although faults or fissures clearly control the locus of vents, the volcanic field is not underlain by a sedimentary basin or graben substantially deeper than the adjacent areas. The majority of extensional faulting and graben development appear to have taken place during and shortly following uplift of the Ḩijāz and ‘Asīr highlands. Since then, extensional faulting was relatively minor within and near the harrats and has been outpaced by volcanism.

Magnetotelluric methods were employed to investigate the possibility of a sizeable magma reservoir in the crust beneath northern Harrat Rahat (Bedrosian and others, 2019; Peacock and others, 2023). Aboud and others (2018) inverted magnetotelluric measurements yielding results that appeared to show low-resistivity anomalies, 5–10 km across, at depths of 15–18 km beneath parts of northern Harrat Rahat that those authors proposed could be the top of a sizeable crustal magma body. The possibility of middle-to-upper crustal magma storage was also suggested by well-water temperatures that increase modestly but consistently toward the region of most abundant volcanic vents (Roobol and others, 2007). On the other hand, active magma reservoirs in the middle and upper crust are characteristically overlain and surrounded by abundant low-magnitude seismicity generated by hydrothermal activity above and around the magma body. Such characteristic seismicity is absent from northern Harrat Rahat, as are other direct indications of a vigorous shallow geothermal system, such as exposed hydrothermally altered rocks, high-temperature fumaroles or hot springs, or known emissions of sulfur or carbon dioxide. Unlike the Aboud and others (2018) survey, the SGS-USGS survey reported by Bedrosian and others (2019) and Peacock and others (2023) extended well beyond the limits of the volcanic field to distinguish between magmatic signals, features of the Precambrian crust, and modeling artifacts. Major results included (1) the detection of a conductive zone at depths equal to the base of the volcanic section interpreted to be conductive groundwater ponded in deep volcanic rocks and in possible underlying Cenozoic graben sediments that overlie the Precambrian basement, (2) an absence of conductive anomalies in the upper third of the 38-km-thick crust beneath the volcanic field, and (3) the appearance of sizeable apparent conductive anomalies in the middle and lower crust that extend far beyond the limits of the volcanic field. These apparent conductivity anomalies are too large, strong, and inappropriately oriented to be magma reservoirs but are consistent with being artifacts of the three-dimensional modeling approach routinely applied to magnetotelluric survey results. Those methods for interpreting magnetotelluric data rely on the rocks having directionally uniform (isotropic) resistivity, but if the rocks are strongly anisotropic, the traditional isotropic inversion approach yields severe artifacts. Two-dimensional cross-section inversions avoid this shortcoming and show no conductive anomalies in the crust beneath Harrat Rahat detectable at the resolution of the survey (Bedrosian and others, 2019; Peacock and others, 2023). Although dikes and small igneous intrusions are undoubtedly abundant in the crust beneath Harrat Rahat, no sizeable (multi-kilometer scale), integrated magma reservoir has been detected, consistent with the absence of seismicity concentrated in the upper crust beneath the volcanic field. The two-dimensional magnetotelluric analysis does show the shallow depth (60 km) to the base of the mantle lithosphere beneath the volcanic field that is also imaged by seismic tomographic methods (Yao and others, 2017) and seismic receiver functions (Blanchette and others, 2018, 2023).

Estimates of the seismic shear-wave velocity, composition, and temperature of the crust and upper mantle beneath northern Harrat Rahat were obtained by processing seismic waves recorded by the SGS seismic network (Yao and others, 2017; Blanchette and others, 2018, 2023; Civilini and others, 2019, 2023). Shear-waves are slowed or stopped by the presence of melt, so images of the shear-wave velocity of the crust are sensitive probes for the presence of sizeable or widespread magma bodies. A detailed study of shear-wave velocities beneath northern Harrat Rahat and vicinity does not show a magma reservoir in the upper 30 km of the crust, within the resolution of the survey (Civilini and others, 2019, 2023). An independent regional study (Tang and others, 2018) found modestly reduced shear-wave velocities at 15–30 km depth at sites generally between Harrats Khaybar, Lunayyir, Rahat, and Hadan. Those authors proposed the anomalies could be active reservoirs of magma related to the harrats, but the strongest anomalies do not actually underlie the harrats, suggesting they result from other causes, perhaps lightly metamorphosed, and therefore seismically slow, Precambrian sedimentary and volcanic rocks. Seismic receiver functions (Blanchette and others, 2023) measure the thickness of the Arabia Plate crust and show that it is appreciably thinned only west of the Ḩijāz and ‘Asīr highlands, and that deep crustal extension does not extend to beneath the region of abundant subaerial volcanism.

Pallister and others (2010) described and analyzed the failed eruption of 2009 at Harrat Lunayyir that ruptured the ground and generated abundant shallow seismicity. Remarkably, the ongoing seismic activity includes micro-earthquakes (magnitudes 1–2) located in the upper mantle beneath that volcanic field. Ordinarily, earthquakes are exceptionally uncommon in the upper mantle beneath stable continents, and upper mantle rocks must be relatively cold to fail brittlely and generate seismicity, consistent with the late Precambrian (Neoproterozoic) age of the overlying shield. However, seismic tomography (Yao and others, 2017) shows that the transition from the base of the lithosphere to the top of the asthenosphere[5] is considerably shallower (60–80 km) beneath the harrat belt of western Arabia than the expected depth (about 150 km) to the base of undisturbed Neoproterozoic lithosphere. The asthenosphere is plastic and flows readily owing to its high temperatures, so the short distance (10–15 km) between the top of the asthenosphere and the sites of mantle seismicity implies a steep thermal gradient that could not be sustained for long times because of the high thermal conductivity of mantle rocks. A possible resolution to this paradox is that a substantial thickness of deeper lithosphere, perhaps on the order of 100 km, was removed relatively recently from beneath the harrat belt by some dynamic process, such as active rifting (Blanchette and others, 2018) or magmatically induced foundering (Sisson and others, 2023).

The 2009 failed eruption of Harrat Lunayyir also provides an example of the abundances, strengths, and depths of earthquakes that may accompany renewed volcanism at northern Harrat Rahat. Earthquakes near Al Madīnah are likely to be caused by magma approaching the surface, so earthquakes are most probable in the area, or areas, of abundant young volcanic vents. Kiuchi and others (2019, 2023a) quantify earthquake ground-motion strength versus epicentral distance for earthquakes in western Saudi Arabia. Kiuchi and others (2023b) use the mapped locations and ages of volcanic vents of northern Harrat Rahat as indicating the probable area and recurrence frequency of earthquakes caused by magmatic activity. They deduce that the area of frequent eruptive vents, centered 25 km southeast of Al Madīnah's interior, has a 2 percent probability over a 50-year period of experiencing a ground acceleration of about 0.14 *g* (*g* is the standard gravitational acceleration at Earth's surface of 9.81 meters per second per second) and a peak ground velocity of about 10 centimeters per second (cm/s). Following the same approach, they estimate Al Madīnah's interior as having a 2 percent probability in a 50-year period of ground motions of about 0.07 *g* and 3 cm/s. Zahran and others (2023) take a different approach to address the same issue, considering the diversity of temporally clustered earthquakes (seismic swarms) that could take place during a period of volcano-seismic activity, and they integrate results from several additional areas of volcanogenic seismicity, including just west of Al Madīnah where an eruption took place outside the limits of the main volcanic field at about the Pleistocene-Holocene boundary (Stelten and others, 2023a). Zahran and others (2023) derive that during a period of volcano-seismic unrest, the interior of Al Madīnah could experience ground accelerations of about 0.09 *g*, and that accelerations in volcanic vent areas could be in the range of 0.13–0.18 *g*. The independently derived results of Kiuchi and others (2023b) and Zahran and others (2023) agree sufficiently to conclude that when volcanic unrest recommences, residents of Al Madīnah will feel earthquakes across the city interior, and that ground motions close to sites of volcanic vents or shallow intrusions could be sufficiently strong to damage buildings.

[5]The asthenosphere is the part of Earth's mantle underlying the lithosphere; although nearly or entirely solid, the asthenosphere is sufficiently hot to deform plastically. Earth's tectonic plates (lithosphere) move atop the soft asthenosphere.

Deeper Origins of Harrat Volcanism

Most of Earth's magmas form by decompression melting wherein regions of the upper mantle that are close to their melting temperatures and that ascend to sufficiently shallow depths partially melt owing to reduced pressures. Melts then segregate from their sources and ascend through overlying rocks, with some portions erupting and others remaining underground as intrusions. Melting can be passive in places where tectonic plates separate and the underlying mantle upwells and decompresses in response, or it can be active, as where a mantle plume or domain ascends from depth because of its thermal or compositional buoyancy. Late Cenozoic harrat volcanism is enigmatic in that its proximity to and approximate parallelism with the Red Sea are consistent with extension and thinning of the Arabia Plate driving passive melting, but the Arabian continental crust lacks indications of substantial thinning along the belt of harrat volcanism, such as numerous seismically active faults that offset young surficial deposits (sabkhas, alluvial fans, and late Cenozoic lava flows). Alternatively, volcanism could be a product of active upwelling and partial melting of a buoyant mantle plume. The major mantle plume of the region ascended beneath what is now the Afar depression and caused widespread basaltic volcanism during the Oligocene in Ethiopia, Sudan, and southwest Yemen, with subsequent basaltic volcanism largely restricted to the African Rift System and the Afar depression. There are two key difficulties with ascribing Arabian harrat volcanism to the Afar plume. Firstly, the harrats are highly localized along the western Arabia Plate but are absent in northeast Africa and in the northwestern Indian Ocean where impingement and spreading of a plume would be expected to also produce volcanism. Secondly, the harrat magmas' chemical and isotopic compositions are more similar to magmas of the midocean ridges than to products of the Afar plume. The controversial deeper origin of the harrat volcanism is addressed in two petrological papers in this volume (Salters and others, 2023; Sisson and others, 2023).

Salters and others (2023) show that basalts of northern Harrat Rahat differ only modestly in Sr, Nd, Pb, and Hf isotopic values from midocean ridge basalts (MORB) that derive from widespread "depleted" (modified by the previous loss of basaltic melt) asthenospheric upper mantle. Differences of their isotopic values from MORB can be accounted for by the presence in their source of as much as a few tens of percent, by mass, of material similar to the Afar plume. However, since there is no generally agreed upon single chemical and isotopic composition for the Afar plume, proportions of a plume-like component cannot be defined narrowly. Salters and others (2023) also show that progressively more evolved (marked by the succession from basalt through hawaiite, mugearite, and benmoreite, to trachyte) volcanic rocks of northern Harrat Rahat incorporated increasingly larger amounts of material derived from the Precambrian crust, but that the total amounts incorporated are small (less than 5 percent), and that most melting to produce the basalts took place at a depth greater than about 70 km in the garnet peridotite stability field.

Sisson and others (2023) show that the trace-element composition of the mantle source of the basalts is also similar to that of depleted asthenospheric upper mantle, except for an enrichment of strontium, and that the average degree of melting is low (about 3 percent by mass, versus about 6–10 percent for typical MORB). The major-element compositions of basalts are consistent with their having segregated from the deeper parts of the spinel peridotite stability field (on the order of 70–80 km depth) with mantle potential temperatures not discernably greater than those of MORB (1,350–1,400 °C) sources. Trace-element evidence for melting at pressures where garnet is stable can be reconciled with major-element evidence for segregation at slightly lower pressures if the melts are aggregates of liquids produced within a depth interval spanning the garnet-peridotite to spinel-peridotite transition.

Implications of these results are that the basalts are the product of low-degree partial melting of mantle sources only modestly different from those that feed the midocean ridges, rather than predominantly from a high-temperature mantle plume, and that the melts segregate from their sources at depths close to the lithosphere-asthenosphere boundary beneath the harrat belt. Seismic studies indicate that the lithosphere-asthenosphere boundary beneath typical Proterozoic continental crust is at a depth of about 150 km, whereas the lithosphere-asthenosphere boundary beneath the harrat belt is closer to 60–80 km deep. Elsewhere, sites of intracontinental basaltic volcanism away from extensional belts have been interpreted as overlying shallow zones, or "arches," along the base of the lithosphere (Ebinger and Sleep, 1988). A feedback mechanism that could sustain magmatism (Elkins-Tanton, 2005) involves mantle upwelling that would initially channel by buoyancy into such an arch, with melts produced during such decompression solidifying as high-density eclogites concentrated in the deep lithospheric roof of the arch. Accumulation of dense eclogite causes foundering of the lithospheric roof of the arch, leading to further upwelling and partial melting of asthenosphere focused into that region. Continued emplacement of eclogite into the roof leads to additional foundering, focused asthenospheric upwelling, and the cycle continues. Such a process could lead to volcanism localized as a narrow belt, or sites, atop otherwise seemingly ordinary, undisturbed crust.

Reversing the plate-tectonic opening of the Red Sea and Gulf of Aden places the south end of the Arabian harrat belt and its shallow lithosphere-asthenosphere boundary against what is now the Afar depression at the north end of the East African Rift Zone. Prior to plate separation, the regions now marked by the harrat belt and the northern East African Rift Zone may, therefore, have overlain a continuous shallow anomaly along the base of the lithosphere. Arrival of the Afar plume may then have initiated the type of feedback of lithospheric delamination outlined above that would continue after plate separation. In this scenario, the locations and orientations of the Red Sea and Gulf of Aden resulted from forces that rifted the Africa and Arabia Plates apart, whereas those of the East African Rift Zone and harrat belt resulted from prior relief on the base of the Precambrian lithosphere impinged upon and initiated by the Afar mantle plume, leading to subsequent focused upwelling of asthenosphere, partial melting, and eventually volcanism (Sisson and others, 2023).

Directions for Future Research on Harrat Volcanism

The SGS-USGS project on northern Harrat Rahat demonstrated the utility and importance of detailed geologic mapping and precise dating of volcanic rocks of the Arabian harrats. Volcanism is a serious hazard to Al Madīnah that was quantified and assessed more accurately than was possible in prior studies that were unable to date the eruption ages of young volcanic rocks directly or precisely. There are many other young-appearing lava flows elsewhere on the Arabia Plate whose eruption ages are unknown but could be determined readily by the ^{36}Cl exposure-age method. Dating all the young-appearing lavas would allow for a synoptic and quantitative assessment of volcanic activity and hazards on the Arabia Plate. The older histories of the harrats are also very poorly understood, hindering interpretation of their ultimate origins. Erosion has subdued or destroyed the former raised margins and edges of the older individual lava flows, precluding the levels of detailed mapping and subdivision that were possible at northern Harrat Rahat, but stratigraphic relations between lavas are well exposed in the walls of many wadis, or could be sampled by targeted shallow core drilling. The collected rocks could then be dated with the $^{40}Ar/^{39}Ar$ method and analyzed with modern geochemical and isotopic methods. Such work would greatly advance the understanding of the longer term tectonic and magmatic development of the Arabian volcanic province.

As the Saudi Arabian national seismic network continues to expand, the seismological studies presented herein can be extended to the other harrats, as well as to the entire Kingdom of Saudi Arabia. The excellent quality but presently limited amounts of available seismic recordings suggest that the lithosphere of the western Arabian Shield is significantly thinner than beneath the Arabian Platform and has considerable relief on its base. The inferred configuration of the lithosphere-asthenosphere boundary differs from one recent study to another (Chang and others, 2011; Yao and others, 2017; Lim and others, 2020) mainly owing to access to small quantities of seismic data. Characterizing the seismic properties of the crust and mantle lithosphere of the Arabia Plate would provide a major advance in understanding its geological evolution, as well as contributing to the ongoing assessment of natural hazards.

Finally, important non-research work includes developing response plans for renewed volcanic activity. As at Harrat Lunayyir in 2009, this activity can take the form of a period of days to months of frequent strong earthquakes (seismic swarms) that then cease with no eruption, or magma can reach the surface and erupt. Eruption at one of the more remote harrats would be a spectacular opportunity for scientific study and public education, but an eruption close to an urban area would require rapid deployment of instruments to augment and optimize monitoring, and concerted communications between scientists and public safety officials to manage the potential crisis prudently. Experience with eruptions elsewhere shows that the public expects their government to possess crisis-response plans and capabilities. Such capabilities will include rapidly acquiring, installing, and operating portable monitoring equipment, conducting observational overflights (including with drones), safely deploying and retrieving field parties, communicating observations to one or more incident command centers, and then interpreting and reporting developments to non-scientist government officials who will be faced with difficult decisions, including to evacuate some areas for periods of time that can be hard to determine. The long-standing partnership between the SGS and the USGS is a foundation for developing such plans and capabilities.

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