Explosive Trachyte Eruptions from the Al Efairia Volcanic Center in Northern Harrat Rahat, Kingdom of Saudi Arabia

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

Cover. Photograph of trachyte pyroclastic flows and lava flows within the northern Harrat Rahat volcanic field. The dome, lava spine, and surrounding pyroclastic flows in the background on the left side of the photograph are from the trachyte of Um Rgaibah that erupted at 4.2±5.2 thousand years ago (ka). The nested craters in the middle ground on the right side of the photograph were formed during the eruption of Al Efairia around 88.0±1.8 ka. Most of the tan-colored pyroclastic flows within this photograph are from these two eruptions, the latter of which is the largest known explosive eruption within the Harrat Rahat volcanic field. U.S. Geological Survey photograph by Andrew Calvert, 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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Abdullah bin Mufter Al-Shamrani, Chief Executive Officer

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

Contents

Figures

Tables

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)

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

$$°F = (1.8 \times °C) + 32.$$

Abbreviations

C.E.	Common Era
DRE	dense rock equivalent
ICP-MS	inductively coupled plasma mass spectrometry
ka	kilo-annum
Ma	mega-annum
mg	milligram
ppm	part per million
XRF	X-ray fluorescence

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Chapter G

Explosive Trachyte Eruptions from the Al Efairia Volcanic Center in Northern Harrat Rahat, Kingdom of Saudi Arabia

By Drew T. Downs,[1] Mark E. Stelten,[1] Hannah R. Dietterich,[1] Duane E. Champion,[2] Gail A. Mahood,[3] Thomas W. Sisson,[1] Andrew T. Calvert,[1] and Jamal Shawali[4]

Abstract

Harrat Rahat is an alkali basalt, continental, intraplate volcanic field located within the central-western part of the Kingdom of Saudi Arabia. The northern quarter of Harrat Rahat contains evolved volcanic products that achieve trachyte compositions (>60 weight percent SiO_2). Within the Al Efairia volcanic center, pyroclastic-flow and -surge deposits that reflect explosive trachyte volcanism (and minor exposed lava domes that reflect effusive trachyte eruptions) sit at the surface as the youngest expression of volcanic activity within this part of the Harrat Rahat volcanic field. Five trachyte deposits emplaced explosively have been identified within the Al Efairia volcanic center based on geologic mapping, petrography, geochemistry, and paleomagnetism. These units are the trachytes of Um Rgaibah, Gura 5, Gura 4, Al Efairia, and Al Qayf, in descending stratigraphic order. Here, we present 14 $^{40}Ar/^{39}Ar$ analyses from four of these units, which yield eruption ages of 4.2±5.2 thousand years (ka) for the trachyte of Um Rgaibah, 79.7±1.6 ka for the trachyte of Gura 5, 84.3±1.6 ka for the trachyte of Gura 4, and 88.0±1.8 ka for the trachyte of Al Efairia. The eruption age of the trachyte of Al Qayf has been constrained to between 410.3±3.4 and 418.8±1.9 ka using paleomagnetic correlations and $^{40}Ar/^{39}Ar$ ages from overlying and underlying intermediate composition lava flows. Most of these trachytes have distinct geochemical compositions, petrographic characteristics, and directions of remanent magnetization. The exceptions are for the trachytes of Gura 4 and Gura 5, which overlap in their geochemical, petrographic, paleomagnetic, and geochronologic affinities. Based on these similarities, we interpret the trachytes of Gura 4 and Gura 5 to have erupted during a closely spaced (a few decades) time interval from the same magma batch but from craters that are >2 kilometers (km) apart. The eruption of the trachyte of Al Efairia at 88.0±1.8 ka is the result of a different magma batch that erupted a few thousand years prior to the trachytes of Gura 4 and Gura 5. The Al Efairia volcanic center is remarkably different from the Matan volcanic center located ~10 km to the north, which has also erupted young (<150 ka) trachytes. The Matan volcanic center has been shown to produce trachyte compositions only after eruption of basalt followed by intermediate lava flows, whereas only trachyte compositions have erupted within the Al Efairia volcanic center over this same time interval.

[1]U.S. Geological Survey.

[2]U.S. Geological Survey, now deceased.

[3]Stanford University.

[4]Saudi Geological Survey.

Introduction

The Arabia Plate hosts more than 15 continental, intraplate volcanic fields that stretch >3,000 kilometers (km) from the Gulf of Aden to the Mediterranean Sea (fig. 1). In total, these volcanic fields cover an area of ~180,000 square kilometers (km^2) and have constructed one of the largest preserved alkalic volcanic provinces on Earth (Coleman and others, 1983). Volcanic activity initiated ~30 million years ago (Ma) and has continued to the present day with the most recent eruption in 1937 C.E. near the town of Dhamar, Yemen (Coleman and others, 1983; Brown and others, 1989; Camp and Roobol, 1989; Camp and others, 1991, 1992; Shaw and others, 2003; Duncan and Al-Amri, 2013; Moufti and others, 2013; Duncan and others, 2016; Dietterich and others, 2018; Downs and others, 2018, 2023; Stelten and others, 2018, 2023a,b). Most eruptions associated with the late Cenozoic Arabian intraplate volcanic fields produced mafic lava flows and scoria cones (basalt and hawaiite) with minor intermediate magmas (mugearite and benmoreite) and even fewer evolved magmas with >60 weight percent SiO_2 (trachyte and comendite). These more evolved late Cenozoic magmas are mostly confined to the Harrat Rahat volcanic field and composite Harrat Khaybar, Ithnayn, and Kurá volcanic fields in Saudi Arabia (Moufti, 1985; Camp and Roobol, 1989, 1991; Camp and others, 1991; Roobol and Camp, 1991; Moufti and others, 2013; Stelten and others, 2018). Quantification of eruption ages, extents and volumes, and understanding eruptive behavior is fundamental to interpreting the evolution of a predominantly mafic volcanic field such as Harrat Rahat.

Here we investigate a series of explosively emplaced trachyte pyroclastic deposits within the northern part of the Harrat Rahat volcanic field in western Saudi Arabia (figs. 1, 2). These trachytes erupted from a cluster of high-standing vents within a part of Harrat Rahat that is termed the Al Efairia volcanic center (names of volcanic features largely follow Moufti [1985]). Field relations, geochemistry, petrography, paleomagnetism, and $^{40}Ar/^{39}Ar$ radiometric ages have allowed us to assemble a high-resolution map of trachytes that erupted explosively within the Al Efairia volcanic center

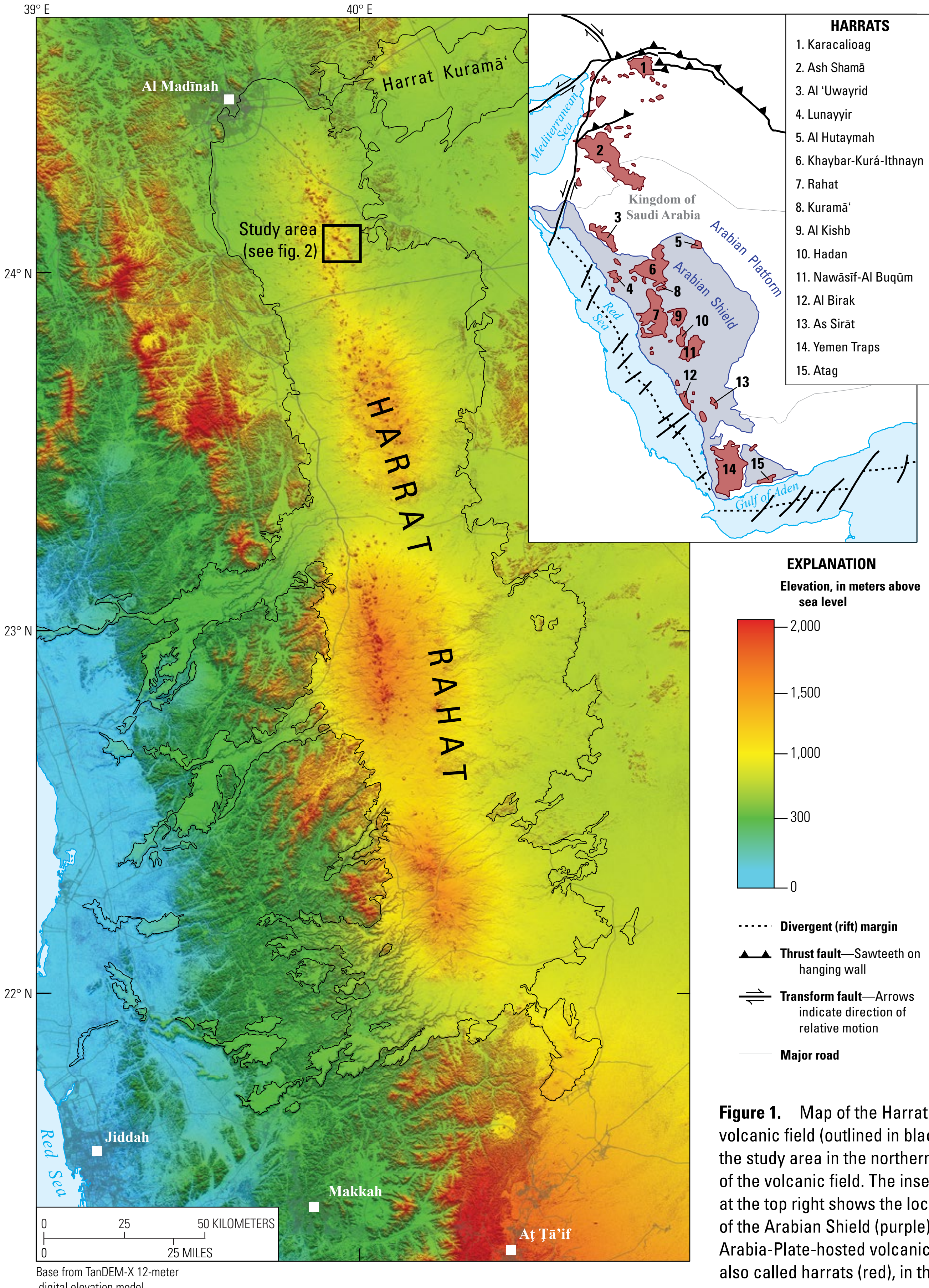

Figure 1. Map of the Harrat Rahat volcanic field (outlined in black) and the study area in the northern part of the volcanic field. The inset map at the top right shows the location of the Arabian Shield (purple) and Arabia-Plate-hosted volcanic fields, also called harrats (red), in their regional tectonic context.

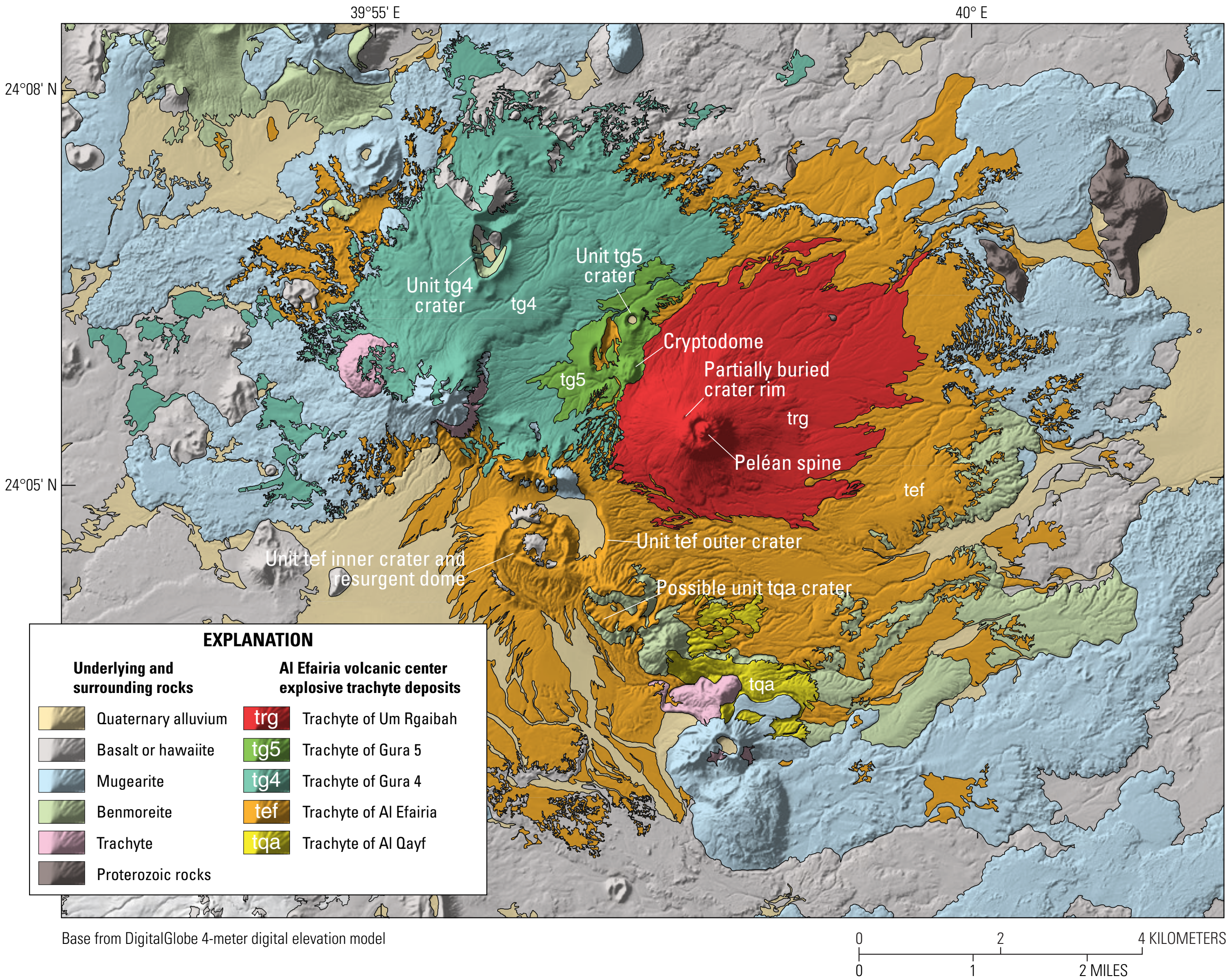

Figure 2. Geologic map of the Al Efairia volcanic center (modified from Downs and others, 2019). Only the most explosively emplaced trachyte deposits are highlighted and geomorphic features of interest are labeled. Surrounding mafic lava flows and scoria cones, silicic lava domes, Proterozoic rocks, and Quaternary alluvium are shown, but not discussed in detail in the text.

(fig. 2). Overall, these volcanic products represent the most explosive products from Harrat Rahat and allow their geologic context with surrounding mafic and intermediate lava flows and scoria cones to be resolved. Additionally, we consider these deposits and their eruptive behavior in the context of trachyte lava domes and pyroclastic deposits from the Matan volcanic center to the north (Stelten and others, 2018).

Geological Setting

Harrat Rahat is the largest volcanic field located entirely within the Kingdom of Saudi Arabia at ~20,000 km^2 in area and a volume of ~2,000 cubic kilometers (km^3) (Camp and Roobol, 1989, 1991). Volcanic and magmatic activity initiated ~10 Ma and continues to the present day with the most recent eruption historically documented in 1256 C.E. (Al-Samhūdī, 1488; Camp and others, 1987; Camp and Roobol, 1989; Moufti and others, 2013). Volcanic rock types, as mapped by Camp and Roobol (1989, 1991), include >95 percent basalt and hawaiite with the remaining eruptive products consisting of mugearite, benmoreite, and trachyte (nomenclature after Cox and others, 1979). Mafic and silicic volcanism yield various characteristic landforms based on eruptive styles. Some of the more distinctive landforms include lava domes and pyroclastic-flow deposits constructed during the eruption of trachytic magmas (fig. 3). Trachytes are almost exclusively restricted to the northern part of Harrat Rahat in the Matan volcanic center, Al Efairia volcanic center, and a single trachyte eruption at Al Wabarah (Moufti, 1985; Stelten and others, 2018; Downs and others, 2019). Here, we focus on the geochronology and field relations of the most explosively emplaced trachyte eruptive products from the Al Efairia volcanic center.

Mafic magmas erupted over the entire ~10-million-year history of Harrat Rahat. Quaternary volcanic strata restricted to northern Harrat Rahat were subdivided into seven units (units Qm_1 through Qm_7 of Camp and Roobol, 1989, 1991, based on the degree of erosion, amount and size of loess-filled depressions on lava-flow surfaces, archeological arguments, and historical records) spanning from ~1.7 Ma to 1256 C.E. (Camp and Roobol, 1989, 1991). These seven units were underpinned by eight K-Ar radiometric ages (Pellaton, 1981; Camp and Roobol, 1989), and refined to lasting from 10.31 Ma to the present with 25 ^{40}Ar/^{39}Ar ages from Moufti and others (2013). Trachytes are known to be among the youngest eruptive products based on stratigraphic superposition. Two trachytes within the Al Efairia volcanic center were dated by K-Ar in the 1980s (Pellaton, 1981), yielding ages of 2.13 Ma for the trachyte of Al Efairia (all unit names are from Downs and others, 2019) and 1.47 Ma for the trachyte of Um Rgaibah. However, many of these K-Ar ages from Harrat Rahat are known to be anomalously old based on more recent ^{40}Ar/^{39}Ar dating (Downs and others, 2018, 2019; Stelten and others, 2018, 2023) and no explosively emplaced trachytes from the Al Efairia volcanic center have previously been dated by the ^{40}Ar/^{39}Ar method. We present 14 ^{40}Ar/^{39}Ar ages from the most widespread trachyte pyroclastic deposits within the Al Efairia volcanic center.

Moufti (1985) described the stratigraphy and assigned names to the trachytic pyroclastic deposits of the Al Efairia volcanic center. He recognized the sequence of eruptions, from oldest to youngest, as unnamed tuff and dome (includes our trachyte of Al Qayf), followed by the trachytes of Al Efairia, Gura 4, Gura 5, and Um Rgaibah. The present

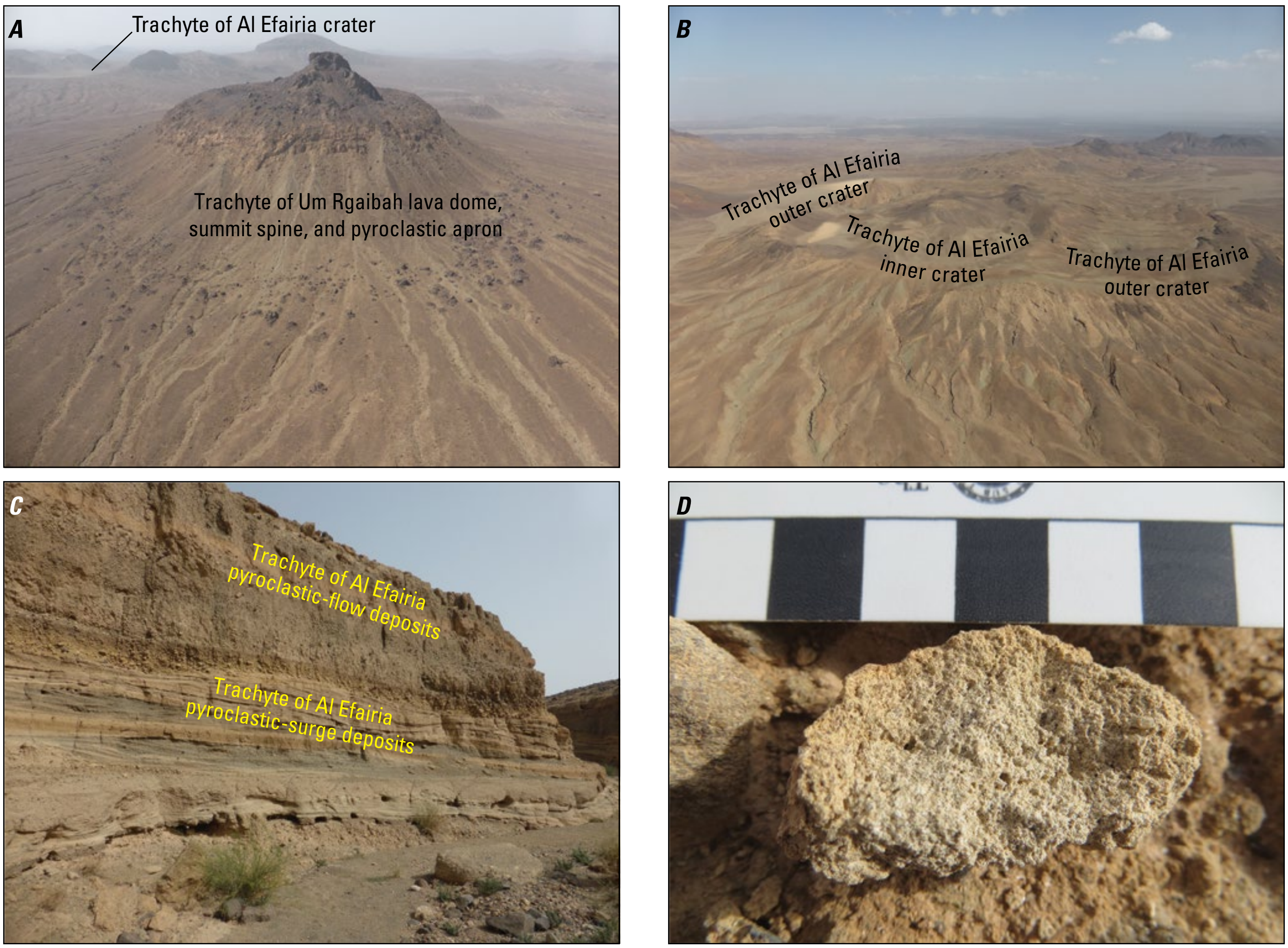

Figure 3. Photographs of the trachytes of Um Rgaibah and Al Efairia, and juvenile pumice from the trachyte of Gura 4. *A*, Photograph looking northwest at the lava dome, summit spine, and surrounding pyroclastic apron of the 4.2±5.2-thousand-year-old (ka) trachyte of Um Rgaibah. The crater for the 88.0±1.8-ka trachyte of Al Efairia is in the back left of the photograph. Photograph by Andrew Calvert, 2014. *B*, Photograph looking southeast at the two nested craters that make up the vent for the 88.0±1.8-ka trachyte of Al Efairia. The inner crater has undergone partial resurgence. Photograph by Andrew Calvert, 2014. *C*, Photograph of interbedded pyroclastic-flow and -surge deposits of the trachyte of Al Efairia erupted at 88.0±1.8 ka. Photograph by Drew Downs, 2016. *D*, Moderately inflated pumice clast from the 84.3±1.6-ka trachyte of Gura 4. Scale interval is 1 centimenter. Photograph by Hannah Dietterich, 2016.

investigation confirms and builds on that work. These trachyte deposits cluster along a high-standing (~100 to 400 meters [m] above the surrounding volcanic plain) north-to-south lineament in northern Harrat Rahat termed the main vent axis. The most prominent trachyte landforms are lava domes, craters, and a widespread, relatively level plain of pyroclastic-flow and -surge deposits with deep (>20 m in places) incised drainage channels. Some of the trachytes formed craters during eruption whereas others erupted as Peléan lava domes and spines before undergoing collapse and generating pyroclastic-flow deposits consisting of poorly to moderately inflated juvenile clasts hosted within a fine-grained, poorly sorted matrix (fig. 3*A–D*). Pumiceous air-fall-tephra deposits are rare, but not entirely absent (Moufti, 1985; Camp and Roobol, 1989; Downs and others, 2019). Pyroclastic-flow and bedded-surge deposits can attain thicknesses of multiple tens of meters, which thin away from their sources over the course of no more than ~10 km for the most widespread pyroclastic deposit. Minor sub-Plinian air-fall-tephra deposits have been identified, but Plinian air-fall-tephra deposits are considered unlikely.

Methods

Discrimination of Geologic Map Units

Individual explosively emplaced trachyte deposits were mapped in the field and on aerial and shaded-relief images, with contacts confirmed by a combination of hand-specimen and thin-section petrography, whole-rock geochemistry, and paleomagnetic studies. The geologic contacts between volcanic units from these investigations are presented as a 1:75,000-scale and 1:25,000-scale map by Downs and others (2019) and at 1:100,000 scale by Robinson and Downs (2023). The distribution of deposits, their source vents, and stratigraphic sequences agree with reconnaissance geologic mapping and detailed stratigraphic sections and observations presented by Moufti (1985). We also present 14 $^{40}Ar/^{39}Ar$ ages from the trachytes of Al Efairia, Gura 4, Gura 5, and Um Rgaibah. Names of units were chosen from geographic landforms, most of which were previously employed by Moufti (1985) and Camp and Roobol (1989, 1991), and adopted by Downs and others (2019) and Robinson and Downs (2023).

To aid in mapping, juvenile material from poorly inflated pumice clasts and dense lava domes (64 samples) were collected for major-oxide and trace-element analyses by X-ray fluorescence (XRF) spectrometry and inductively coupled plasma mass spectrometry (ICP-MS) at the GeoAnalytical Laboratory at Washington State University in Pullman, Washington, by the methods of Knaack and others (1994) and Johnson and others (1999). Detailed XRF and ICP-MS methods are discussed by Downs and others (2018) and all whole-rock chemical compositions are provided by Downs (2019).

$^{40}Ar/^{39}Ar$ Radiometric Dating

Samples for $^{40}Ar/^{39}Ar$ dating were collected from all explosively emplaced trachytes exposed within the Al Efairia volcanic center except the trachyte of Al Qayf, which yielded no acceptable material to be directly dated. Both dense feldspar-rich crystalline groundmass and sanidine crystal separates were used for analyses. Each sample was crushed in a roller mill, ultrasonicated, and the 250 to 355-micrometer-size fraction was concentrated. Approximately 150 milligrams (mg) of material was prepared for groundmass and ~50 mg of sanidine was separated using a Frantz LB-1 Magnetic Barrier Laboratory Separator, and carefully handpicked under a binocular microscope. Samples were packaged in copper foil, bracketed by packets of Bodie Hills sanidine monitor minerals (9.7946±0.0033 Ma; Fleck and others, 2019), encapsulated in quartz vials that were wrapped in 0.5-millimeter-thick cadmium foil to shield samples from thermal neutrons during irradiation, and irradiated for 1 hour in the central thimble of the U.S. Geological Survey TRIGA reactor in Denver, Colorado, (Dalrymple and others, 1981) at a power level of 1 megawatt. The reactor vessel was rotated continuously and oscillated vertically during irradiation to minimize vertical and lateral neutron flux gradients.

Argon isotope analyses were conducted at the U.S. Geological Survey in Menlo Park, California, using a MAP216 single-collector mass spectrometer with a Baur-Signer source and a Johnston MM1 electron multiplier. Argon was extracted from fluence monitors in a single heating step (that is, total fusion) using a New Wave CO_2 laser, whereas argon from groundmass separates of unknown age was extracted in 7 to 15 discrete temperature steps (typically spanning the temperature range of 550 to 1,400 degrees Celsius [°C]) using a molybdenum-shielded custom-resistance furnace with a molybdenum crucible. Sanidine crystal separates were analyzed by laser total fusion using the New Wave CO_2 laser coupled with the MAP216 mass spectrometer. Extracted argon was exposed to a 4-ampere tungsten filament, 125 kelvin cold finger, and two SAES St-175 getters (one operated at 300 °C, and one at room temperature) to remove active gases. Prior to measurement of argon isotopic composition, samples were degassed at 500 °C until undesirable gases (for example, water, nitrogen, and hydrocarbons as measured by a Granville-Phillips Series 835 vacuum quality monitor) were reduced to acceptable levels. Instrumental mass discrimination was calculated by repeated measurement of air, assuming atmospheric $^{40}Ar/^{36}Ar = 298.56±0.31$ (Lee and others, 2006). Ages were calculated using the decay constants recommended by Steiger and Jäger (1977). Uncertainties in $^{40}Ar/^{39}Ar$ ages are reported at the one-sigma level unless otherwise noted (table 1) and include propagated uncertainties in counting statistics and J values.

Table 1. $^{40}Ar/^{39}Ar$ ages from explosive trachyte deposits of the Al Efairia volcanic center.

[Samples were irradiated at the U.S. Geological Survey TRIGA reactor using 9.7946-million-year-old Bodie Hills sanidine as a neutron flux monitor. Preferred ages are in bold font, and those in red are anomalous and not used to calculate the weighted mean ages. Weighted mean ages are the preferred ages for units dated multiple times. MSWD, mean square of weighted deviates; IH, incremental heating; LF, laser fusion; T, temperature; ka, kilo-annum]

Sample number	Easting[1]	Northing[1]	Method, material	^{39}Ar, in % (T range,[2] in °C)	Plateau		Isochron			Total gas age ±1σ (ka)
					Age ±1σ (ka)	MSWD	Age ±1σ (ka)	MSWD	$^{40}Ar/^{36}Ar$ ±2σ	
				Trachyte of Um Rgaibah						
R14TRO038	597700	2664563	IH, groundmass	91 (550–1,200)	15.2±2.7	1.9	**4.2±5.2**[3]	1.4	300.9±2.2	20.0±2.0
				Trachyte of Gura 5						
R14AC025	596742	2666166	IH, sanidine	74 (625–1,075)	**79.2±1.8**[3]	1.1	88.8±6.1	0.9	287.1±10.9	108.2±1.5
			LF, sanidine	—	112.4±2.2	1.0	**86.3±13.2**[3]	0.8	310.8±16.6	—
R14AC028	597270	2666652	IH, sanidine	63 (700–925)	**81.5±3.7**[3]	2.4	110.2±17.4	1.6	272.1±34.0	161.4±17.1
Weighted mean age					**79.7±1.6**[3]	0.3				
				Trachyte of Gura 4						
R14AC035[4]	593636	2665094	IH, sanidine	73 (650–1,100)	64.0±3.1	1.4	61.8±8.1	1.4	297.4±20.1	100.0±2.1
R14AC080	594661	2667022	IH, sanidine	71 (600–1,150)	**84.0±1.8**[3]	1.1	80.1±5.2	1.1	298.3±8.4	102.6±1.5
R14AC078	594832	2664097	IH, sanidine	58 (650–1,050)	**85.7±4.1**[3]	1.7	80.4±6.4	1.4	301.2±15.7	135.5±2.4
Weighted mean age					**84.3±1.6**[3]	0.2				
				Trachyte of Al Efairia						
R14AC029[4]	597141	2666662	IH, groundmass	78 (550–950)	72.3±2.8	2.1	68.0±6.2	2.2	296.7±3.8	81.3±2.0
R14AC055	594976	2662545	IH, sanidine	78 (625–1,100)	**83.7±1.6**[3]	1.5	80.4±6.0	1.6	300.1±19.4	88.7±1.2
			LF, sanidine	—	**90.9±1.9**[3]	1.2	88.6±6.5	1.3	296.7±29.9	—
R14AC070	595306	2662928	IH, groundmass	92 (550–1,150)	**86.9±1.9**[3]	0.5	89.5±4.7	0.5	294.7±2.8	88.2±2.0
			IH, sanidine	78 (650–1,150)	**93.1±2.1**[3]	1.2	94.7±3.4	1.2	293.2±7.2	95.2±1.6
			LF, sanidine	—	**86.5±8.7**[3]	0.5	81.0±14.2	0.6	297.0±11.5	—
Weighted mean age					**88.0±1.8**[3]	2.6				

[1]Eastings and northings are given in the World Geodetic System of 1984 (WGS84) datum using the Universe Transverse Mercator (UTM) zone 37N projection.

[2]Temperature range gives the temperature steps that released the stated amount of ^{39}Ar used to calculate the $^{40}Ar/^{39}Ar$ ages.

[3]Preferred age.

[4]Sample not used to calculate the weighted mean age.

Paleomagnetism

Paleomagnetic secular variations were measured from juvenile trachyte pumice clasts within the Al Efairia volcanic center to assess the timing of their eruptions. Though the paleomagnetic directions are used in conjunction with the $^{40}Ar/^{39}Ar$ ages, the ages do not have the precision to indicate whether multiple eruptions were contemporaneous within decades to centuries.

Paleomagnetic samples were collected, processed, and interpreted using the methods of McElhinny (1973). We collected eight cores, each 10 centimeters (cm) long, at each field site using a handheld, gasoline-powered, 2.5-cm coring drill, and oriented exclusively by sun compass. A 2.5-cm-long specimen from each core was measured using an automated cryogenic magnetometer and then subjected to alternating-field demagnetization to remove secondary components of magnetization. An isothermal component from nearby lightning strikes was the most frequent source of secondary magnetization in these volcanic rocks. The characteristic direction of remanent magnetization for each site was calculated using Fisher statistics on data from (1) line fits of data on vector component diagrams, (2) plane fits on equal-area diagrams, and (3) mixtures of lines and planes data. We present site mean directions of magnetization for each group in table 2 with statistics, including 95-percent confidence limits.

Explosively Emplaced Trachytes

Trachyte of Al Qayf

The trachyte of Al Qayf is the stratigraphically lowest, and therefore oldest, of the explosively emplaced trachytes exposed within the Al Efairia volcanic center. The source vent for this unit is unknown and presumed to be buried by younger volcanic products, but a poorly exposed crater ~1 km northwest and west of current outcrops is a probable source (fig. 2). This pyroclastic deposit is only exposed over 1.4 km^2 and reaches 2.2 km in length (or >3 km from its potential source). Assuming a thickness between 10 and 15 m (these thicknesses are used to calculate a conservative volume estimate of all units discussed), the dense rock equivalent (DRE) volume of the exposed trachyte of Al Qayf is between 0.01 and 0.02 km^3.

Moderately inflated juvenile pumice clasts are aphyric. Geochemically, most of the trachyte deposits of the Al Efairia volcanic center are distinct with whole-rock concentrations of TiO_2, FeO*,[5] K_2O, and Zr being particularly useful for designation purposes (fig. 4). For this unit, all TiO_2 analyses yield 0.23 weight percent, FeO* ranges from 4.9 to 5.0 weight percent, K_2O ranges from 5.1 to 5.2 weight percent, and Zr ranges from 1,150 to 1,200 parts per million (ppm) (fig. 4).

[5]FeO* indicates total iron expressed as FeO.

Table 2. Paleomagnetic analyses from explosive trachyte deposits of the Al Efairia volcanic center.

Unit name	Site[1]	Easting[2]	Northing[2]	Cores used[3]	Exp.[4]	I[5]	D[6]	α95[7]	k[8]	R[9]	Pole lat. (°N)[10]	Pole long. (°E)[10]
Trachyte of Um Rgaibah	R17DC018	599693	2665835	8/8	Li	27.5°	8.4°	3.6°	240	7.9709	77.6	178.7
Trachyte of Gura 5	R17DC019	596693	2665991	8/8	Li	50.4°	339.4°	3.0°	345	7.9797	70.5	335.7
Trachyte of Gura 4	R17DC020	594953	2666345	8/8	Mx	51.3°	346.3°	3.2°	306	7.9771	75.6	346.1
Trachyte of Al Efairia	R17DC017	600521	2662364	8/8	Mx	37.8°	4.3°	2.6°	477	7.9853	85.1	165.0

[1]Alphanumeric identifier.

[2]Eastings and northings are given in the World Geodetic System of 1984 (WGS84) datum using the Universe Transverse Mercator (UTM) zone 37R projection.

[3]Number of cores used out of the number of cores originally collected at the site.

[4]Treatment of the demagnetization procedure, where Li indicates that a vector component lines analysis was used and Mx indicates that a mixture of lines and planes was used to define the mean remanent direction.

[5]Remanent inclination, in degrees.

[6]Remanent declination, in degrees.

[7]Radius of the 95-percent confidence limit about the mean direction.

[8]Estimate of the Fisher precision parameter.

[9]Length of the resultant vector.

[10]Location of the virtual geomagnetic pole calculated from the mean direction of the site.

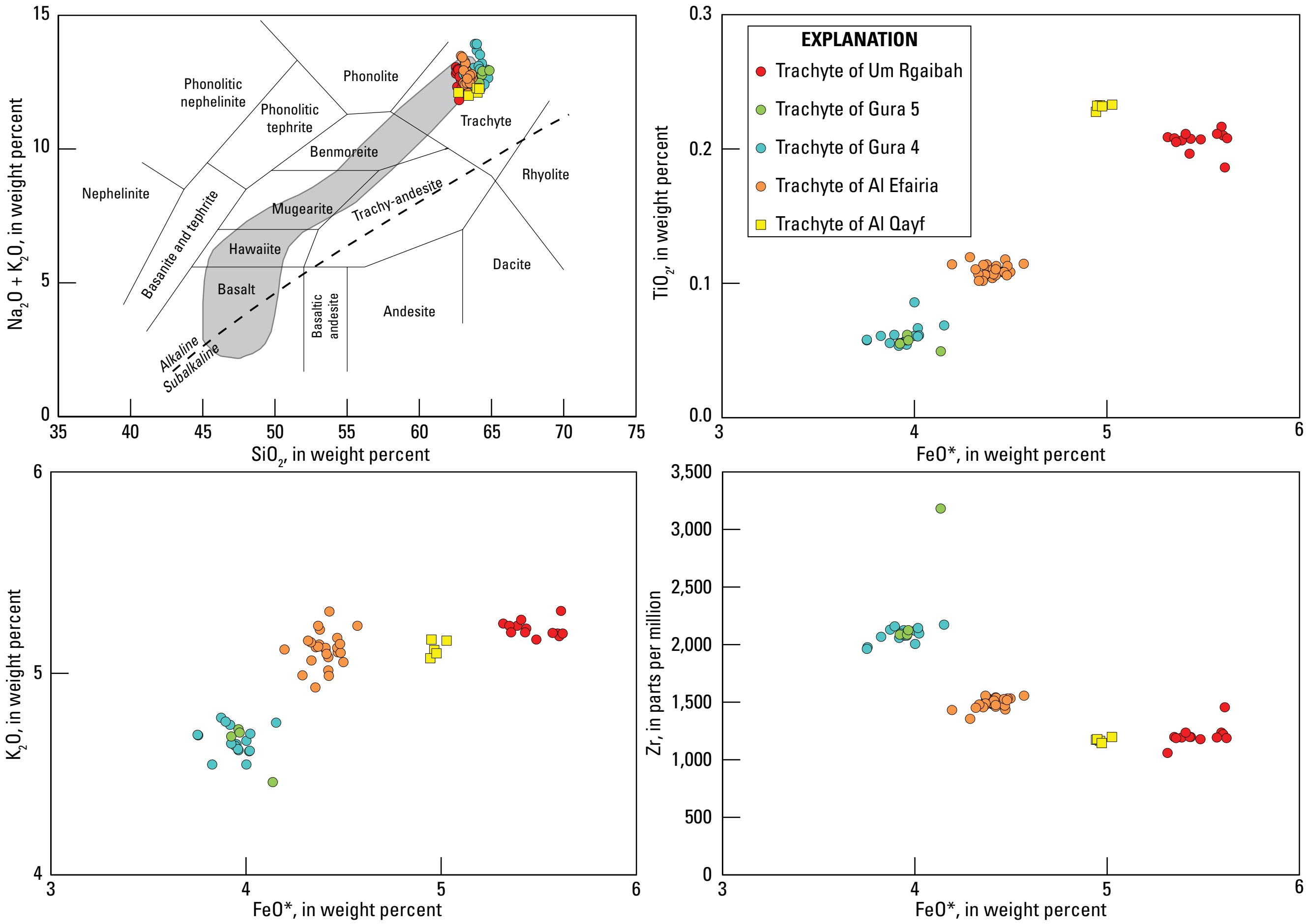

Figure 4. Plots showing whole-rock chemical compositions of the explosively erupted trachytes from the Al Efairia volcanic center. The upper left shows a total alkali versus silica plot (after Cox and others, 1979), in weight percent, with the alkaline and subalkaline fields (after Irvine and Baragar, 1971) defined. The gray field shows the compositional range of all volcanic rocks in the Al Efairia volcanic center as determined by Camp and Roobol (1989), Downs and others (2018), and Stelten and others (2018). The remaining three plots show selected major-oxide and trace-element concentrations versus total iron (all iron as FeO [FeO*]) to demonstrate the distinctions between each unit using whole-rock geochemistry. All whole-rock chemical compositions are provided by Downs (2019).

Trachyte of Al Efairia

The trachyte of Al Efairia is a series of pyroclastic-flow and -surge deposits (fig. 3*C*) that underlies the trachytes of Um Rgaibah, Gura 4, and Gura 5 (Moufti, 1985), and overlies the trachyte of Al Qayf. This unit erupted from two nested craters (fig. 2). The first and largest is a ~1.8-km-diameter by ~30-m-deep crater, which has mugearite and hawaiite scoria-cone and lava-flow material exposed within its crater wall. The second is a ~800-m-diameter crater and is completely nested within the first crater (fig. 3*B*). This second crater has undergone posteruptive uplift of both the trachyte of Al Efairia and previously erupted hawaiite lava flows. The trachyte of Al Efairia covers an area of at least 66.8 km^2 with the pyroclastic deposits reaching at least 9.0 km from the crater. The DRE volume for this unit is estimated to be between 0.57 and 0.86 km^3, making it the most voluminous and widespread trachyte eruption within Harrat Rahat. Pyroclastic deposits from this eruption(s) climbed barriers >150 m higher than their source located ~1.5 km away.

Poorly inflated juvenile pumice clasts contain 1–10 percent K-feldspar (anorthoclase and sanidine) as large as 4 millimeters (mm) in size and <1–10 percent clinopyroxene, of which a minor amount is aegirine, as large as 1 mm. Whole-rock TiO_2 concentrations range from 0.10 to 0.12 weight percent, FeO* ranges from 4.2 to 4.6 weight percent, K_2O ranges from 4.9 to 5.3 weight percent, and Zr ranges from 1,355 to 1,560 ppm (fig. 4). These are the only pyroclastic deposits that contain abundant lithic clasts, which include Proterozoic metasedimentary and metaigneous rocks, as well as previously erupted mafic volcanic rocks from Harrat Rahat.

Trachyte of Gura 4

The trachyte of Gura 4 underlies the trachytes of Um Rgaibah and Gura 5 and overlies the trachyte of Al Efairia. Its eruption produced a ~500-m-diameter by ~100-m-deep crater (fig. 2). The crater wall exposes older benmoreite lava flows and part of a basaltic scoria cone. Trachyte of Gura 4 pyroclastic deposits cover at least 18.2 km^2 with some flowage deposits reaching at least 5.5 km from the crater. The pyroclastic-flow deposits were emplaced energetically enough to climb topographic barriers >150 m higher than their source crater located >1.5 km away. A conservative estimate of the DRE volume for this unit is between 0.15 and 0.22 km^3. Because of the weakly consolidated nature of the pyroclastic-flow deposits, it is easily erodible and includes many small, isolated patches of pyroclastic-flow deposits around its margins. These are easily distinguished from the similar patchy pattern of the trachyte of Al Efairia in that this unit has a distinctive brown outcrop color in aerial imagery whereas the trachyte of Al Efairia is distinctively bright yellow.

The trachyte of Gura 4 contains poorly to moderately inflated juvenile pumice clasts (fig. 3*D*) with 1–40 percent K-feldspar (anorthoclase and sanidine) as large as 10 mm in size and ≤1 percent aegirine as large as 1 mm. Whole-rock chemical compositions for this unit overlap in all major-oxide and trace-element abundances with those from the trachyte of Gura 5 (fig. 4). For this unit, TiO_2 ranges from 0.05 to 0.09 weight percent, FeO* ranges from 3.8 to 4.2 weight percent, K_2O ranges from 4.6 to 4.8 weight percent, and Zr ranges from 1,960 to 2,170 ppm (fig. 4).

Trachyte of Gura 5

The trachyte of Gura 5 is stratigraphically situated below the trachyte of Um Rgaibah and above the trachyte of Gura 4. The eruption of this unit formed a ~200-m-diameter by ~25-m-deep crater (fig. 2). A small sliver of an older mugearite lava flow is exposed within the crater wall. Part of the trachyte has been uplifted during a failed eruption, which is preserved as a ~300-m-diameter by ~50-m-high cryptodome located ~400 m south of the crater (fig. 2). The trachyte of Gura 5 pyroclastic deposits cover an area of ~1.7 km^2 with the pyroclastic-flow deposits reaching ~800 m to the northeast and ~1.7 km to the southwest of its source crater. The DRE volume for the trachyte of Gura 5 is estimated to be between 0.01 and 0.02 km^3.

Juvenile pumice clasts from this unit are poorly to moderately inflated with 5–20 percent K-feldspar (anorthoclase and sanidine) as large as 2 mm and rare sub-millimeter aegirine. For this unit, whole-rock TiO_2 concentrations range from 0.05 to 0.06 weight percent, FeO* range from 3.9 to 4.1 weight percent, K_2O ranges from 4.5 to 4.7 weight percent, and Zr ranges from 2,085 to 2,125 ppm with a single sample yielding a result of 3,180 ppm (fig. 4).

Trachyte of Um Rgaibah

The trachyte of Um Rgaibah is the stratigraphically highest, and therefore youngest, unit within the Al Efairia volcanic center. It directly overlies the trachytes of Gura 5,Gura 4, and Al Efairia. It consists of a prominent ~600-m-diameter lava dome with a spine at the top that rises to ~1,260 m above sea level and towers >300 m above the surrounding volcanic plain (fig. 3*A*). The lava dome is situated within a crater, which is poorly exposed with only a small part visible along the dome's northwest margin (fig. 2). This crater is interpreted to be responsible for at least two distinct pyroclastic-flow deposits and an air-fall tephra of limited extent (fig. 5*A–B*). A third pyroclastic-flow deposit caps the sequence (fig. 5*A–B*) and the large (>1 m diameter in places) dense trachyte clasts near the lava dome are suggestive of emplacement during Peléan dome collapse. This unit covers an area of ~11.8 km^2 and reaches at least 3.9 km distance from the high-standing spine located at its vent. The DRE volume for the trachyte of Um Rgaibah is estimated to be between 0.10 and 0.15 km^3.

Juvenile pumice clasts and lava dome samples from this unit are mostly aphyric with <1 percent K-feldspar (anorthoclase and sanidine) as large as 1 mm and ≤1 percent clinopyroxene as large as 1 mm. For this unit, whole-rock TiO_2 concentrations range from 0.19 to 0.22 weight percent, FeO* ranges from 5.3 to 5.6 weight percent, K_2O ranges from 5.2 to 5.3 weight percent, and Zr ranges from 1,060 to 1,455 ppm (fig. 4).

Timing of Trachyte Volcanism

The 14 $^{40}Ar/^{39}Ar$ analyses used to calculate ages for the trachytes of Um Rgaibah, Gura 5, Gura 4, and Al Efairia indicate that trachytes within the Al Efairia volcanic center are much younger than previously proposed by Pellaton (1981) (table 1). Our $^{40}Ar/^{39}Ar$ analyses (table 1; all errors are at the one-sigma level unless otherwise stated) have yielded an age of 4.2±5.2 ka for the trachyte of Um Rgaibah, 79.7±1.6 ka for the trachyte of Gura 5 (weighted mean of three ages), 84.3±1.6 ka for the trachyte of Gura 4 (weighted mean of two ages), and 88.0±1.8 ka for trachyte of Al Efairia (weighted mean of five ages). In contrast, Pellaton (1981) reported K-Ar ages of 1.47 Ma for the trachyte of Um Rgaibah and 2.13 Ma for the trachyte of Al Efairia. Similar discrepancies in trachyte ages were reported within the Matan volcanic center by Stelten and others (2018, 2023b). Pellaton (1981) reported K-Ar ages of 1.38 Ma for the trachyte of Matan, 660 ka for the trachyte of Gura 2, and 270 ka for the trachyte of Dabaa 1, whereas Stelten and others (2018, 2023b) reported $^{40}Ar/^{39}Ar$ ages of 121.5±1.4 ka for the trachyte of Matan, 93.8±2.1 ka for the trachyte of Gura 2, and 17.6±1.8 ka for the trachyte of Dabaa 1. Moufti and others (2013) and Downs and others (2018, 2023) also report $^{40}Ar/^{39}Ar$ ages from mafic eruptive

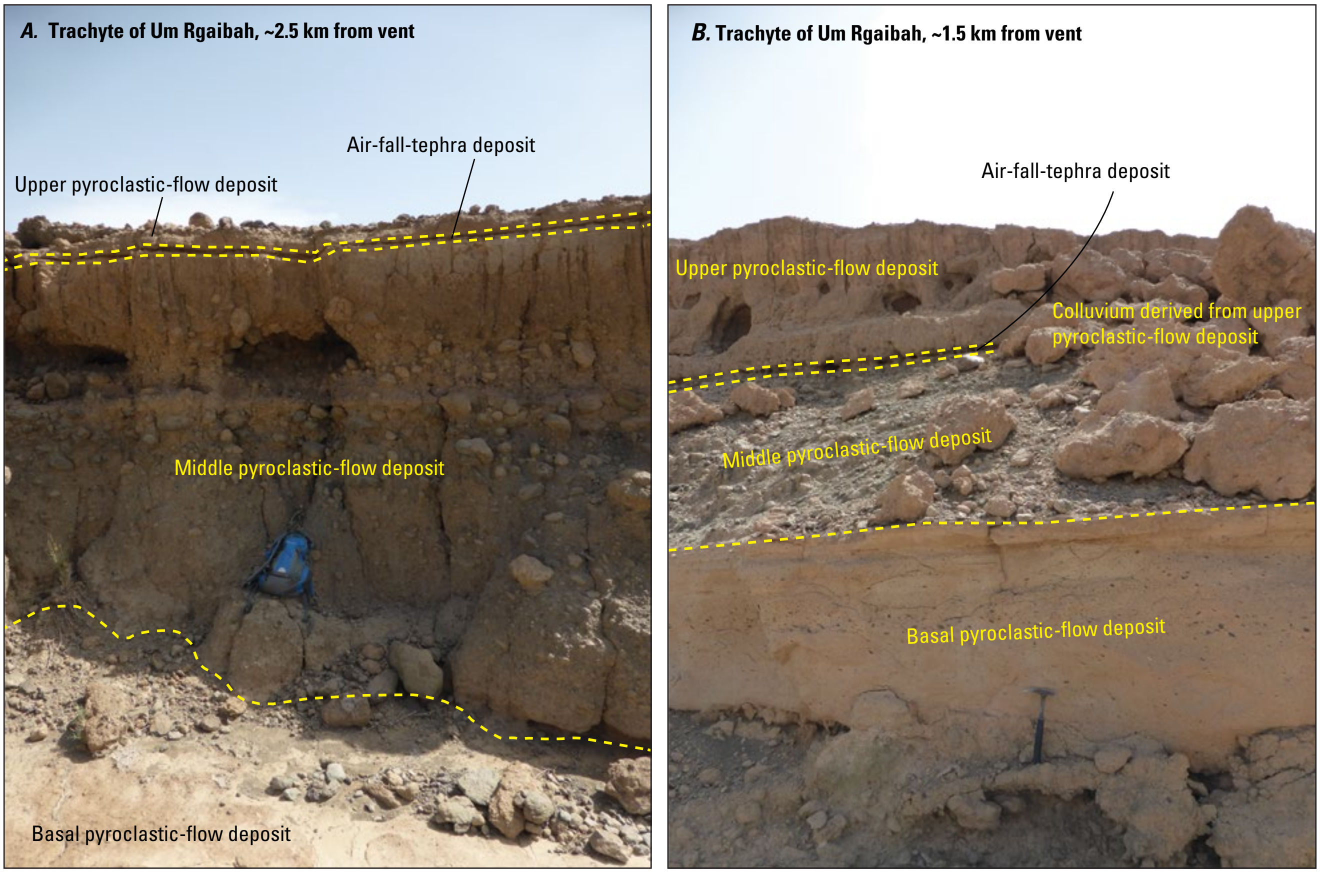

Figure 5. Photographs of pyroclastic deposits of the trachyte of Um Rgaibah. *A*, Photograph of the basal, middle, and upper pyroclastic-flow deposits and the air-fall-tephra deposit of the 4.2±5.2-thousand-year-old (ka) trachyte of Um Rgaibah at ~2.5 kilometers (km) to the northeast of the vent. *B*, Photograph of the basal, middle, and upper pyroclastic-flow deposits and the air-fall-tephra deposit of the 4.2±5.2-ka trachyte of Um Rgaibah at ~1.5 km to the northeast of the vent system. Photographs by Drew Downs, 2015.

products that tend to be significantly younger than previous K-Ar ages from northern Harrat Rahat.

One of the more remarkable results to come from our dating efforts is the recognition that the trachyte of Um Rgaibah erupted during the Holocene (although at the 95-percent confidence level its age uncertainty extends into the late Pleistocene) at 4.2±5.2 ka. The Holocene age overlaps well with a ^{36}Cl cosmogenic surface-exposure age of 9.0±2.5 ka from this unit by Stelten and others (2020, 2023a). Combining the ^{40}Ar/^{39}Ar and ^{36}Cl results yields a weighted mean eruption age of 6.9±2.9 ka. This makes it only the second Holocene eruption from Harrat Rahat to be documented. The other is the historically recorded 1256 C.E. basalt of Al Labah that erupted at the northern end of the Harrat Rahat volcanic field near the city of Al Madīnah (Al-Samhūdī, 1488).

The other three trachyte eruptions dated here all have broadly similar ages (table 1), but they are consistent with their stratigraphic superpositions as mapped in the field (trachytes of Al Efairia, Gura 4, and Gura 5 in ascending stratigraphic order). Despite the measured age of each deposit being consistent with the stratigraphic order, their ^{40}Ar/^{39}Ar ages overlap at the 95-percent confidence level. We therefore undertook paleomagnetic studies (table 2) to further refine the understanding of this cluster of eruptions. The trachyte of Gura 4 has an inclination of 51.3° and declination of 346.3° (with a 3.6º uncertainty at the 95-percent confidence level), whereas the trachyte of Gura 5 has an inclination of 50.4° and declination of 339.4° (with a 3.0º uncertainty at the 95-percent confidence level). The inclination and declination values of both units overlap at the 95-percent confidence level (table 2 and fig. 6). Additionally, both units are geochemically indistinguishable (fig. 4) and yield overlapping ^{40}Ar/^{39}Ar ages at the 95-percent confidence level (table 1). The overlapping ages alone indicate that these two units share an eruptive time interval on the order of no more than ~5,000 years from their age uncertainties. Based on the usual rates of geomagnetic secular variation (4 to 5° per century in the western United States; Champion and Shoemaker, 1977), these paleomagnetic directions establish that these eruptions occurred within a few decades to centuries of each other. Therefore, we infer that both the trachytes of Gura 4 and Gura 5 erupted over a geologically brief time interval at ~80 ka.

At 88.0±1.8 ka, the trachyte of Al Efairia also overlaps at the 95-percent confidence level with the trachytes of Gura 4 and Gura 5. However, with an inclination of 37.8° and

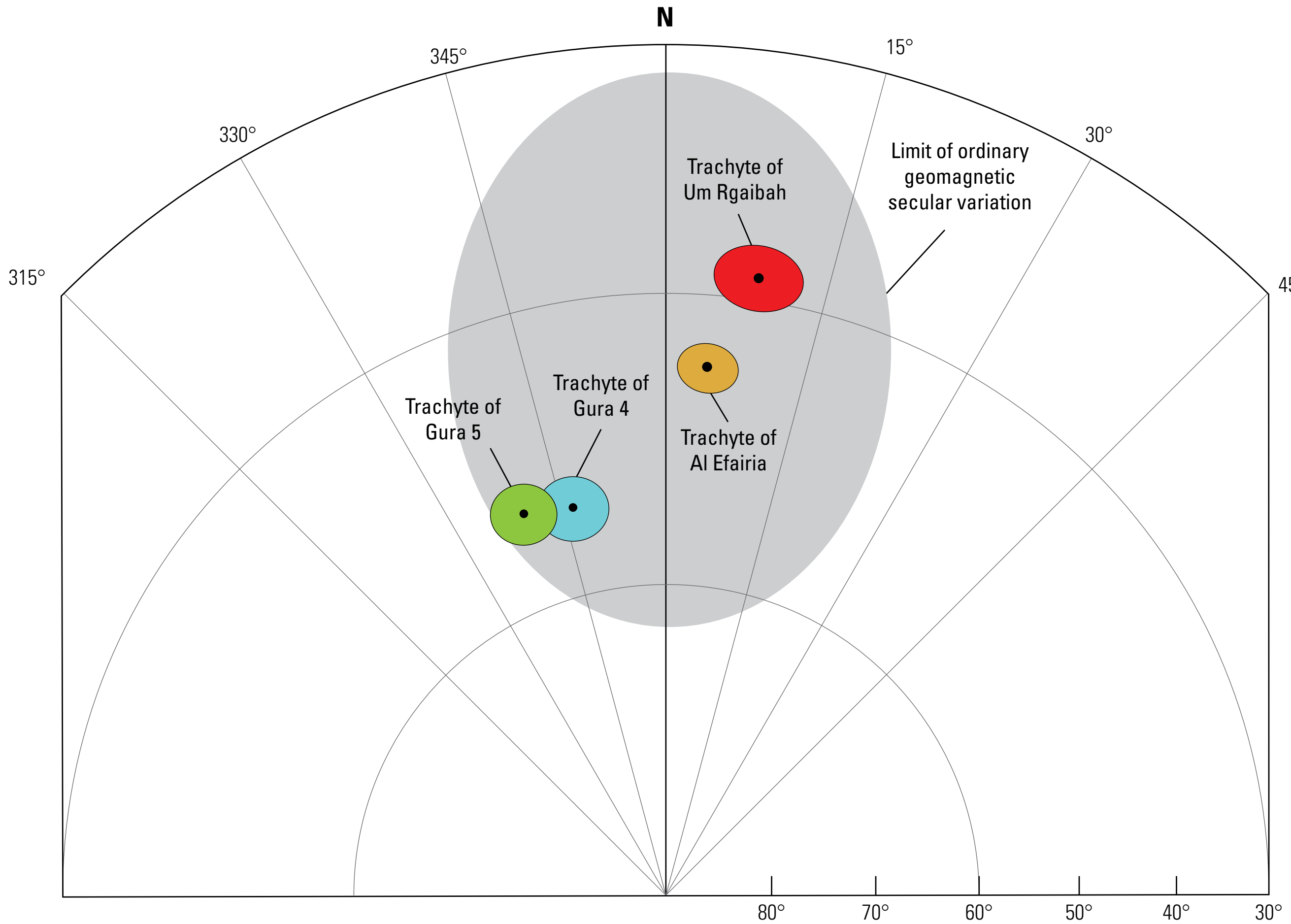

Figure 6. Plot of site mean directions of remanent magnetization (black dots) and ovals at 95-percent confidence of paleomagnetic directions measured on four explosively emplaced trachyte deposits within the Al Efairia volcanic center. Plot is in lower hemisphere equal-area stereographic projection.

declination of 4.3° (with a 2.6° uncertainty at the 95-percent confidence level), the direction of remanent magnetization of the trachyte of Al Efairia is sufficiently different from the trachytes of Gura 4 and Gura 5 to represent a longer time break (fig. 6). Statistical analyses (after Bogue and Coe, 1981) were performed on the trachytes of Gura 4 and Gura 5 and yield a 3±1 percent chance that the similarities in measured remanent magnetizations are the result of random occurrence. The same analysis on the trachytes of Al Efairia and Gura 4 yield a 72±16 percent that the similarities in measured remanent magnetizations are the result of random occurrence. Thus, the differences in the $^{40}Ar/^{39}Ar$ age, geochemistry, and paleomagnetism of the trachyte of Al Efairia indicate that it represents a distinct volcanic event despite occurring within a few thousand years of the trachytes of Gura 4 and Gura 5.

The trachyte of Al Qayf has not been directly dated; however, Downs and others (2019) provide paleomagnetic and $^{40}Ar/^{39}Ar$ age constrained stratigraphic evidence for the age of this trachyte pyroclastic deposit. This unit directly overlies the benmoreite of As Zayinah, a lava flow with a $^{40}Ar/^{39}Ar$ age of 418.8±1.9 ka (Downs and others, 2019), which provides a maximum eruption age. The trachyte of Al Qayf also overlies an undated trachyte lava dome (trachyte of Um Znabah 6; Downs and others, 2019) and underlies an undated mugearite lava flow (mugearite of Um Znabah 6; Downs and others, 2019). These undated units are time correlative based on similar directions of remanent magnetization, which therefore means that the trachyte of Al Qayf is also time correlative with them, based on its stratigraphic position. The trachyte of Um Znabah 6 underlies a mugearite lava flow with a $^{40}Ar/^{39}Ar$ age of 410.3±3.4 ka, which provides a minimum eruption age. Therefore, the eruption age of the trachyte of Al Qayf is constrained between 410.3±3.4 and 418.8±1.9 ka, making it one of the oldest known trachyte eruptions within northern Harrat Rahat.

Comparison with the Matan Volcanic Center

One of the fundamental discoveries about the Al Efairia volcanic center is how it differs in eruptive behavior compared to the Matan volcanic center located ~10 km to the north along the trend of the main vent axis. Stelten and others (2018, 2023b) used field relations, geochemistry, and geochronology (both $^{40}Ar/^{39}Ar$ radiometric and ^{36}Cl cosmogenic surface-exposure ages) to demonstrate that there is a predictable, and repeated, eruptive sequence within the Matan volcanic center. This sequence started ~150 ka and encompasses four repeatable compositional sequences of basalt followed by intermediate composition magmas (hawaiite, mugearite, or benmoreite) and ending with trachyte eruptions. Based on geochemical and isotopic evidence that each sequence resulted from an episode of mantle-derived basalt injected into the crust, Stelten and others (2018, 2023b) used the time between eruptions of different compositions to calculate the time interval necessary to differentiate from basalt to intermediate composition magmas (≤2 thousand years on average) and then further to produce trachyte (maximum of 6.6±4.3 to 22.5±3.2 thousand years).

Unlike the Matan volcanic center, volcanism within the Al Efairia volcanic center since the eruption of the trachyte of Al Efairia at 88.0±1.8 ka has only been trachytic. This implies that there is an important difference between the Matan volcanic center and the Al Efairia volcanic center. Both volcanic centers must be receiving mantle-derived basaltic magma injected into the crust to either fractionate or add heat to the system to produce trachytic magmas. Yet, only in the Matan volcanic center do the mafic or intermediate magmas reach the surface during eruptions prior to trachyte erupting (Stelten and others, 2018, 2023b).

Conclusions

Whereas most of the volcanic fields situated on the Arabia Plate are comprised of continental, intraplate basalts, there are a few volcanic fields that erupted trachytic magmas. The northern part of Harrat Rahat within the central-western part of the Kingdom of Saudi Arabia is one of these volcanic fields, with numerous young trachyte eruptive products. We investigated the young, explosively emplaced trachyte volcanic products within the Al Efairia volcanic center within the northern quarter of Harrat Rahat. These young pyroclastic-flow and -surge deposits erupted from craters or were generated during the collapse of hot lava dome material. In total, five distinct explosively emplaced trachyte units—the trachytes of Um Rgaibah, Gura 5, Gura 4, Al Efairia, and Al Qayf—were mapped based on their interpreted eruptive center and field observations, petrography, geochemistry, and paleomagnetism, and all but one (trachyte of Al Qayf) have been directly dated by the $^{40}Ar/^{39}Ar$ method. Our $^{40}Ar/^{39}Ar$ geochronology yields eruption ages of 4.2±5.2 ka for the trachyte of Um Rgaibah, 79.7±1.6 ka for the trachyte of Gura 5, 84.3±1.6 ka for the trachyte of Gura 4, and 88.0±1.8 ka for the trachyte of Al Efairia. Using paleomagnetic correlations and $^{40}Ar/^{39}Ar$ ages from surrounding intermediate composition lava flows, we infer that the trachyte of Al Qayf erupted between 410.3±3.4 and 418.8±1.9 ka. The trachyte of Um Rgaibah at 4.2±5.2 ka is only the second Holocene eruption documented within Harrat Rahat, the other being a basaltic eruption (basalt of Al Labah) in 1256 C.E. at the northernmost limit of the volcanic field.

Geochemistry, petrography, paleomagnetism, and geochronology all indicate that the trachytes of Um Rgaibah, Al Efairia, and Al Qayf erupted from distinct magma batches, whereas the trachytes of Gura 4 and Gura 5 overlap in petrographic textures, whole-rock chemical compositions, and paleomagnetic directions. The similarities in geochemistry and petrography argue for the trachytes of Gura 4 and Gura 5 to have erupted from the same magma batch and the overlap in directions of remanent magnetization (at the 95-percent confidence level) indicate that these two units erupted within decades of each other at most.

Trachytes have also erupted from the Matan volcanic center, which is located ~10 km north of the Al Efairia volcanic center. Matan volcanic center trachyte eruptive products also have predominantly late Pleistocene eruption ages (<150 ka), but there is a fundamental difference in their eruptive sequence. Trachyte deposits from the Matan volcanic center follow a predictable pattern wherein basalt erupts, followed by intermediate composition eruptions, which are then followed by the eruption of trachyte (Stelten and others, 2018, 2023b). This eruptive sequence is proposed to be related to the timescales by which mantle-derived basaltic magmas differentiate to create intermediate and evolved magmas.

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