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Key Points:

- Mafic volcanism at Harrat Uwayrid records the geodynamic evolution of the Arabian plate margin since the Oligocene
- Mio-Pliocene lavas formed from adiabatic melting as a result of lithospheric extension associated with spreading of the Red Sea
- Volatile-rich Quaternary alkaline basalts reflect melting of hydrated metasomatized lithosphere

Supporting Information:

Supporting Information may be found in the online version of this article.

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Geodynamic Controls on Basaltic Volcanism in the Arabian Peninsula: Evolution of Harrat Uwayrid, Saudi Arabia

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Abstract Basaltic lavas from Harrat Uwayrid, Saudi Arabia, record the evolving magmatic and tectonic context of the Arabian Peninsula from at least the mid-Miocene to the present day. New ⁴⁰Ar/³⁹Ar ages spanning from the mid to late Miocene reveal that mid-Miocene mafic volcanism formed a large, subalkaline volcanic plateau parallel to Red Sea rifts. Subsequent volumetrically subordinate late Miocene-Quaternary alkaline volcanism erupted monogenetic cinder cones roughly orthogonal to the earlier volcanic field. The source region for all samples was affected by both fluid and silicate metasomatism; inferred mantle mineral assemblages include amphibole for mid-Miocene lavas and phlogopite for late Miocene-Quaternary samples. Calculated melting depths become shallower with time across the Miocene volcanic episode (~20–15 Ma) but become deeper in the late Miocene to Quaternary (~10–0 Ma), indicating melting pressures and temperatures significantly higher than those recorded in Miocene lavas despite progressive lithospheric thinning. We offer a two-stage model for the formation of Harrat Uwayrid: (a) Early- and mid-Miocene rifting associated with the Red Sea opening facilitated adiabatic melting of uppermost mantle lithosphere to form the early volcanic plateau and (b) Plate motion changes in the mid- and late-Miocene initiated the Dead Sea Fault and destabilized a dense pyroxenitic lower lithosphere leading to foundering or lithospheric drip beneath Harrat Uwayrid that allowed deep lithospheric melting and formed the young volatile-rich eruptives.

1. Introduction

Continental basalts are the most common subaerial volcanic feature on Earth; however, as melting beneath continents is difficult to achieve, their presence presents a thermodynamic conundrum (e.g., Valentine & Gregg, 2008). Mantle melting typically occurs by one of three mechanisms: (a) depressurization as by the ascent of fertile asthenosphere beneath mid-ocean ridges or thinned continental lithosphere, (b) raising the temperature, either intrinsically as within an upwelling plume or by introducing contact between lithospheric and sub-lithospheric materials, or (c) modifying the mantle mineralogy through metasomatic reactions that lower the melting temperature. These conventionally invoked mechanisms of mantle melting do not accurately describe regions that experience continental basalt volcanism, and thus further investigation is needed for understanding the lithosphere/asthenosphere geodynamics that lead to continental volcanism.

The Arabian Peninsula is an ideal location to study continental basalt volcanism because it has experienced protracted volcanism throughout the Cenozoic. These volcanics have sampled a source region which has been modified from the Precambrian Pan-African Orogeny (~850 Ma) to the present day, thus providing time-integrated insights into the development of continental basalt source regions. Widespread volcanism from Yemen to southern Turkey covers an area over 200,000 km² with lava thicknesses up to 1,500 m (Figure 1, Guba & Mustafa, 1988). Nearly 2% of the peninsula is covered by basalt fields (harrats) which erupted during two main stages in the Cenozoic: older volcanism is roughly contemporaneous with the emplacement of the Afar Plume (~30 Ma; e.g., C. Hofmann et al., 1997), opening of the Red Sea (Early Miocene; e.g., Szymanski et al., 2016), and final suturing of Arabia and Eurasia (mid-Miocene; Hafkenscheid et al., 2006; Szymanski et al., 2016); younger volcanism began after the activation of the Dead Sea Fault (DSF) system and is contemporaneous with slowing of the northern Red Sea spreading (~10 Ma; e.g., Stockli & Bosworth, 2019). This most recent period of volcanism has continued until the present day along the Arabian Margin (Camp & Roobol, 1992). The petrogenetic origins of

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both stages of volcanics are poorly constrained and the underlying geodynamic processes that drive the volcanic pulses remain enigmatic. In this paper, we use the geochemistry of primitive basalt lavas from Harrat Uwayrid to decipher the lithosphere/asthenosphere geodynamics beneath the Arabian Peninsula and the long-term history of chemical modification in the lithosphere.

Existing studies on nearby harrats (Figure 1) center on Ash Shaam (HAS, M. Krienitz et al., 2007, 2009; Shaw et al., 2003; Weinstein et al., 2006), Hutaymah (Duncan et al., 2016; Konrad et al., 2016), Lunayyir (Duncan & Al-Amri, 2013), and the harrats that comprise the Makka-Medinah-Nafud line (MMN, Downs et al., 2018; Moufti et al., 2012, 2013; Murcia et al., 2014, 2016; Stelten et al., 2018, 2020). These authors recognized a metasomatized source region and progressive lithospheric thinning as important factors in the generation of the Arabian harrat basalts, but there is no consensus on the causes of either lithospheric thinning or mantle melting. The two competing, yet not mutually exclusive, mechanistic models to explain lithospheric thinning and melting are (a) lithospheric heating imposed by a sub-lithospheric thermal anomaly, for example, Afar plume material and (b) extension-driven adiabatic melting associated with the Red Sea opening. M. Krienitz et al. (2007, 2009) and Weinstein et al. (2006) suggest that the occurrence of post-Miocene basalts in the northernmost Arabian Peninsula reflects northward migration of Afar plume material. A decrease in Ce/Yb values in Harrat Lunayyir basalts from Miocene to Quaternary and the presence of low-velocity anomalies beneath the western harrats led Duncan and Al-Amri (2013) to ascribe melting and lithospheric thinning to migration of Afar plume material beneath the Arabian Plate margin. In contrast, Shaw et al. (2003) attributed a progressively deeper melting regime at HAS to fault-controlled lithospheric extension and associated thinning, and Moufti et al. (2012, 2013) argued that the pulsed and long-lived volcanism observed along the Makkah Medina Nafud volcanic line (MMN) reflects a periodic extension along the Red Sea fault system. These models do not provide a comprehensive geodynamic explanation for the generation of both the older and younger volcanic episodes on the Arabian Peninsula.

In this paper, we explore temporal changes in source mineralogy and melting depths as recorded by the geochemistry of primitive mafic lavas from Harrat Uwayrid by integrating our new data with prior insights from both lavas (Altherr et al., 2019) and mantle xenoliths (Kaliwoda et al., 2007, 2008). Through this approach, we attribute specific aspects of the surface expression of mafic magmatism to key tectonic events. These results place important constraints on the geochemical and geodynamic processes active in Saudi Arabia from the Oligocene through the present day.

2. Geological Setting

2.1. Geodynamic Setting of the Arabian Peninsula

The crystalline basement of the Arabian Peninsula consists of accreted island arcs that formed as East and West Gondwana collided during the closure of the Mozambique Ocean (e.g., Stern, 1994). Basement rocks are exposed on the western side of the peninsula, where they form part of the Arabian-Nubian Shield. The eastern side of the peninsula is dominated by the sedimentary Arabian Platform, which formed during the opening of the Neo-Tethys in the Mesozoic (e.g., Alsharhan & Nairn, 1997; Murris, 1980; Powers et al., 1966). Cretaceous closure of the Neo-Tethys led to the formation of a series of suture zones between Arabia and Eurasia and the Palmyra fold belt in the NW Arabian Peninsula (Figure 1; e.g., Bar et al., 2016; Garfunkel, 1981, 1998).

The Arabian Peninsula's Cenozoic history is characterized by intense tectonic activity. Earliest opening of the Red Sea is marked by NW-SE striking rifting and regional rift-normal extension between 27 and 23 Ma related to Afar plume impingement (Bosworth et al., 2005; Omar & Steckler, 1995). The extension in the southern Red Sea was largely restricted to a 200 km wide rift zone, but the northern extension was accomplished via widespread faulting that stretched across a 1,000 km zone extending several hundred kilometers into the Arabian Peninsula (Figure 1, Bosworth et al., 2015; Lyakhovsky et al., 2012; Segev & Rybakov, 2011; Stockli & Bosworth, 2019; Szymanski, 2013).

Miocene continental collision between Arabia and Eurasia signaled the slowing of Red Sea extension by as much as a factor of 10 in the northern Red Sea (Stockli & Bosworth, 2019). Coincident with this closure, a large basement transform fault now called the DSF formed ca. 14 Ma, linking the Gulf of Aqaba to the northern suture zones, thereby accommodating plate motion and changing the direction of extension from rift-normal to oblique (Figure 1, Bosworth et al., 2005; Garfunkel, 1981; Garfunkel et al., 1981; Patton et al., 1994). Spreading in the southern Red Sea continued, eventually linking with the Gulf of Aden by 1 Ma, while the extension in the northern Red Sea was accommodated primarily by movement along the DSF system.

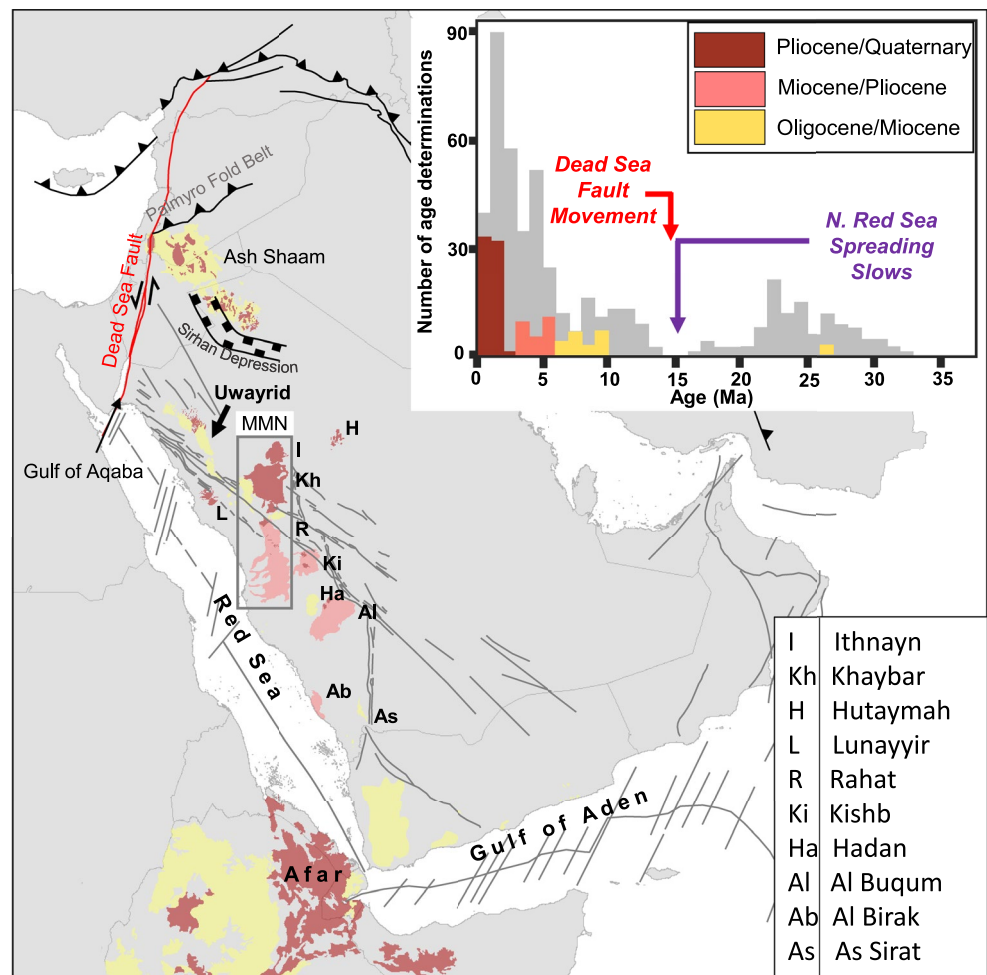


Figure 1. Tectonic setting of Arabian plate and harrats. Harrat Uwayrid is located ~70 km inland from the Red Sea within the zone of diffuse rifts. Oligo—mid-Miocene basalts are oriented parallel to the Red Sea and inland diffuse rifts, while late-Miocene—Quaternary Uwayrid volcanism is oriented parallel to the Dead Sea Fault and the nearby Makkah Medina Nafud volcanic line. Inset: Arabian harrats record two magmatic pulses from 30 to 15 and 10 to 0 Ma (gray bars after Camp and Roobol (1992); colored bars show Harrat Uwayrid ages from this study and Altherr et al. (2019)).

2.2. Arabian Peninsula Volcanism

Roughly coincident with the tectonic activity on the Arabian Peninsula are two prolonged magmatic episodes that are manifested in Harrat Uwayrid: an early period from ~30 to 15 Ma followed by a later period from roughly 10–0 Ma (inset on Figure 1, Camp & Roobol, 1992). Magmatism related to the initial opening of the Red Sea formed Oligo-Miocene NW-SE striking tholeiitic dikes parallel to Red Sea faults throughout the NW Arabian Peninsula, after which volcanism ceased in the northern Red Sea by 22 Ma (Sebai et al., 1991). During the continued opening of the Red Sea in the early and mid-Miocene, tholeiitic-alkalic volcanism across the western Arabian Peninsula formed several large basalt fields oriented NW-SE, including Harrats Ash Shaam and Uwayrid (Figure 1, Ilani et al., 2001; Szymanski, 2013).

After a hiatus of several million years, volcanism in Arabia began again in the late-Miocene and has continued until the present day, initiating or rejuvenating eruptive activity at several major harrats mainly on the NW part of the Peninsula (e.g., Altherr et al., 2019; Camp & Roobol, 1992; Camp et al., 1991; Ilani et al., 2001; Figure 1). Notable among these are Harrats Uwayrid and Ash Shaam (the most northerly harrats and the only Oligocene-Quaternary harrats on the Peninsula) and the Mecca-Medina-Nafud (MMN) line harrats Ithnayn, Khaybar, and Rahat (Figure 1). The MMN harrats have generally received more scientific and cultural attention than other harrats due to their ease of access and proximity to the holy sites in Mecca and Medina (a flow in

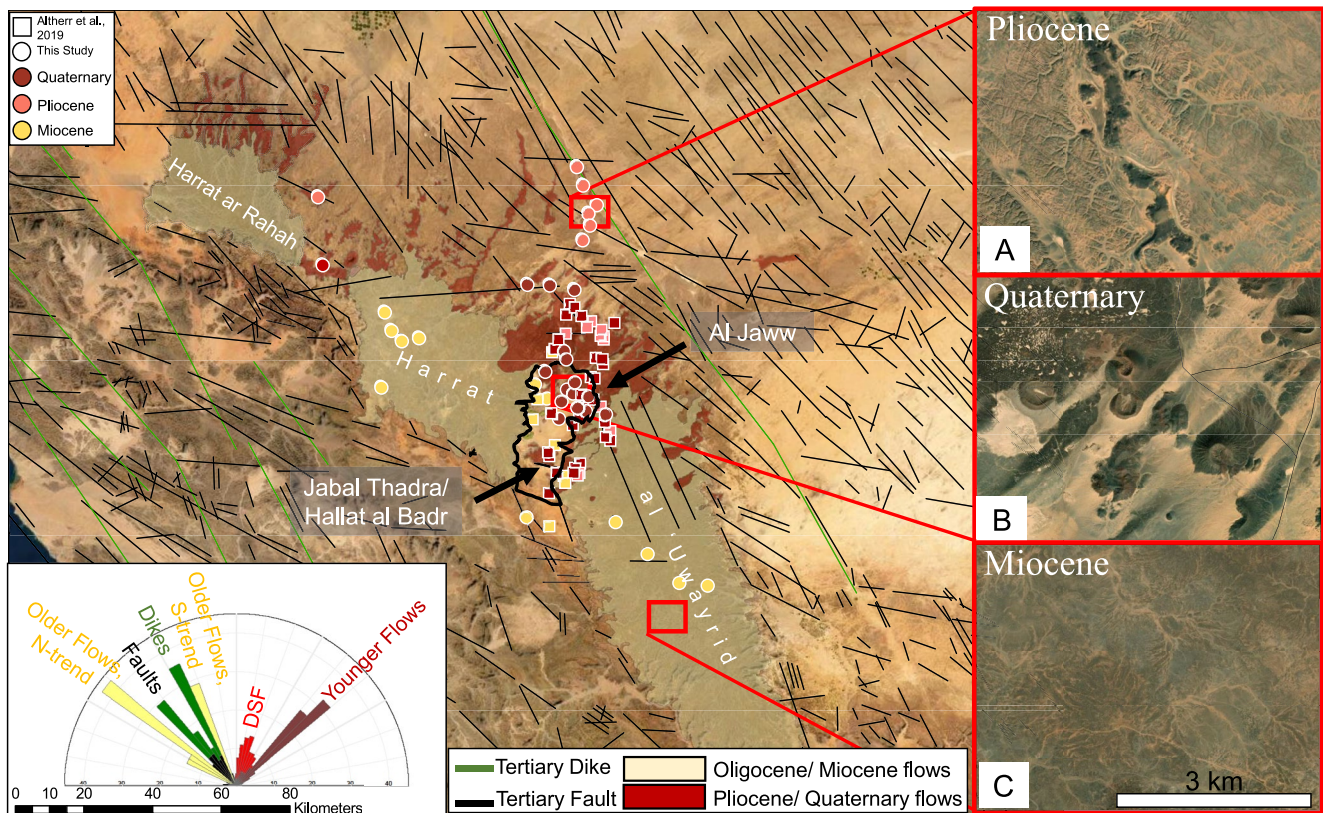


Figure 2. Landsat image of Harrat Uwayrid. Inset rose diagram indicates the characteristic volcanic and structural morphologies associated with age: (a) Pliocene flows strike N-S, (b) Quaternary cinder cones and flows roughly strike N-S, and (c) Oligo—mid-Miocene volcanic plateau strikes NW-SE and volumetrically comprises most of the harrat. Note the strike change that occurs between the Oligo-Miocene and younger basalts and is mirrored by the regional structure, highlighted in the rose diagram. Samples from Altherr et al. (2019) are represented as squares, those from this study are circles.

the 1200s came within 4 km of Medina). Post-Miocene volcanism at the MMN harrats produced consistently larger volume and less alkaline lava flows than those at Harrats Uwayrid and Ash Shaam (Figure 1, Camp & Roobol, 1992).

2.3. Harrat Uwayrid

Harrat ar Rahah-Uwayrid is one of the major Arabian Peninsula basalt fields; it consists of the small northwestern Harrat ar Rahah and the larger southeastern Harrat al Uwayrid, with the two fields together commonly referred to as Harrat Uwayrid (Figure 2). The field forms a $\sim 7,800 \text{ km}^2$ incised volcanic plateau 1,750–1,950 m above sea level that was emplaced upon the exposed Arabian Shield at the boundary of the shield with the Arabian Platform. The plateau strikes roughly NW-SE parallel to the Red Sea but has a convex bend with an apex to the northeast. Harrat ar Rahah is separated from Harrat al Uwayrid by a narrow strip of young cinder cones, but otherwise the harrats form a continuous series of basalt flows. Al Jaww is a $\sim 600 \text{ km}^2$ and $\sim 200 \text{ m}$ deep depression in the center of Harrat al Uwayrid (Figure 2). Rising 50–300 m from Al Jaww are several dozen cinder cones and associated flows striking N-S, nearly orthogonal to the general strike of the volcanic plateau (Figure 2).

Harrat Uwayrid has been active since the at least the early-Miocene, with the most recent volcanism occurring at Hallat al Badr on Jabal Thadra around 640 AD (Musil, 1926; Figure 2). As observed by previous authors who carried out K-Ar dating in this area (Altherr et al., 2019; Brown et al., 1989; Coleman et al., 1983), a close relationship exists between volcanic center morphology, geometry, and age: Quaternary lavas are represented by N-S striking monogenetic cinder cones and fresh, small flows; Pliocene and late-Miocene lavas form N-S striking small lava flows separate from cinder cones; and Oligo-Miocene NW-SE striking plateau basalt flows form the majority of the volcanic plateau (Figure 2). The oldest reported date from Harrat Uwayrid is a K-Ar whole rock age of $26.7 \pm 2.6 \text{ Ma}$ from a basal flow on the southwestern edge of the Harrat (Altherr et al., 2019; Coleman

et al., 1983). Basal samples from both the northern and southern ends of the harrat have younger whole rock K-Ar ages of 9.4 ± 2.5 and 9.4 ± 1.1 Ma (Brown et al., 1989; Coleman et al., 1983). While the accuracy of these K-Ar ages has been questioned (e.g., Duncan et al., 2016) the overall correspondence between relative ages, weathering extent, and field occurrence support the interpretive framework presented here.

3. Methods

Sampling carried out in field seasons in 2016 and 2020 targeted primarily the younger, N-S striking central region of Harrat Uwayrid, augmented by samples of the basaltic plateau (Figure 2); care was taken to not sample rocks that displayed an obvious surficial alteration. A total of 40 basaltic lavas and ~60 mantle xenoliths were collected. Prior work by Altherr et al. (2019) and Kaliwoda et al. (2007, 2008) focused on a large sample suite collected primarily in and around Al Jaww; we aimed our sampling at both the young, fresh cinder cones that had not yet been sampled and the older basalt flows. Fractures were mapped using 1 Arc-Second SRTM and Sentinel-1 InSAR data. Fractures mapped remotely were compared to the work of Roobol and Stewart (2018) for ground-truthing. Approximate lava ages were determined from LANDSAT imagery by comparing the distinctive morphology-age relationships described in Altherr et al. (2019).

Weathered surfaces were removed from bulk rock samples before cutting, polishing off saw marks, and chipping in an alumina ceramic crusher. These rocks contain abundant vugs that are commonly filled with secondary caliche which was removed prior to chemical analysis via light leaching: Phenocryst-poor chips 1–2 mm across were picked and leached in 2.5 N HCL for 5 min before rinsing three times with ultra-pure water. Leached chips were then powdered in a ceramic shatterbox.

Major element oxides were analyzed using a ThermoFisher ICAP 7400 ICP-OES in Penn State's Laboratory for Isotopes and Metals in the Environment (LIME). Rock samples and 36 standards (including BHVO and BCR) were fused using lithium metaborate flux and dissolved in dilute HNO_3 before analysis (Tables S1 and S2, Ingamells, 1970; Medlin et al., 1969). Trace elements in solution were analyzed using an iCAP RQ ICP-MS in the LIME lab following a 3:1 HNO_3 :HF digestion (Table S2). Sr and Nd were separated from the matrix using three cation exchange columns. Major cations were separated from the sample using BioRad 50WX8 (200–400 mesh) resin in a 20 cm $\times$ 6 mm column. Nd was separated using LN spec (50–100 mesh) resin in a 7.2 cm $\times$ 4 mm column. Sr was separated with Sr Spec (100–150 mesh) resin. The Sr fraction was loaded onto a single tungsten filament using 1 μL of 2N HNO_3 , 1 μL each of Ta gel and 10% phosphoric acid were added to the filament before drying down to glow. $^{87}\text{Sr}/^{86}\text{Sr}$ was analyzed on a Thermo Scientific Triton Plus TIMS at Penn State. An $^{86}\text{Sr}/^{88}\text{Sr}$ ratio of 8.37520938 as normalizing value and interference with $^{87}\text{Rb}/^{85}\text{Rb}$ was corrected using a ratio of 0.386. NIST SRM 987 was used as an external standard at the beginning and end of each sample turret (Table S1). The Nd fraction was loaded onto double rhenium filaments using 1 μL of 2N HNO_3 , 1 μL each of 10% phosphoric acid was added to the filament before drying down to glow. Nd composition was measured using a $^{146}\text{Nd}/^{144}\text{Nd}$ ratio of 0.7219 as a normalizing value and interference correcting for ^{144}Sm , ^{147}Sm , ^{148}Sm , and ^{150}Sm . JNd-I was used as an external standard and run at the beginning and ending of each turret on the TIMS at Penn State (Table S1).

Major element oxides and selected trace element abundances in olivines, clinopyroxenes, and metal oxides were analyzed using a Cameca SX Five Electron Probe Micro Analyzer at Penn State's Material Characterization Laboratory (Table S3). Analyses were performed over 255 s at 15 kV with a 20 nA current. Background was measured every third analysis or when switching minerals. Trace elements in pyroxenes were measured using a Thermo Scientific iCAP RQ-ICPMS attached to a Teledyne/Photon Machines Analyte G2 Excimer Laser (193 nm) Ablation System (Table S4). The laser was operated at 20 Hz with ablation spot sizes of 40 μm in diameter. Ablation time was 20 s with a fluence of 2.74 J/cm^2 . Data reduction was accomplished using the Iolite software with ^{29}Si (from EPMA analyses) as an internal standard (Paton et al., 2011; Woodhead et al., 2007). KLG2 was used as a primary standard and NIST 612, CPX 777, GOR-132, GOR-128, and MLB3 were secondary standards, all of which reproduced measured elements to within 5% error. Standards were measured for each element every 10 sample spots.

Fe-Mg spinel interdiffusion rates were calculated using the diffusion coefficient and pre-exponent from Vogt et al. (2015) and EPMA transects across zoned crystals in MATLAB. A holding temperature was provided to the model by calculating the olivine-spinel equilibrium temperature following Wan et al. (2008) and Ballhaus et al. (1991). Pressure was estimated on the basis of bulk-rock thermobarometry (see Figure 12).

Table 1
Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology of Harrat Uwayrid Lavas

Sample	Age	$\pm 2\sigma$	MSWD	% ^{39}Ar
U1-16	15.63	0.24	0.39	99.94
U2	7.381	0.075	0.88	100
U2-16	13.54	0.02	1.15	75.1
U7-16	16.13	0.16	0.43	100
U8-16	15.44	0.19	0.87	88.4
U9-16	11.10	0.25	1.14	73.2
U13-16	5.50	0.08	0.60	91.6
U20	15.80	0.11	1.40	87

olivine phenocrysts with frequent rim alteration to iddingsite $\pm$ minor diopside both as phenocrysts and within poikilitic textured groundmass. Opaque oxides include Cr-rich and Cr-poor spinel with minor ilmenite. Cr-poor spinels are small ($<5\ \mu\text{m}$) and abundant in the groundmass. Cr-rich spinels are large ($10\text{--}50\ \mu\text{m}$), rare in the groundmass, and most often found either within or on the boundaries of olivine phenocrysts. Cr-rich spinels found on the boundaries of olivines are strongly zoned (Cr- and Mg-poor rims/Cr- and Mg-rich cores). Ilmenite is rare, of similar size to the Cr-rich spinels, and displays well-developed Fe-Ti exsolution lamellae. The older rocks contain between 4 and 15 vol.% phenocrysts (primarily olivine; $<1\ \mu\text{m}\text{--}2.5\ \text{mm}$) with plagioclase laths that range in size from $1\ \mu\text{m}$ to $2\ \text{mm}$. Older (mid-Miocene and earlier) samples are commonly holocrystalline with rare devitrified glass. The younger rocks are generally glassy, lack holocrystalline textures, and have little to no plagioclase feldspar crystals. Phenocrysts range from 5 to 15 vol.%, consisting of rare clinopyroxene and more common olivine phenocrysts that are up to $3.5\ \text{mm}$ in size.

Argon ($^{40}\text{Ar}/^{39}\text{Ar}$) ages were obtained from eight bulk rock samples on a GLM-110 mass spectrometer at the Auburn Noble Isotope Mass Analysis Laboratory (ANIMAL, Table 1). Detailed methodology is presented in Table S5 and Schaen et al. (2020). Ages for all samples were determined by the best incremental heating plateau age. U2 was chosen for dating because it is within a volcanic lineament north of the main harrat that has no age constraints, and the other seven samples were selected as probable candidates for some of the oldest flows on the main harrat, which lacks reliable argon dates.

4. Results

4.1. Petrography

Harrat Uwayrid lavas (Altherr et al., 2019) and xenoliths (Kaliwoda et al., 2007, 2008) have been studied previously, and we integrate these data with our new results. Samples from all age groups are characterized by

4.2. Bulk Rock Geochemistry

We observe age-correlative geochemical trends similar to those reported in Altherr et al. (2019): the Quaternary rocks are mildly to highly alkaline basanites through trachydacites with a small grouping of basalts (Figure 3), whereas the older group comprises primarily subalkaline basalt and trachybasalt. With the exception of one very high SiO_2 sample, Mg#s (molar $100^*\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$) span a narrow range of 50–66. Loss on ignition values range from 0% to 3.6% and are not correlated with sample age.

Contents of SiO_2 , Al_2O_3 , Na_2O , and K_2O correlate broadly negatively with MgO , while TiO_2 , FeO_r , and CaO show flat or slightly negative slopes at high MgO , and positive slopes at lower MgO contents (Figure 4 and Figure S1 in Supporting Information S1). These trends are broadly consistent with progressive removal of the observed phenocryst phases. The Uwayrid lavas are geochemically distinct from both younger and contemporaneous basalts from the nearby MMN harrats: they extend to more primitive compositions (higher MgO wt. %) and show a much greater variation in most element oxides at comparable MgO contents (Figure S1 in Supporting Information S1).

Abundances of compatible trace elements (Ni, Figure 4; Cr, Sc, V, not shown) decrease broadly with a decrease in MgO content of the lava, but they display considerable scatter within each age group. The most primitive lavas contain $\sim 300\ \text{ppm}$ Ni, $\sim 500\ \text{ppm}$ Cr, and $20\text{--}30\ \text{ppm}$ Sc, suggesting they are near-primary mantle melts and have not accumulated olivine or clinopyroxene crystals. Incompatible minor and trace element abundances (e.g., P_2O_5 , Rb, Th, La, Zr) are enriched relative to values measured in MMN lavas and do not correlate well with MgO (Figure 4). Despite the scatter of incompatible

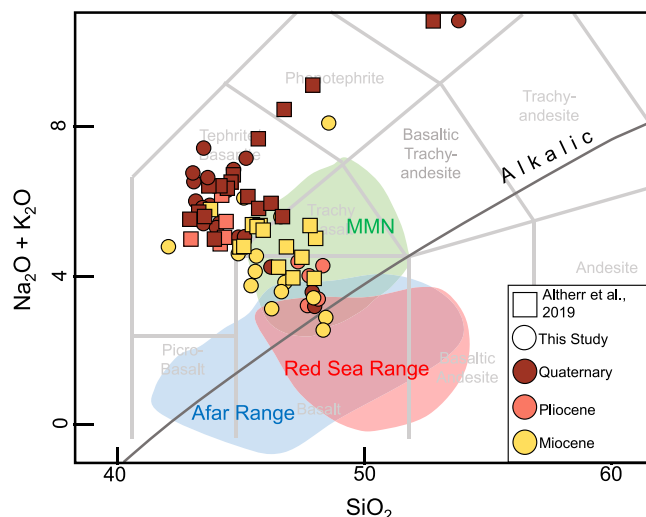


Figure 3. Plot of total alkalis against silica shows the young Uwayrid samples are generally more alkaline than both older Uwayrid samples and lavas from harrats Ithnayn and Rahat in the nearby Makkah Medina Nafud volcanic line, Red Sea, and Afar (sources of data: Altherr et al., 1988, 1990; Barrat et al., 1998; Camp & Roobol, 1989; Downs et al., 2018; Eissen et al., 1989; Haase et al., 2000; Murcia, 2015; Stelten et al., 2018, 2020). Squares represent samples from Altherr et al. (2019); round symbols are samples from this study. All samples have been normalized to 100% anhydrous with $\text{Fe}_2\text{O}_3 = \text{FeO}_{\text{total}} * 0.15$. In this and all subsequent figures, 2 standard error is smaller than the symbol size.

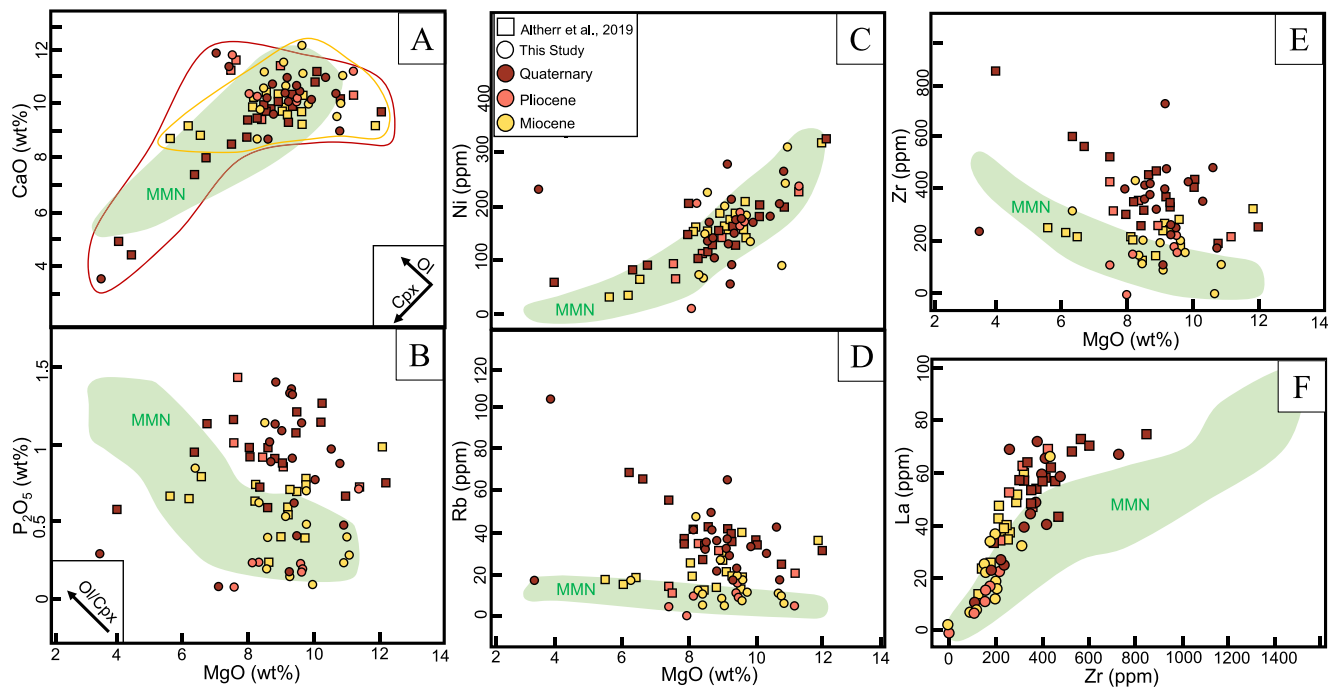


Figure 4. Major element variations in Uwayrid lavas of all ages are broadly consistent with progressive crystallization of olivine followed by clinopyroxene, with a very limited role for plagioclase in the more evolved lavas. Phosphorus does not form clear trends with MgO, in contrast to its behavior in Makkah Medina Nafud lavas (represented herein by basalts from harrats Ithnayn and Rahat), which have much more consistent trends. Abundances of incompatible minor and trace elements do not form coherent trends when plotted against MgO, suggesting their petrogenesis involves heterogeneous mantle sources or melting processes. These elements correlate well with each other (panel f), suggesting that their abundances are controlled by consistent processes. Positive correlations between Ni, Cr, Co (not shown) and MgO are consistent with fractional crystallization of olivine.

elements versus MgO, incompatible elements correlate well with each other (Figure 4 and Figure S1 in Supporting Information S1). We note that these results contrast with those of the major harrats along the MMN, which display very consistent incompatible trace element abundance variations (Stelten et al., 2018, 2020).

Primitive mantle (PM) normalized incompatible trace element abundances of all Uwayrid mafic lavas with >7 wt.% MgO (Figure 5a) show overall enrichment over ocean island basalts; Quaternary lavas show the highest abundances of all incompatible trace elements. Primitive mantle normalized diagrams lack Eu anomalies and display negative Cs, Pb, P, and Rb anomalies. They are enriched slightly in high field strength elements (HFSE: Zr, Hf, Ti, Y) relative to rare earth elements (REE) of similar compatibility (Sm, Eu, Tb, Yb). Ta contents that are high relative to Nb values cannot be attributed to sample preparation because crushing was done in an agate shatterbox rather than in a WC.

Chondrite-normalized REE diagrams (Figure 5b) show LREE enrichment and overall shallow slopes [La/Sm_n (1.7–7), La/Yb_n (3–24), Tb/Yb_n (1.3–3.5)]. Samples of all ages have Ce/Pb (16–48; Figure 6a) and Nb/U values (35–139, not shown) that plot either within, or near, the MORB/OIB array (A. Hofmann et al., 1986; Salters & Stracke, 2004). All samples have Th/Yb and Nb/Yb values that plot within the mantle array (Figure 6b). While Quaternary and mid-Miocene samples are readily distinguishable from one another in geochemical terms, the late Miocene and Pliocene samples are less distinctive and often plot within both Quaternary and mid-Miocene groups (e.g., Figures 3 and 6).

Sr-Nd isotopic values measured in Uwayrid mafic lavas fall below the mantle array within a restricted range ($^{87}\text{Sr}/^{86}\text{Sr} = 0.703268\text{--}0.703706$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512787\text{--}0.512911$) (Figure 7a). $^{87}\text{Sr}/^{86}\text{Sr}$ values are slightly higher in mid-Miocene (≤ 0.703706) than late-Miocene to Quaternary (≤ 0.703414) samples. While our Quaternary samples have nearly the same $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios as those measured in Quaternary samples by Altherr et al. (2019), our mid-Miocene samples extend to higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ values (Figure 7a).

Our new high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ ages for samples classified as Miocene based on field and petrographic appearance define groupings in the mid-Miocene (16.13–11.10 Ma) and late-Miocene (7.4–5.5 Ma, Figure 8). The new late-Miocene ages are within the Miocene/Pliocene K-Ar age range from Altherr et al. (2019), but our

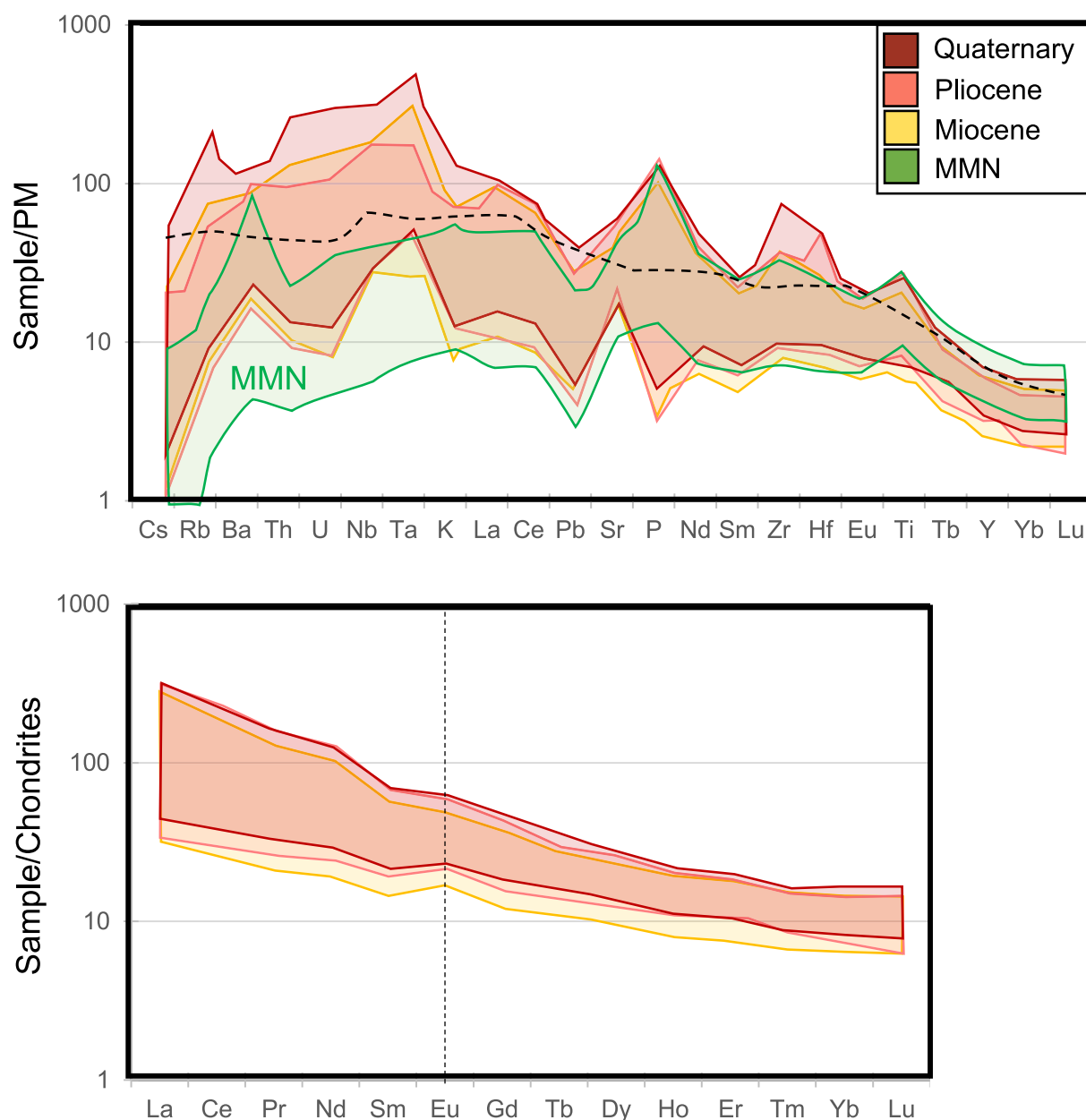


Figure 5. Primitive mantle normalized multi element diagram of Quaternary (red), Pliocene (pink), and Miocene (yellow) Uwayrid lavas of both samples from Altherr et al. (2019) and this study. Also shown is the Makkah Medina Nafud field (green). The dashed black line indicates the OIB trend from Sun and McDonough (1989). Chondrite normalized (Sun & McDonough, 1989) rare earth elements (REE) diagram shows fields for Uwayrid lavas. Samples from all age groups have broadly parallel trends, but the youngest (Quaternary) samples tend to have higher abundances of REE and overall steeper patterns.

mid-Miocene ages are considerably older than previously reported ages (oldest sample of Altherr et al. (2019) is 8.22 ± 0.13 Ma) and are the oldest reported ages from Harrat Uwayrid other than the lone Oligocene K-Ar age from Coleman et al. (1983).

4.3. Mineral Chemistry

The vast majority of olivine phenocrysts are magnesian (Fo_{70-85} ; Table S3). Olivines range in Ca content from 200 to 11,000 ppm and have generally higher values (1.2–0.5 wt.%) amongst lower Mg# olivines. Ni contents range from 100 to 4,000 ppm and correlate inversely with Ca abundances. Fe-Mg exchange coefficients between

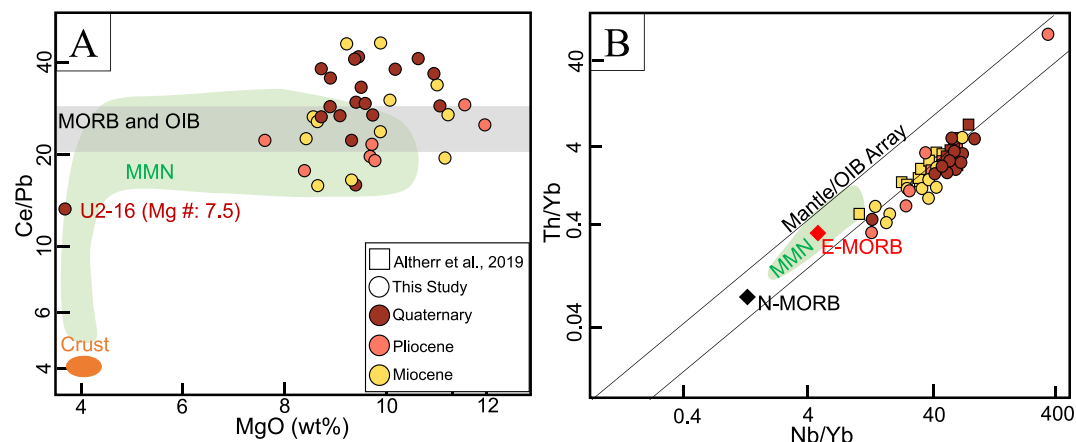


Figure 6. (a) Mafic lavas from Harrat Uwayrid and Makkah Medina Nafud (MMN) harrats have Ce/Pb values near or above the range of global mantle-derived mafic lavas (A. Hofmann et al., 1986), suggesting a limited role of crustal assimilation; negative Pb anomalies in the figure support this interpretation. (b) Nb/Yb-Th/Yb values of Uwayrid and MMN mafic lavas plot within and slightly below the mantle array.

ehedral (non-groundmass) olivines and bulk rock vary between 0.45 and 0.15 and do not correlate with other chemical trends.

Pyroxenes in all age groups are diopside. Clinopyroxene TiO_2 and Al_2O_3 contents are higher in Quaternary samples (0.2–6.5 and 2.6–12 wt.%, respectively) than in Plio-Miocene samples (0.8–3.5 and 1.8–8.5 wt.%, respectively). REE contents measured in pyroxenes (normalized to chondritic values of Sun and McDonough (1989)) show distinctive patterns for each age group. Clinopyroxenes in Miocene and Pliocene volcanics exhibit negative Eu anomalies (Figures 8a and 8b, Table S4). REE patterns of Miocene and Pliocene clinopyroxenes are similar (La/Sm_n 0.64 and 0.67, respectively; Tb/Yb_n 1.98 and 1.86, respectively). Clinopyroxenes in Quaternary samples define two groups with distinct REE patterns: Group 1 has a slightly positive LREE/MREE slope ($\text{La}/\text{Sm}_n = 0.86$) and a negative MREE/HREE slope ($\text{Tb}/\text{Yb}_n = 2.32$); Group 2 has a slightly negative LREE slope ($\text{La}/\text{Sm}_n = 1.62$) and a flat or slightly positive HREE slope ($\text{Tb}/\text{Yb}_n = 0.52$ –1.54). Group 1 pyroxenes have higher REE contents overall, while Group 2 pyroxenes have lower REE abundances, lack Eu anomalies, and are enriched in fluid mobile elements such as Th and Na (Figure 9c).

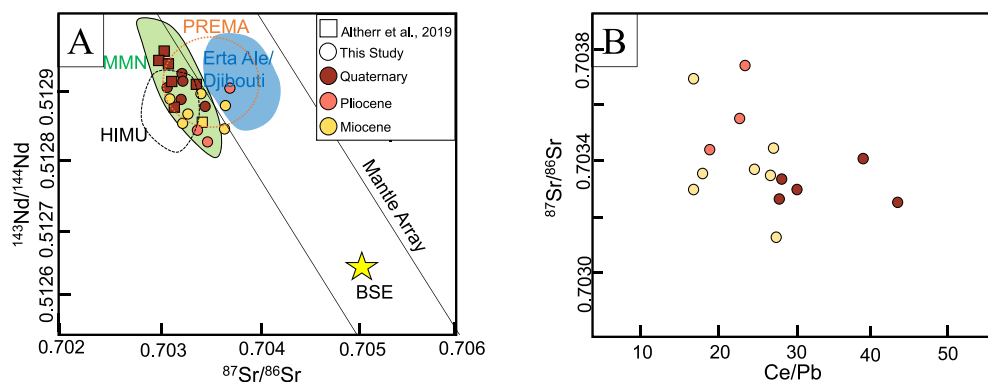


Figure 7. (a) $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ values measured on the Harrat Uwayrid lavas plot in a restricted region shared by the Makkah Medina Nafud lava, HIMU, and PREMA mantle reservoirs (2 standard error is smaller than the size of symbols). Nearly all samples plot below the mantle array with a composition that is commonly associated with contributions from melts of subducted slabs (Stracke et al., 2005). Older Uwayrid mafic lavas extend to more radiogenic values than the youngest basalts. (b) A negative relationship between $^{87}\text{Sr}/^{86}\text{Sr}$ and Ce/Pb suggests that the younger samples are more compositionally primitive.

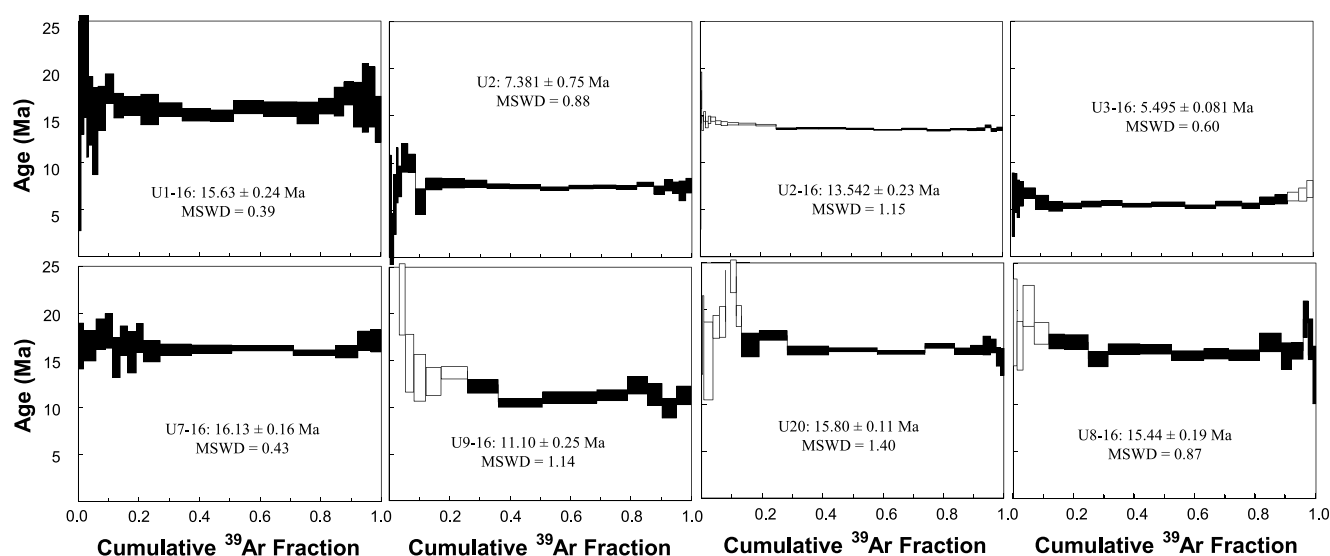


Figure 8. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for bulk rock lavas from Harrat Uwayrid. All samples except U2 were chosen to identify the older basalt flows. Ages are determined by the best incremental heating plateau. Errors are presented as 1σ precision and include the error in j -value.

Metal oxides in the lavas are dominated by spinels. The majority of spinels within the matrix are Cr-poor (average $\text{Cr}\# (\text{Cr}/\text{Cr} + \text{Al}) = 0.32$) while spinels found within olivines are Cr-rich (average $\text{Cr}\# = 0.62$). Several Quaternary samples contain spinels zoned in Al, Cr, Fe, and Mg. These zoned spinels are found nearly exclusively at the grain boundaries of olivines and show the lowest abundance of MgO and Al_2O_3 and highest Cr_2O_3 and Fe_2O_3 at spinel-olivine grain boundaries.

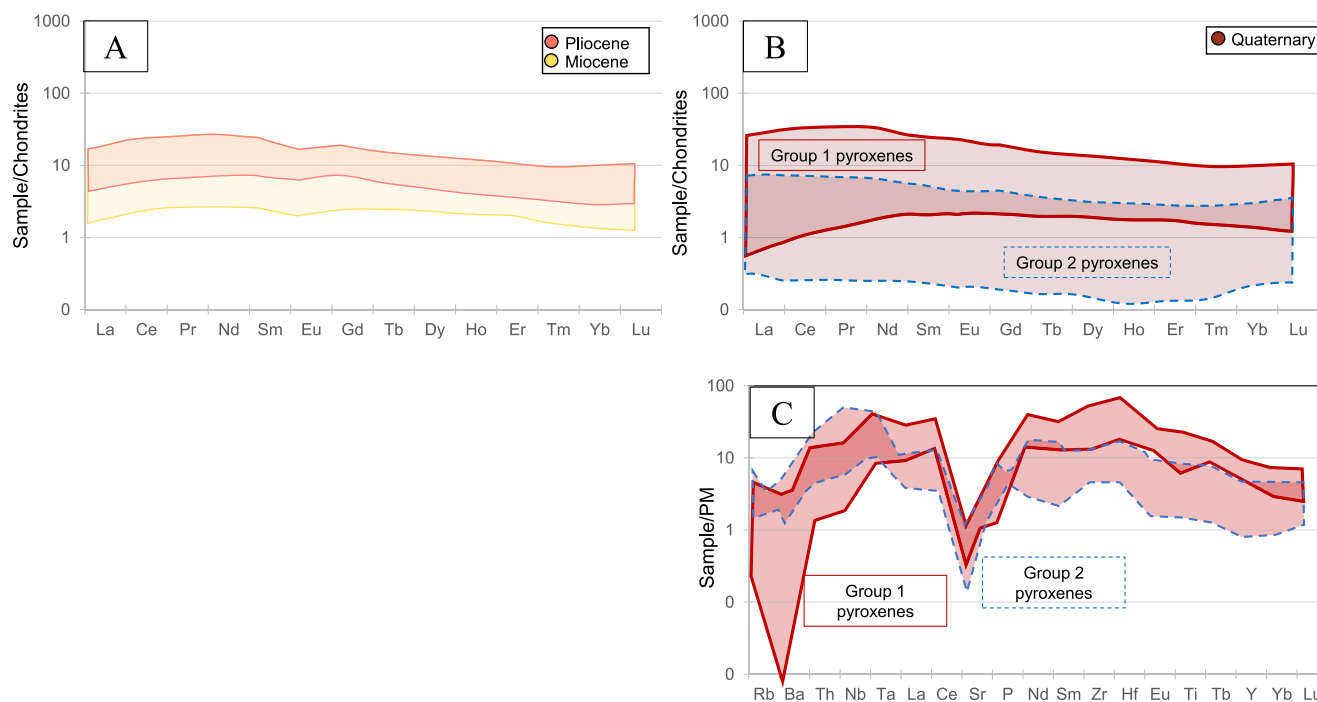


Figure 9. Chondrite-normalized rare earth elements (REE) profiles of clinopyroxenes from (a) Miocene and Pliocene and (b) Quaternary Uwayrid lavas. Mio-Pliocene pyroxenes have slightly shallower MREE/HREE slopes than Quaternary samples and exhibit a slightly negative Eu anomaly consistent with the growth of minor plagioclase. Quaternary samples define two groups: one more enriched in REE with a fractionated LREE slope (solid red region) and one with depleted REE and largely unfractionated LREE (dotted blue region).

5. Discussion

Geochemical data allow us to place key constraints on the petrogenesis of primitive basalts, to specify the mineralogy of the source region and depth of melting, and to explore changes in those parameters over time that provide insights into the evolving geodynamic environment. First order observations on the geomorphology of the Uwayrid region set the stage for our work: the older lavas are fissure and plateau basalts, while the youngest magmatism is characterized by monogenetic cinder cones and small flows. We also observe a profound change in trend between the NW-SE trending volcanic plateau of the mid-Miocene lavas and the N-S oriented cinder cones and flows of the younger samples. Our geochemical analyses allow us to delve into these observations and explore the processes that created these features.

5.1. Crustal Contamination

We concur with Altherr et al. (2019) that Uwayrid mafic lavas have not been appreciably contaminated by assimilation of continental crust. The high Mg#, high Ni and Cr contents, and negative Pb anomalies measured in lavas of all ages suggest they are PM melts, and the apparent low viscosity and volatile-rich nature of the late-Miocene—Quaternary lava flows and cinder cones do not favor extended residence in crustal chambers. All samples have Ce/Pb (16–50), Nb/U (43–140), and Nb/Rb (<6) values that overlap the range of mantle melts (A. Hofmann et al., 1986), and low K/La (<750) and Rb/La (<1) values overall, as expected for primitive mafic lava. We note that some Miocene and Pliocene lavas, particularly those with lower MgO contents, have Ce/Pb values < 20 that trend toward crustal values (Figure 6).

Post-melting alteration plays an insignificant role in the geochemistry of Uwayrid mafic lavas. Restricted $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{144}\text{Nd}/^{143}\text{Nd}$ values in Quaternary lavas (Altherr et al., 2019; this study) which overlap the Red Sea axial trough ratios (Eissen et al., 1989; Haase et al., 2000) indicate at most a minor role for post-melting alteration (Figure 7). $^{87}\text{Sr}/^{86}\text{Sr}$ values are higher in older Uwayrid basalts and exhibit a slight negative correlation with Ce/Pb (Figure 7b). These trends suggest that the older samples may have experienced minor assimilation of crustal material; however, we note that the amount of interaction must be limited as reflected in the low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Elemental ratios that are sensitive to crustal contamination, such as K/Nb and Ba/Zr, are low in Harrat Uwayrid lavas (<275 and <2.5, respectively) and do not correlate with $^{87}\text{Sr}/^{86}\text{Sr}$ values, suggesting that any assimilation of crustal material is very slight.

5.2. Fractional Crystallization

The compatible trace elements Ni, Co, Sc, and Cr show trends supportive of fractional crystallization of the observed mineral phases among all sample groups (Figure 4 and Figure S1 in Supporting Information S1). Major element variations in Uwayrid bulk rocks are consistent with early crystallization of olivine, followed by clinopyroxene at ~6–7 wt.% MgO (Figure 4 and Figure S1 in Supporting Information S1). The overall incompatible behavior of Na_2O , K_2O , and Al_2O_3 and the lack of Eu anomalies support a limited role for the crystallization of plagioclase feldspar, consistent with the limited abundance of this mineral in the petrographic assemblages from all Quaternary and most Mio-Pliocene samples. Slightly negative Eu anomalies in Mio-Pliocene clinopyroxenes ($\text{Eu}^* = 0.97$ and 0.86 , respectively; Figure 9a) and the absence of an Eu anomaly in their bulk rock chemistry reflects the inconsequential amount of plagioclase crystallization on the overall chemistry.

While the major element trends share broad patterns, significant geochemical heterogeneity exists both within and between age groups. Incompatible major and trace element abundances do not correlate with MgO (although they do correlate with one another; Figure 4; Figure S1 in Supporting Information S1). Thus, while fractional crystallization may explain the overall major element trends, incompatible element trends (e.g., Ba, La, Zr in Figure 4) require melting of either a markedly heterogeneous mantle source or multiple sources with distinct geochemical characteristics that vary over small spatial scales. Specifically, we found significant variation in the abundances of all incompatible trace elements among contemporaneous samples with high MgO values from the same area (Figure 4). Strong correlations between elements with very different compatibilities in the observed phenocryst phases (e.g., La vs. Zr and Ba vs. La; Figure 4 and Figure S1 in Supporting Information S1) preclude the observed variations at common MgO content from reflecting simple crystallization processes. Rather, the availability of multiple parental melt compositions suggests the availability of different mantle source(s) and/or melting processes. This heterogeneity greatly exceeds that observed among Quaternary MMN samples from

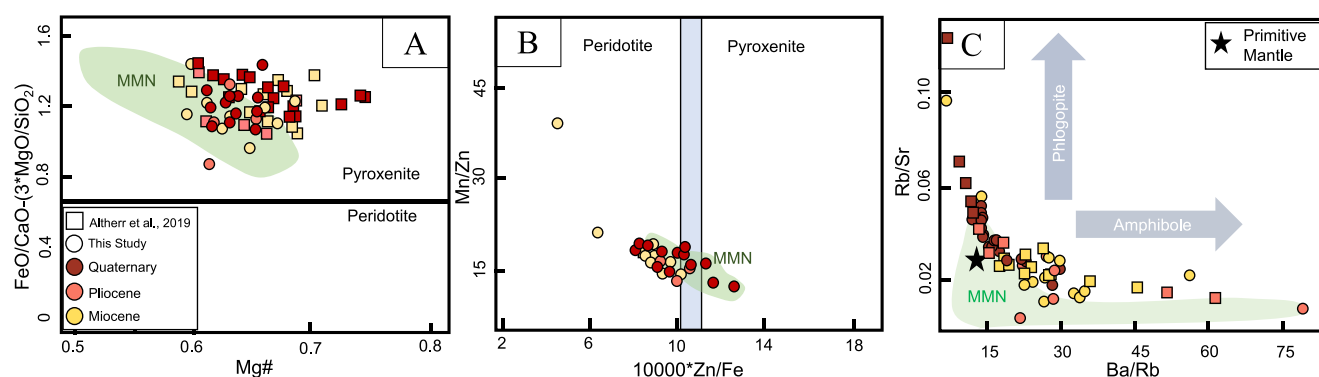


Figure 10. Bulk rock geochemical evidence for silicate and fluid metasomatism in the source region of Uwayrid mafic lava: (a) High FeO/CaO at a given MgO/SiO_2 value (represented here as $\text{FeO/CaO}-(3*\text{MgO/SiO}_2)$) is associated with melts of a pyroxenite source region (Yang & Zhou, 2013); (b) Zn/Fe values > 11 indicate melts from a source with clinopyroxene $\pm$ garnet since Zn/Fe fractionates heavily when melting in the presence of pyroxenite (Le Roux et al., 2010); (c) High values of Rb/Sr suggest Quaternary lavas equilibrated with a phlogopite-bearing source (which preferentially incorporates Rb over Sr) while Miocene and Pliocene lavas equilibrated with a source containing amphibole (which preferentially incorporates Ba over Rb).

several harrats (green fields on Figure 4), that is, MMN lavas show much more coherent trends supporting a significant role for fractional crystallization of a common parental magma composition (Stelten et al., 2018, 2020).

5.3. Source Mineralogy and Metasomatic History

Uwayrid mafic samples of all ages record melting of source(s) that experienced pervasive metasomatism by both silicate melts (which forms pyroxene at the expense of olivine) and hydrous fluids. High FeO/CaO at a given MgO/SiO_2 , which when represented as $\text{FeO/CaO}-(3*\text{MgO/SiO}_2)$ allows CaO to be viewed as pressure-independent, has shown success in fingerprinting pyroxenitic source regions in global basalt data (Yang & Zhou, 2013). Within this compositional space, Harrat Uwayrid lavas appear to have originated from a pyroxenitic source material (Figure 10a). This observation is supported by minor element abundances: $\text{Zn}*10000/\text{Fe}$ values > 11 in several Quaternary primitive lavas which suggests pyroxenite was present, though not ubiquitous, in the source material for Uwayrid mafic lavas (Figure 10b, Le Roux et al., 2010). We note that these metasomatic indicators are supported by both experimental data and geochemical studies of areas where melting of a metasomatized source has been inferred (e.g., Ducea et al., 2020; Le Roux et al., 2010, 2011; Pillet et al., 2008; Yang & Zhou, 2013). The patterns of enrichment in incompatible trace elements (Figure 5) closely resemble those of experimentally derived melts of clinopyroxene-bearing hornblende presented in Pillet et al. (2008), with similar positive Sr, Rb, and Ba anomalies and high Nb/La and La/Yb values.

Harrat Uwayrid olivine phenocryst compositions further suggest a metasomatized pyroxenite source, for example, high Ni (1,000–3,400 $\mu\text{g/g}$), high Fe/Mn (45–110), and low CaO relative to olivine in MORB. The partitioning of Ni and CaO into the melt reflects the presence of residual clinopyroxene and/or garnet, which will retain CaO while excluding Ni relative to olivine (Figure 10a, Herzberg, 2011; Sobolev et al., 2005). Melting in the presence of pyroxene will cause fractionation of Fe/Mn and result in values higher than what is expected from a peridotite-controlled melt (Herzberg, 2011; Sobolev et al., 2007). The range of Ni and CaO contents of Uwayrid olivines extends well into the field of values observed at Mauna Kea, which has a well-established pyroxenite-dominated source region (Figure 11a, Sobolev et al., 2007). High values of chondrite-normalized Zr/Yb and Ti/Eu, especially in clinopyroxene from Quaternary samples, provide further evidence of a pyroxenite source region. Enrichment in Zr and Ti is expected from the percolation of a silicate melt, which would form clinopyroxene at the expense of olivine in the lithospheric mantle.

Phases associated with fluid metasomatic reactions appear to be present in the mantle source for Uwayrid basalts of all ages, although the specific phases differ between lava age groups. High Ba/Rb values in Miocene and some Pliocene samples suggest the presence of amphibole in the source region, which is a phase present in xenoliths from Harrats Uwayrid and Ash Shaam (Figure 10c, Kaliwoda et al., 2007, 2008; K. Krienitz & Haase, 2011). In contrast, Quaternary and some Pliocene samples show elevated Rb/Sr relative to PM, which points toward melting in the presence of phlogopite. Both amphibole and phlogopite are common in pyroxenitic lithospheric

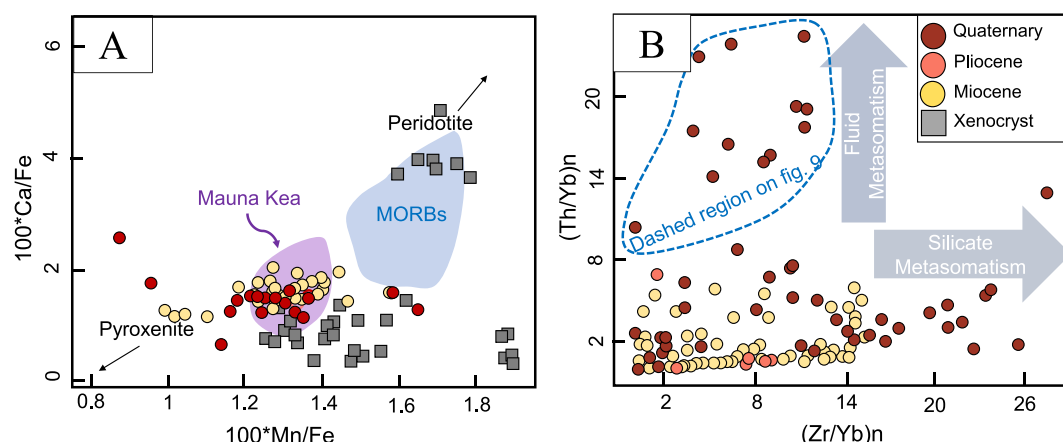


Figure 11. Trace element systematics of olivines and clinopyroxenes document silicate and fluid metasomatism in the source region of Harrat Uwayrid lavas: (a) Low CaO in Uwayrid olivines is controlled by clinopyroxene and garnet in the source region (lower Ca and Mn at a given Fe is associated with melting of pyroxenite, Herzberg, 2011; Sobolev et al., 2005). We note that sampled xenoliths (shown here as gray squares) correspond to the observed mineralogy of the samples: true pyroxenites, pyroxene-bearing peridotites, and true peridotites; (b) Relative values of Zr/Yb and Th/Yb in clinopyroxenes allow us to distinguish between the effects of silicate melt and fluid metasomatism. Quaternary samples with the highest Th/Yb values (circled in dashed blue field) also have distinct rare earth elements profiles of Group 2 clinopyroxenes shown in Figure 8b.

mantle xenoliths from Harrat Uwayrid, although they are not observed to coexist (Kaliwoda et al., 2007, 2008). Enrichment in fluid mobile elements (Th, Na) in clinopyroxene also suggests that fluid metasomatism affected the chemistry of the source region for all age groups (Figure 11b); clinopyroxenes from Quaternary samples have the highest concentrations of fluid mobile elements. These samples are the most depleted in REEs and exhibit limited LREE fractionation (dotted blue region in Figure 11b), consistent with LREE partitioning in fluid phases within the source.

It is our expectation that pyroxenite is distributed, along with hydrous phases, in metasomatic veins in the lower lithosphere (Pillet et al., 2008; Rooney et al., 2017). While metasomes likely constitute a volumetrically small percentage of the lithospheric mantle beneath Saudi Arabia, their hydrous and pyroxene-dominated mineralogies are more readily fusible than peridotite and contain higher abundances of many incompatible trace elements, so the geochemical features of the resulting melts contain a disproportionately high contribution from the metasomes (e.g., Rooney et al., 2017).

A similar geochemical pattern attributed to metasomatism by hydrous fluids is observed in mafic volcanics of the Yerer–Tulul Wellal Volcano-Tectonic Lineament in Ethiopia (Bowden et al., 2022; Rooney et al., 2017). This region is underlain by the same Arabian-Nubian Shield basement and has likely undergone the same orogenic history that characterizes the Harrat Uwayrid region (Bowden et al., 2020). The Arabian-Nubian Shield that dominates both regions formed from island-arc accretion, which likely provided the fluids necessary for the observed metasomatic effects (Blades et al., 2015; Bowden et al., 2020).

The two distinct metasomatic events—one by hydrous fluids and one by silicate melts—are manifested nearly ubiquitously across the northern Arabian Peninsula. Both HAS and MMN basalts have Zn/Fe and Fe/Ca values overlapping those of Harrat Uwayrid basalts, suggesting that a mixed pyroxenite-peridotite source is present beneath both areas. Textural evidence of silicate metasomatism in xenoliths (i.e., hydrous veins within pyroxenite) requires the silicate metasomatic event to predate the fluid metasomatic reactions, one or both of which may be related to the Neoproterozoic Pan African Orogeny (M. Krienitz et al., 2007).

We identify evidence of hydrous metasomatic phases in all northern Arabian harrats. High Rb/Sr and Ba/Rb in Quaternary HAS and Harrat Rahat samples indicate that a hydrous metasomatized source region extends at least to these basalt fields (M. Krienitz et al., 2007; Shaw et al., 2003; Stelten et al., 2018). However, important differences exist between the northernmost Harrats Uwayrid and Ash Shaam and the Quaternary MMN basalts. The latter are notably less alkaline, less compositionally heterogeneous, and have lower abundances of incompatible elements than contemporaneous Uwayrid mafic lavas (Figure 4). We note that the Sr-Nd isotopic values of

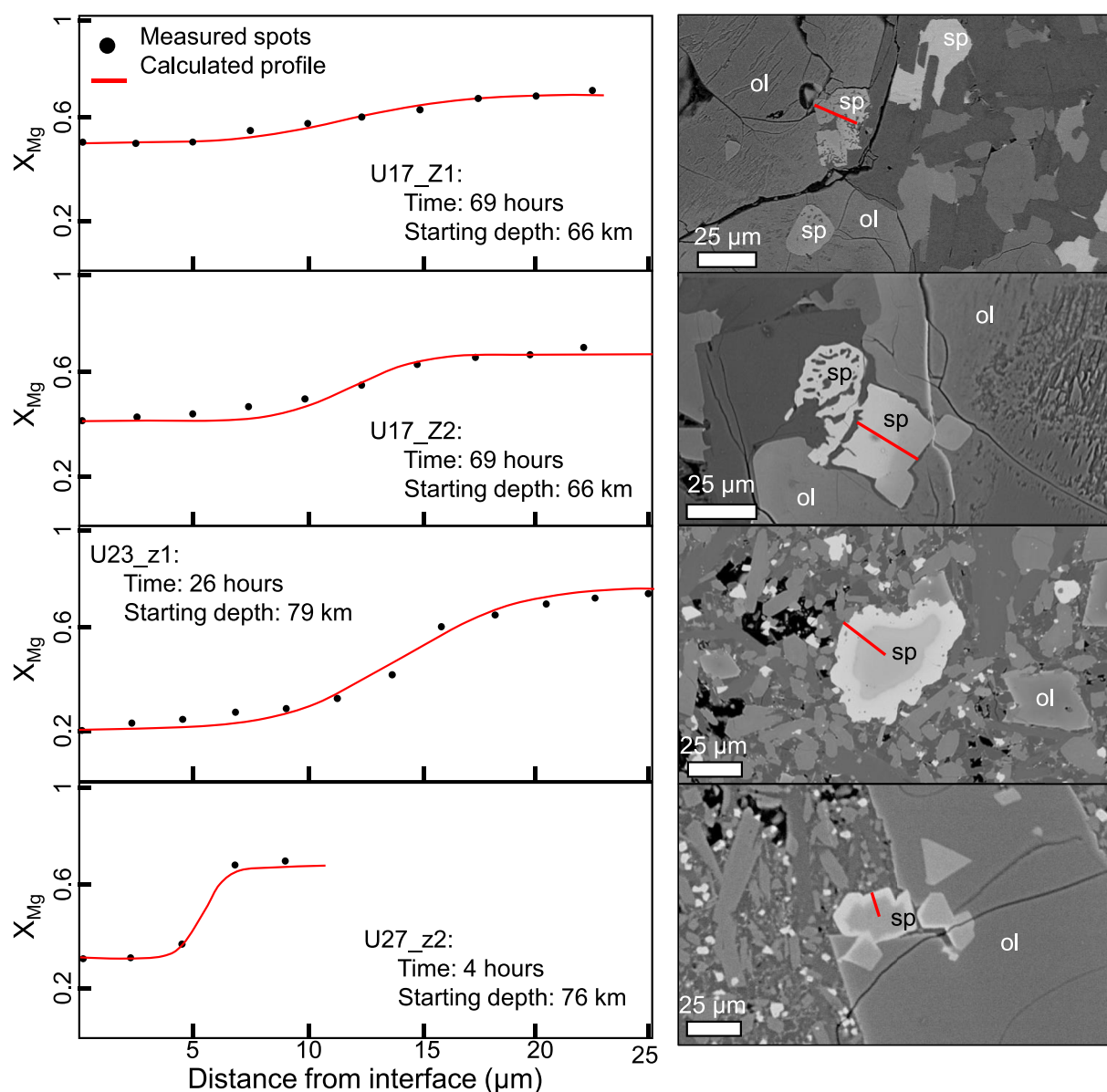


Figure 12. Measured (black dots) and calculated (red lines) Fe-Mg diffusion profiles from zoned spinels found within Quaternary lava. All models result in short diffusion timescales of the order of less than a week. These data suggest that the chemical event which induced diffusion occurred shortly before the eruption.

Uwayrid lavas are distinct from those of contemporaneous volcanics from Erta Ale and Djibouti (the modern Afar plume tail; Figure 7), suggesting that metasomatism and magmatism at Harrat Uwayrid does not require material contributions from the Afar plume.

5.4. Eruptive Processes and Timescales

Several lines of evidence suggest the time lapsed between melting and eruption decreased progressively from Miocene to the present. Mid-Miocene samples are holocrystalline with large amounts of plagioclase and clinopyroxene REE patterns with negative Eu anomalies; late-Miocene-Pliocene samples are less crystalline than mid-Miocene samples and contain small amounts of plagioclase; Quaternary samples are glassy, plagioclase-absent, and their clinopyroxenes lack negative Eu anomalies. These observations are consistent with progressively shorter residence times in the lithosphere.

Elemental zoning in Cr-rich Quaternary spinel records short timescales of eruptive processes. These spinels that are zoned in Fe, Mg, Al, and Cr are found almost exclusively within or at the grain boundaries of phenocrystic

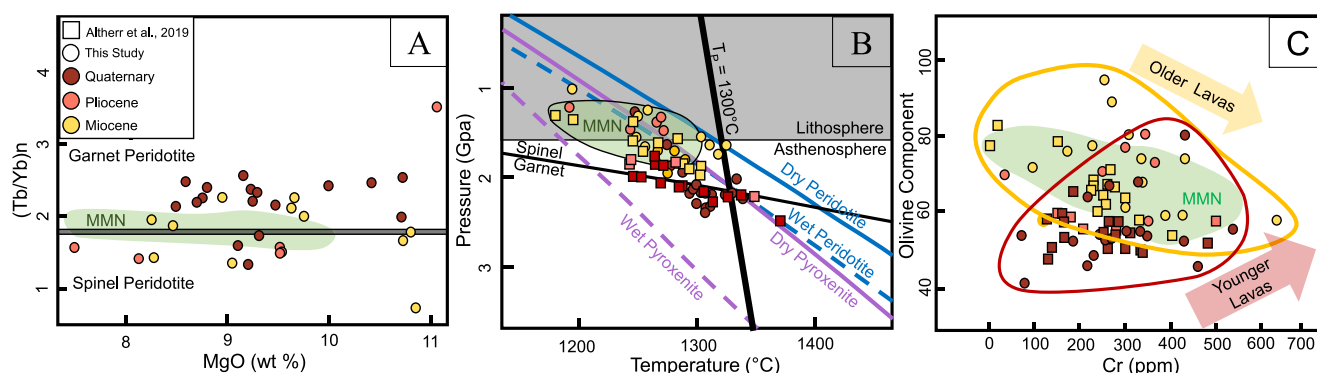


Figure 13. Melting depths for Harrat Uwayrid lavas: (a) Most Quaternary samples have chondrite-normalized Tb/Yb_n values indicative of melting within the garnet stability field, whereas most older lavas plot near or below the spinel-garnet transition (normalizing values from Sun and McDonough (1989); line from Wang et al. (2002)); (b) Melt equilibration pressure and temperatures calculated following Putirka (2008) indicate the youngest samples are derived from the greatest depths (i.e., beneath the present-day lithosphere-asthenosphere boundary), which is not expected in an adiabatic melting scenario; (c) Correlations between olivine component (after Sack et al. (1987)) of primitive mafic melts and their Cr contents distinguish trends for adiabatic decompression (Makkah Medina Nafud lavas; early-mid Miocene and Late Miocene Uwayrid lavas) from those established for products of drip melting (Pliocene and Quaternary samples). The effects of fractional crystallization are minimized by adding olivine to the major element composition until $Fo = 90$, which is assumed to be the primitive composition of the mantle.

olivines; zoned spinels are rarely found in the matrix, which contains small, abundant Cr-poor spinels. This relationship suggests that the chromian spinels predate the growth of the groundmass and are coincident with the initial growth of olivine. We suggest that partial diffusive re-equilibration resulting in zoning and the growth of Cr-poor spinels are roughly contemporaneous and occurred shortly before eruption. Modeling the step functions defined by EPMA transects across the zoned spinels reveals timescales on the order of days to weeks between initiation and cessation of diffusion (Figure 11). These observations support a scenario of rapid ascent through the lithosphere. Modeling of the drag force on xenoliths (~1–30 cm diameter) within Quaternary lavas using Stokes' law requires rapid ascent of a few days, which is consistent with our diffusion models.

5.5. Depth and Extent of Mantle Melting

Geochemical evidence suggests that the depth of melting beneath Harrat Uwayrid was greater during the most recent phase of volcanism than in Miocene time. Bulk rock MREE/HREE values (Tb/Yb_n ; Figure 13a) indicate most Plio-Quaternary samples were derived from melting within the garnet stability field, while the older samples plot primarily along the spinel-garnet transition zone or within the spinel stability field. An increase in Tb/Yb_n over time is also observed in clinopyroxene: mid-Miocene samples have shallower slopes than Plio-Quaternary crystals (Figure 9b), consistent with HREE partitioning in garnet in the source region of the younger lavas. The hydrous mineralogy of the source region shows a similar pattern: Older basalts with Ba/Rb values ~15–80 record equilibration with an amphibole-bearing source, while Quaternary basalts with Rb/Sr ~0.03–0.07 equilibrated with a phlogopite-bearing (and thus likely deeper) source (Figure 10c, Mengel & Green, 1986).

Melt equilibrium pressure and temperature estimates calculated for bulk lava compositions (following Albarede (1992) and Putirka (2008)) show an increase in melting depth from ~1 GPa in the mid-Miocene to >3 GPa in the Quaternary (Figure 13b). These calculations place the Quaternary melting regime substantially below the regional lithosphere-asthenosphere boundary (approximately ~1.5 GPa, based on velocity models from Hansen et al. (2007)), a result that is unexpected given the thinned lithosphere beneath Harrat Uwayrid. Nonetheless, these depths are supported by REE and large iron lithophile elements systematics (Figures 5 and 6). The calculated melting depths are consistent with those from an analogous nascent rift in SW Uganda (Pitcavage et al., 2023) and are supported by melt modeling of carbonated and hydrous peridotite at 4–6 GPa (Foley et al., 2009, 2012).

In marked contrast, Quaternary MMN samples appear to have substantially shallower melting depths than contemporaneous Harrat Uwayrid basalts. MMN samples have $(Tb/Yb)_n$ values ranging from 1.5 to 2.2, indicating a shallower melt region than beneath Harrat Uwayrid. Calculated melt equilibration depths for Quaternary mafic lavas from the MMN are also shallower than those of young Uwayrid lavas (Figure 13).

The change in melting depth documented at Harrat Uwayrid corresponds to an increase in the extent of melting in younger lavas. Figure 13c shows a broadly positive correlation between the calculated olivine component

(after Sack et al. (1987)) and Cr content in young primitive Uwayrid lavas. Here we have minimized the effects of fractional crystallization by adding olivine to the major element composition until the calculated equilibrium olivine composition is Fo_{90} , which is taken to be the composition in the mantle. A higher olivine component (at the expense of diopside and nepheline) indicates greater melting depths, while Cr abundance serves as a proxy for melting extent. Here we have only employed primitive lavas with $MgO > 7.5$ wt.%, all of which have Ni and Cr contents of < 330 and < 484 ppm, respectively, and thus appear not to have accumulated olivine crystals. The relationship observed among the late-Miocene-Quaternary basalts contrasts with the broadly negative trend defined by mid-Miocene Uwayrid basalts, which show a greater degree of melting at shallower depths similar to that observed among MMN lavas. This latter relationship is characteristic of regions of adiabatic decompression melting, including mid-ocean ridges (e.g., Holbig & Grove, 2008; Kinzler, 1997; Kinzler & Grove, 1992). The positive correlation we observe for the young Harrat Uwayrid lavas, that is, that melting extent increased with depth, is at odds with adiabatic melting (Elkins-Tanton, 2005, 2007).

5.6. Geodynamic Evolution of the Uwayrid Region

The recognition that young Harrat Uwayrid mafic lavas reflect a greater degree and depth of melting than the older lavas presents a geodynamic conundrum. This relationship is not expected in a rifting or plume-driven melting environment, where the melting region becomes shallower with time and the degree of melting is predicted to be greatest at shallow depths following adiabatic ascent of the source material. The Uwayrid late-Miocene—Quaternary data instead require a physical model wherein the lithospheric source of the younger lavas becomes available to melt at greater depths over time. There are two principal scenarios that provide this melting opportunity: lithospheric drip magmatism (e.g., Ducea et al., 2013, 2020; Elkins-Tanton, 2005, 2007; Furman et al., 2016), and edge convection (e.g., Cordoba & Ballmer, 2021; Kaislaniemi & van Hunen, 2014) both of which reflect steep topography on the lithosphere-asthenosphere boundary. These geodynamic scenarios—which need not be mutually exclusive—involve abrupt, localized removal (i.e., descent) of lithospheric material in the absence of extension sufficient to trigger adiabatic asthenospheric upwelling.

Source mineralogy of the younger Harrat Uwayrid lavas supports lithospheric removal and melting. Pyroxenite veins inferred from basalt geochemistry, xenolith mineralogy (Kaliwoda et al., 2007, 2008), and geophysical evidence promote foundering via a density instability in the lithosphere, as predicted in geophysical models of lithospheric removal (i.e., Elkins-Tanton, 2005, 2007). Bouguer gravity modeling (Hansen et al., 2007) indicates that the lithospheric mantle beneath the western edge of the Arabian Shield is denser than the underlying asthenosphere (Figure 14). This densification likely reflects regional silicate metasomatism and is enhanced by the presence of mafic cumulates from the ~Oligo—mid-Miocene volcanic episode at the coastal harrats. Pyroxenite and hydrous phases encourage melting of both the foundered material and the newly exposed deep lithospheric walls by lowering the solidus (Hirschmann & Stolper, 1996; Lambart et al., 2009; Pertermann & Hirschmann, 2003). These geochemical observations are consistent with numerical modeling that indicates only the observed combination of a metasomatized lithology and its transport to regions of higher potential temperature will result in melting beneath continents (e.g., Elkins-Tanton, 2005, 2007; Figure 13).

Fundamental observations of the geological and magmatic evolution of Harrat Uwayrid are consistent with predictions from geophysical modeling of laminar lithospheric removal and subsequent melting. For the individual 10s of km wide density driven laminar detachment, the total time from the onset to 20%–50% thinning of the lithosphere is roughly 5–15 Ma (Conrad & Molnar, 1999; Elkins-Tanton & Hager, 2000). Magmatism is predicted to occur after thinning permits upwelling of the warm asthenosphere, that is, after a hiatus of several million years. We observe this predicted magmatic gap at Harrat Uwayrid: following the cessation of Mid-Miocene activity, renewed volcanism began at around 10 Ma (Altherr et al., 2019) and has continued until the present.

First-order morphological features of Harrat Uwayrid are also consistent with geophysical models of laminar lithospheric removal: the upper lithosphere in areas undergoing lithospheric removal will initially experience a $> \sim 120$ m depression as the lower lithosphere begins to be removed; after detachment, topographic rebound may return the elevation to heights greater than the unperturbed level (Elkins-Tanton, 2005). These predictions are met at several localities that are interpreted to have experienced recent lithospheric removal (e.g., Ethiopia: Bowden et al., 2022; the Anatolian Plateau: Gall et al., 2021; Göğüş et al., 2017). The youngest volcanism at Harrat Uwayrid is restricted to topographic depressions, most notably the ~60 km across, ~200 m deep Al Jaww in the center of the harrat (Figure 2). This topographic anomaly fully satisfies the predictions made by modeling efforts and signals a dynamic lithosphere that is changing in response to drip removal at its base.

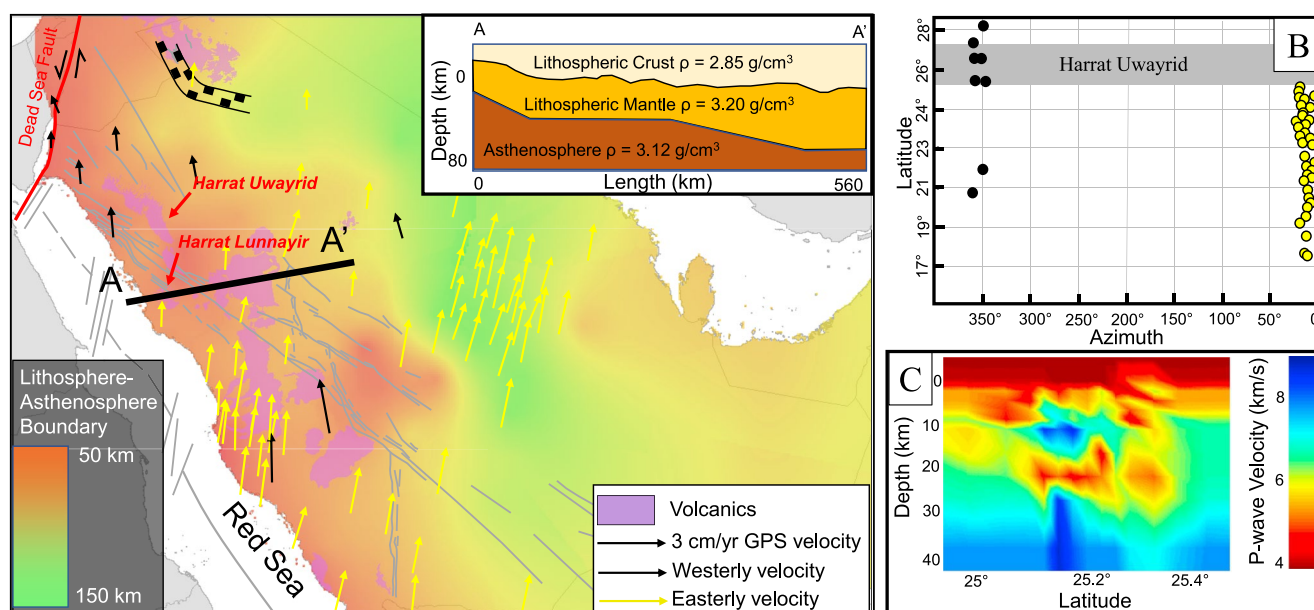


Figure 14. (a) Lithosphere-asthenosphere boundary depths (Hansen et al., 2007) show variably thinned lithosphere beneath the Arabian Harrats. Arrows indicate calculated GPS velocities (stable Nubia) from Alotaibi (2019). Yellow arrows point northeast while black arrows point northwest and highlight the differential plate motion from the southern to northern Red Sea area. (b) GPS vectors displayed by latitude versus azimuth, showing differential plate motion across the Arabian Peninsula. (c) Double difference velocity model performed at nearby Harat Lunayir from Hansen et al. (2007) shows a detachment at shallow levels in the lithosphere, analogous to our model for processes occurring beneath Harat Uwayrid. Inset: Density structure from Bouguer gravity modeling beneath the harrats along Section A-A' shows a lithospheric mantle that is denser than the underlying asthenosphere (Hansen et al., 2007) and hence likely to founder in response to tectonic stresses.

S-wave receiver functions show a broadly thinned lithosphere of 50–60 km beneath the Red Sea margin of the Arabian Shield (Figure 14, Hansen et al., 2007) with an abrupt boundary against the unperturbed eastern side of the Arabian Peninsula that exceeds 115 km in thickness (Hansen et al., 2007). Small-scale lithospheric removal is documented via double difference tomography beneath Harat Lunayir, 100 km south of Harat Uwayrid (Figure 14c) where seismic imaging suggests an isolated and detached packet of lithosphere at <50 km depth is surrounded by seismically slower material consistent with upwelling asthenosphere (Hansen et al., 2013). This scenario sets the stage for both melting of the detached material as it heats and small-scale convection along the abrupt and steep lithosphere-asthenosphere boundary that detachment creates. We favor this lithospheric drip model over an edge convection model as Harat Uwayrid is far from the area of steep LAB topography and is consistent with the field expression of subsidence at Al Jaww.

Our mid-Miocene $^{40}\text{Ar}/^{39}\text{Ar}$ dates represent minimum age constraints on the earliest volcanism at Harat Uwayrid and are likely not the oldest flows on the volcanic plateau. Early basalt volcanism at Uwayrid is thus roughly contemporaneous with the main period of Red Sea opening. These basalts are subalkaline and characterized by an effusive NW-SE trending volcanic plateau aligned parallel to the Red Sea main axis/diffuse northern rifts (Figure 2, Stockli & Bosworth, 2019). Our new data and K-Ar ages from Altherr et al. (2019) both document a ~5 Ma volcanic hiatus that begins during the suture of Arabia and Eurasia ~14 Ma and ends in the late-Miocene with a period of rejuvenated volcanism around 10 Ma. This later volcanic period began after the slowing of the Northern Red Sea spreading and the initiation of the DSF. These basalts are alkaline and form cinder cones in a roughly N-S alignment, roughly parallel to the DSF system (Stockli & Bosworth, 2019; Figure 14). The change in plate motion recorded by DSF initiation is observed at Harat Uwayrid when viewing GPS velocity anomalies, where extension switches from NE- to NW-directed (Figure 14, Alotaibi, 2019). The older volcanic plateau itself records this change, which fractured the previously continuous Harat (Figure 15) into the curved harat observed at present (Figure 15b). Rejuvenated volcanism is restricted to areas where extension is greatest, that is, Al Jaww, located at the outer curve of the older volcanic plateau (Figures 2 and 15). These observations suggest that both magmatic episodes are structurally controlled and that lithospheric destabilization during plate boundary evolution played a key role in late-Miocene–Quaternary magma genesis. This process is a potentially critical mechanism for crustal thinning (leading to magma-assisted rifting) in areas like Uwayrid where extension has ceased yet magmatism continues to the present day (McKenzie & Bickle, 1988).

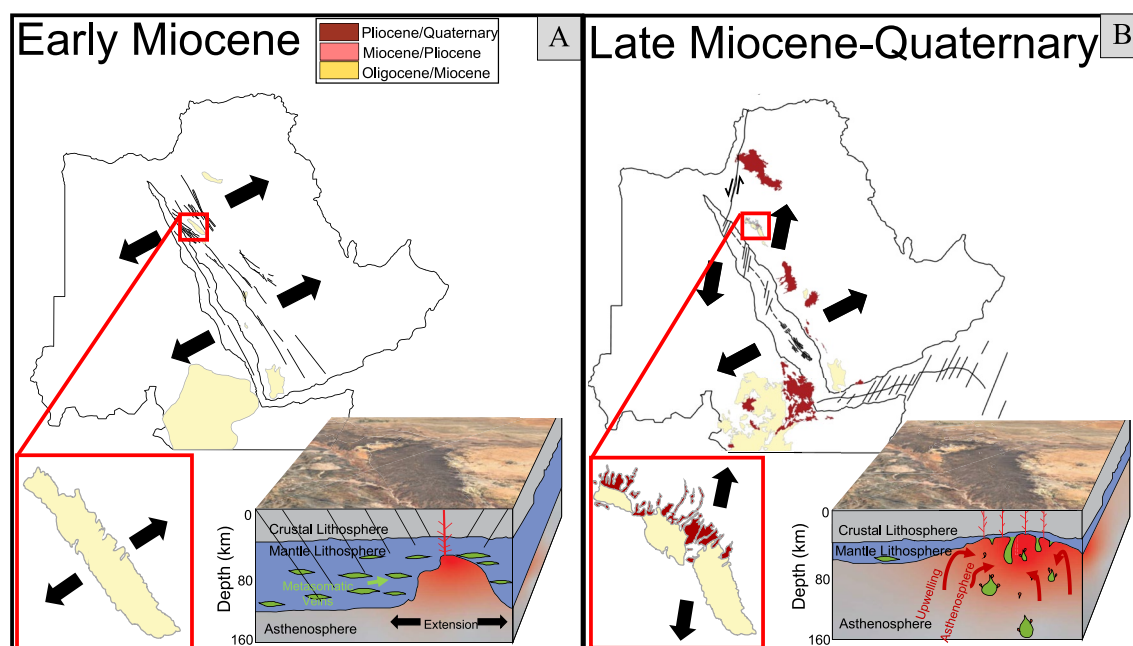


Figure 15. Two-stage geodynamic model for mantle melting beneath Harrat Uwayrid. (a) Early to Mid-Miocene volcanism was driven by rifting normal to the NW-SE Red Sea axis where adiabatic decompression melting is associated with lithospheric extension. (b) Ca. 14 Ma, slowing of Northern Red Sea spreading and inception of the Dead Sea Fault caused extensional plate motion to change from normal to oblique along the northern Red Sea axis. Zones of lithospheric weakness formed orthogonal to existing volcanic trends, facilitating the removal and sinking of anomalously dense and hydrated lower lithosphere.

We propose a multi-stage model for the formation of Harrat Uwayrid (Figure 15): Early tectonic events (possibly Neoproterozoic) formed widespread regions of pyroxenite from silicate metasomatism and heterogeneously distributed hydrous metasomatic veins in the lithosphere. Two Cenozoic magmatic events likely induced melting of these metasomatic phases, both of which are related to the evolving geodynamic setting of the Arabian Peninsula. First, early (Oligo—mid-Miocene) rifting associated with opening of the Red Sea initiated adiabatic melting and erupted basalts parallel to the rift fabric. This first magmatic episode was followed by a period of tectonic and magmatic quiescence after Red Sea rifting slowed around 14 Ma. A second phase of volcanism began around 10 Ma following the initiation of the DSF, which changed the plate motion in the NW Arabian Peninsula from rift-normal to rift-oblique. These far-field stresses as well as the fracturing observed in the central portion of the mid-Miocene volcanic plateau likely initiated foundering of the inherently unstable metasomatized (dense, veined pyroxenite) lower lithosphere. Basalt genesis during this second phase of volcanism was likely accomplished via progressive melting of detached lithosphere as it encountered hot asthenosphere upwelling along the steep boundary between these domains. We note that $^3\text{He}/^4\text{He}$ values from olivine, amphibole, and pyroxenes in Harrat Hutaymah basalts and xenoliths ($7.54 \pm 0.03_{\text{RA}}$) do not require a mantle plume component (Konrad et al., 2016).

6. Conclusions

Field, bulk rock, and single mineral elemental and isotopic geochemical data on Miocene-Quaternary basaltic lavas from Harrat Uwayrid enable us to address the thermodynamically difficult process of melting the mantle beneath thick continental crust. Mid-Miocene and earlier lavas formed NW-SE trending volcanic plateaus, while late-Miocene—Quaternary samples formed isolated monogenetic cinder cones and small flows in an N-S orientation. Harrat Uwayrid lavas of all ages derive from a source region affected by both silicate and fluid metasomatic reactions, which increase the density of the source region and promote melting by lowering the solidus. Older lavas appear to have melted amphibole-spinel pyroxenite near the paleo lithosphere-asthenosphere boundary and record progressive shallowing of the melting region. The morphology and chemistry of the young lavas require individual melt batches from a markedly heterogeneous phlogopite-garnet pyroxenite mantle source(s). Melt equilibration pressure-temperature estimates for the Quaternary lavas are substantially higher than those of

the Miocene samples and broadly show a deepening of the melt region throughout time. These observations are consistent with a model wherein Oligo-Miocene samples formed from adiabatic upwelling associated with the Red Sea formation. Slowing of the Red Sea spreading and initiation of the DSF destabilized the lower lithosphere beneath Harrat Uwayrid which detached and progressively melted to form the rejuvenated volcanic period. This work demonstrates how an actively changing geodynamic environment may destabilize an inherently unstable lithosphere and encourage lithospheric foundering or drip beneath continents.

Data Availability Statement

All geochemical data are available via GEOROC (Bowden, 2024) and also from the authors upon request. Thin section slides, lab notes, and field notes are available from the authors upon request.

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References

- Albarede, F. (1992). How deep to common basaltic magmas form and differentiate? *Journal of Geophysical Research*, 97(B7), 10997–11009. <https://doi.org/10.1029/91JB02927>
- Alotaibi, T. (2019). *Lithospheric geodynamics of the Arabian margin*, Doctor of Philosophy Dissertation. The Pennsylvania State University.
- Alsharhan, A., & Nairn, A. (1997). *Sedimentary basins and petroleum geology of the middle East*. Elsevier.
- Altherr, R., Henjes-Kunst, F., & Baumann, A. (1990). Asthenosphere versus lithosphere as possible sources for basaltic magmas erupted during formation of the Red Sea: constraints from Sr, Pb and Nd isotopes. *Earth and Planetary Science Letters*, 96(3–4), 269–286. [https://doi.org/10.1016/0012-821x\(90\)90007-k](https://doi.org/10.1016/0012-821x(90)90007-k)
- Altherr, R., Henjes-Kunst, F., Puchelt, H., & Baumann, A. (1988). Volcanic activity in the Red Sea axial trough - Evidence for a large mantle diapir? *Tectonophysics*, 150(1–2), 121–133. [https://doi.org/10.1016/0040-1951\(88\)90298-3](https://doi.org/10.1016/0040-1951(88)90298-3)
- Altherr, R., Mertz-Kraus, R., Volker, F., Kreuzer, H., Henjes-Kunst, F., & Lange, U. (2019). Geodynamic setting of Upper Miocene to Quaternary alkaline basalts from Harrat al “Uwayrid (NW Saudi Arabia): Constraints from K-Ar dating, chemical and Sr-Nd-Pb isotope compositions, and petrological modeling”. *Lithos*, 330–331, 120–138. <https://doi.org/10.1016/j.lithos.2019.02.007>
- Ballhaus, C., Berry, R., & Green, D. (1991). High pressure experimental calibration of the olivine-orthopyroxene-spinel oxygen geobarometer: Implications for the oxidation state of the upper mantle. *Contributions to Mineralogy and Petrology*, 107(1), 27–40. <https://doi.org/10.1007/bf00311183>
- Bar, O., Zilberman, E., Feinstein, S., Calvo, R., & Gvirtzman, Z. (2016). The uplift history of the Arabian Plateau as inferred from geomorphologic analysis of its northwestern edge. *Tectonophysics*, 671(7), 9–23. <https://doi.org/10.1016/j.tecto.2016.01.004>
- Barrat, J., Fourcade, S., Jahn, B., Cheminee, J., & Capdevila, R. (1998). Isotope (Sr, Nd, Pb, O) and trace-element geochemistry of volcanics from the Erta’ Ale range (Ethiopia). *Journal of Volcanology and Geothermal Research*, 80(1–2), 85–100. [https://doi.org/10.1016/S0377-0273\(97\)00016-4](https://doi.org/10.1016/S0377-0273(97)00016-4)
- Blades, M., Collins, A., Foden, J., Payne, J., Xu, X., Alemu, T., et al. (2015). Age and hafnium isotopic evolution of the Didessa and Kemashi Domains, western Ethiopia. *Precambrian Research*, 270, 267–284. <https://doi.org/10.1016/j.precamres.2015.09.018>
- Bosworth, W., Huchon, P., & McClay, K. (2005). The Red Sea and Gulf of Aden basins. In O. Catuneanu, R. Guiraud, P. Eriksson, B. Thomas, R. Shone, & R. Key (Eds.), *Phanerozoic evolution of Africa* (Vol. 43, No. (1–3), pp. 334–378).
- Bosworth, W., Stockli, D., Helgeson, D., & Cosca, M. (2015). Integrated outcrop, 3D seismic, and geochronologic interpretation of Red Sea dike-related deformation (ca. 23 Ma) in the western Desert, Egypt – The role of the Cairo “mini-plume”. *Journal of African Earth Sciences*, 109, 107–119. <https://doi.org/10.1016/j.jafrearsci.2015.05.005>
- Bowden, S. (2024). Geodynamic controls on basaltic volcanism in the Arabian Peninsula: Evolution of Harrat Uwayrid, Saudi Arabia [Dataset]. GRO.data, V1. <https://doi.org/10.25625/MPR46W>
- Bowden, S., Gani, N., Alemu, T., O’Sullivan, P., Abebe, B., & Tadesse, K. (2020). Evolution of the Western Ethiopian shield revealed through U-Pb geochronology, petrogenesis, and geochemistry of syn- and post-tectonic intrusive rocks. *Precambrian Research*, 338, 105588. <https://doi.org/10.1016/j.precamres.2019.105588>
- Bowden, S., Gani, N., Furman, T., Gani, R., VanSoest, M., Abebe, T., et al. (2022). Feedback between topography and lithosphere-asthenosphere dynamics beneath the Yerer-Tulu Wellel Volcano-Tectonic Lineament: Insights from apatite thermochronology and basalt geochemistry. *Geological Journal*, 57(9), 3569–3586. <https://doi.org/10.1002/gj.4488>
- Brown, G., Schmidt, D., & Huffman, C. (1989). *Geology of the Arabian Peninsula, shield area of western Saudi Arabia*. US Geological Survey Professional Paper. <https://doi.org/10.3133/ofr84203>
- Camp, V., & Roobol, M. (1989). The Arabian continental alkali basalt province: Part II. Evolution of the Harrat Rahat, Kingdom of Saudi Arabia. *Geological Society of America Bulletin*, 101(1), 71–95. [https://doi.org/10.1130/0016-7606\(1989\)101<0071:tacabp>2.3.co;2](https://doi.org/10.1130/0016-7606(1989)101<0071:tacabp>2.3.co;2)
- Camp, V., & Roobol, M. (1992). Upwelling asthenosphere beneath western Arabia and its regional implications. *Journal of Geophysical Research*, 97(B11), 15255–15271. <https://doi.org/10.1029/92JB00943>
- Camp, V., Roobol, M., & Hooper, P. (1991). The Arabian continental alkali basalt province: Part II. Evolution of Harrats Khaybar, Ithnayn, and Kura, Kingdom of Saudi Arabia. *GSA Bulletin*, 103(3), 363–391. [https://doi.org/10.1130/0016-7606\(1991\)103<0363:TACABP>2.3.CO;2](https://doi.org/10.1130/0016-7606(1991)103<0363:TACABP>2.3.CO;2)
- Coleman, R., Gregory, R., & Brown, G. (1983). *Cenozoic volcanic rocks of Saudi Arabia*. United States Department of the Interior Geological Survey. Open-File Report 83-788. <https://doi.org/10.3133/ofr83788>
- Conrad, C. P., & Molnar, P. (1999). Convective instability of a boundary layer with temperature- and strain-rate-dependent viscosity in terms of “available buoyancy”. *Geophysical Journal International*, 139(1), 51–68. <https://doi.org/10.1046/j.1365-246X.1999.00896.x>
- Cordoba, A., & Ballmer, M. (2021). The role of edge-driven convection in the generation of volcanism – Part 1: A 2D systematic study. *Solid Earth*, 12(3), 613–632. <https://doi.org/10.5194/se-12-613-2021>
- Downs, D., Stelten, M., Champion, D., Dietrich, H., Nawab, Z., Zahran, H., et al. (2018). Volcanic history of the northernmost part of the Harrat Rahat volcanic field, Saudi Arabia. *Geosphere*, 14(3), 1253–1282. <https://doi.org/10.1130/GES01625.1>
- Ducea, M., Barla, A., Stoica, A., Panaiotu, C., & Petrescu, L. (2020). Temporal-geochemical evolution of the Persani volcanic field, eastern Transylvania basin (Romania): Implications for slab rollback beneath the SE Carpathians. *Tectonics*, 39(5), e2019TC005802. <https://doi.org/10.1029/2019TC005802>

- Ducea, M., Seclaman, A., Murray, K., Jianu, D., & Schoenbohm, L. (2013). Mantle-drip magmatism beneath the Altiplano-Puna plateau, central Andes. *Geology*, 41(8), 915–918. <https://doi.org/10.1130/G34509.1>
- Duncan, R., & Al-Amri, A. (2013). Timing and composition of volcanic activity at Harrat Lunayyir, western Saudi Arabia. *Journal of Volcanology and Geothermal Research*, 260(15), 103–116. <https://doi.org/10.1016/j.jvolgeores.2013.05.006>
- Duncan, R., Kent, A., Thornber, C., Schlieder, T., & Al-Amri, A. (2016). Timing and composition of continental volcanism at Harrat Hutaymah, western Saudi Arabia. *Journal of Volcanology and Geothermal Research*, 313(1), 1–14. <https://doi.org/10.1016/j.jvolgeores.2016.01.010>
- Eissen, J., Juteau, T., Joron, J., Dupre, B., Humler, E., & Al'Mukhamedov, A. (1989). Petrology and geochemistry of basalts from the Red Sea axial rift at 18° North. *Journal of Petrology*, 30(4), 791–839. <https://doi.org/10.1093/petrology/30.4.791>
- Elkins-Tanton, L. T. (2005). Continental magmatism caused by lithospheric delamination. *Geological Society of America Special Paper*, 388, 449. <https://doi.org/10.1130/0-8137-2388-4.449>
- Elkins-Tanton, L. T. (2007). Continental magmatism, volatile recycling, and a heterogeneous mantle caused by lithospheric gravitational instabilities. *Journal of Geophysical Research*, 112(B3), B03405. <https://doi.org/10.1029/2005JB004072>
- Elkins-Tanton, L. T., & Hager, B. H. (2000). Melt intrusion as a trigger for lithospheric foundering and the eruption of the Siberian flood basalt. *Geophysical Research Letters*, 27(23), 3937–3940. <https://doi.org/10.1029/2000GL011751>
- Foley, S., Link, K., Tiberindwa, J., & Barifaijo, E. (2012). Patterns and origins of igneous activity around the Tanzanian craton. *Journal of African Earth Sciences*, 62, 1–18. <https://doi.org/10.1016/j.jafrearsci.2011.10.001>
- Foley, S., Yaxley, G., Rosenthal, A., Buher, S., Kiseeva, E., Rapp, R., & Jacob, D. (2009). The composition of near-solidus melts of peridotite in the presence of CO₂ and H₂O between 40 and 60 kbar. *Lithos*, 112, 274–283. <https://doi.org/10.1016/j.lithos.2009.03.020>
- Furman, T., Nelson, W., & Elkins-Tanton, L. (2016). Evolution of the East African rift: Drip magmatism, lithospheric thinning and mafic volcanism. *Geochimica et Cosmochimica Acta*, 185(15), 418–434. <https://doi.org/10.1016/j.gca.2016.03.024>
- Gall, H., Furman, T., Hanan, B., Kurkcuoglu, B., Sayit, K., Yurur, T., et al. (2021). Post-delamination magmatism in south-central Anatolia. *Lithos*, 398–399, 106299. <https://doi.org/10.1016/j.lithos.2021.106299>
- Garfunkel, Z. (1981). Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics. *Tectonophysics*, 80(1–4), 81–108. [https://doi.org/10.1016/0040-1951\(81\)90143-8](https://doi.org/10.1016/0040-1951(81)90143-8)
- Garfunkel, Z. (1998). Constrains on the origin and history of the Eastern Mediterranean basin. *Tectonophysics*, 298(1–3), 5–35. [https://doi.org/10.1016/S0040-1951\(98\)00176-0](https://doi.org/10.1016/S0040-1951(98)00176-0)
- Garfunkel, Z., Zak, I., & Freund, R. (1981). Active faulting in the Dead Sea rift. *Tectonophysics*, 80(1–4), 1–26. [https://doi.org/10.1016/0040-1951\(81\)90139-6](https://doi.org/10.1016/0040-1951(81)90139-6)
- Göğüş, O., Pysklywec, R., Şengör, C., & Gun, E. (2017). Drip tectonics and the enigmatic uplift of the Central Anatolian Plateau. *Nature Communications*, 8(1), 1538. <https://doi.org/10.1038/s41467-017-01611-3>
- Guba, I., & Mustafa, H. (1988). Structural control of young basaltic fissure eruptions in the plateau basalt area of the Arabian Plate, northeastern Jordan. *Journal of Volcanology and Geothermal Research*, 35(4), 319–334. [https://doi.org/10.1016/0377-0273\(88\)90026-1](https://doi.org/10.1016/0377-0273(88)90026-1)
- Haase, K., Muhe, R., & Stoffers, P. (2000). Magmatism during extension of the lithosphere: Geochemical constraints from lavas of the Shaban deep, northern Red Sea. *Chemical Geology*, 166(3–4), 225–239. [https://doi.org/10.1016/S0009-2541\(99\)00221-1](https://doi.org/10.1016/S0009-2541(99)00221-1)
- Hafkenscheid, E., Wortel, M., & Spakman, W. (2006). Subduction of the Tethyan region derived from seismic tomography and tectonic reconstructions. *Journal of Geophysical Research*, 111(B8), B08401. <https://doi.org/10.1029/2005JB003791>
- Hansen, S., DeShon, H., Moore-Driskell, M., & Al-Amri, A. (2013). Investigating the P wave velocity structure beneath Harrat Lunayyir, northwestern Saudi Arabia, using double-difference tomography and earthquakes from the 2009 seismic swarm. *Journal of Geophysical Research: Solid Earth*, 118(9), 4814–4826. <https://doi.org/10.1002/jgrb.50286>
- Hansen, S., Rodgers, A., Schwartz, S., & Al-Amri, A. (2007). Imaging ruptured lithosphere beneath the Red Sea and Arabian Peninsula. *Earth and Planetary Science Letters*, 259(3–4), 256–265. <https://doi.org/10.1016/j.epsl.2007.04.035>
- Herzberg, C. (2011). Identification of source lithology in the Hawaiian and Canary Islands: Implications for origins. *Journal of Petrology*, 52(1), 113–146. <https://doi.org/10.1093/petrology/egq075>
- Hirschmann, M., & Stolper, E. (1996). A possible role for garnet pyroxenite in the origin of the “garnet signature” in MORB. *Contributions to Mineralogy and Petrology*, 124(2), 185–208. <https://doi.org/10.1007/s004100050184>
- Hofmann, A., Jochum, K., Seufert, M., & White, W. (1986). Nd and Pb in oceanic basalts: New constraints on mantle evolution. *Earth and Planetary Science Letters*, 79(1–2), 33–45. [https://doi.org/10.1016/0012-821X\(86\)90038-5](https://doi.org/10.1016/0012-821X(86)90038-5)
- Hofmann, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E., & Pik, R. (1997). Timing of the Ethiopian flood basalt event and implications of Plume birth and global change. *Nature*, 389(6653), 838–841. <https://doi.org/10.1038/39853>
- Holbig, E., & Grove, T. (2008). Mantle melting beneath the Tibetan Plateau: Experimental constraints on ultrapotassic magmatism. *Journal of Geophysical Research*, 113(B4), B04210. <https://doi.org/10.1029/2007JB005149>
- Ilani, S., Harlavan, Y., Tarawneh, K., Rabba, I., Weinberger, R., Ibrahim, K., et al. (2001). New K–Ar ages of basalts from the Harrat Ash Shaam volcanic field in Jordan: Implications for the span and duration of the upper-mantle upwelling beneath the western Arabian plate. *Geology*, 29(2), 171–174. [https://doi.org/10.1130/0091-7613\(2001\)029<0171:nkaab>2.0.co;2](https://doi.org/10.1130/0091-7613(2001)029<0171:nkaab>2.0.co;2)
- Ingamells, C. (1970). Lithium metaborate flux in silicate analysis. *Analytica Chimica Acta*, 52(2), 323–334. [https://doi.org/10.1016/S0003-2670\(01\)80963-6](https://doi.org/10.1016/S0003-2670(01)80963-6)
- Kaislaniemi, L., & van Hunen, J. (2014). Dynamics of lithospheric thinning and mantle melting by edge-driven convection: Application to Moroccan Atlas Mountains. *Geochemistry, Geophysics, Geosystems*, 15(8), 3175–3189. <https://doi.org/10.1002/2014GC005414>
- Kaliwoda, M., Altherr, R., & Meyer, H. (2007). Composition and thermal evolution of the lithospheric mantle beneath the Harrat Uwayrid, eastern flank of the Red Sea rift (Saudi Arabia). *Lithos*, 99(1–2), 105–120. <https://doi.org/10.1016/j.lithos.2007.06.013>
- Kaliwoda, M., Ludwig, T., & Altherr, R. (2008). A new SIMS study of Li, Be, B and 87 Li in mantle xenoliths from Harrat Uwayrid (Saudi Arabia). *Lithos*, 106(3–4), 261–279. <https://doi.org/10.1016/j.lithos.2008.07.009>
- Kinzler, R. (1997). Melting of mantle peridotite at pressures approaching the spinel to garnet transition: Application to mid-ocean ridge basalt petrogenesis. *Journal of Geophysical Research*, 102(B1), 853–874. <https://doi.org/10.1029/96JB00988>
- Kinzler, R., & Grove, T. (1992). Primary magmas of mid-ocean ridge basalts: 2 applications. *Journal of Geophysical Research*, 97(B5), 6907–6926. <https://doi.org/10.1029/91JB02841>
- Konrad, K., Graham, D., Thornber, C., Duncan, R., Kent, A., & Al-Amri, A. (2016). Asthenosphere-lithosphere interactions in western Saudi Arabia: Inferences from ³He/⁴He in xenoliths and lava flows from Harrat Hutaymah. *Lithos*, 248–251, 339–352. <https://doi.org/10.1016/j.lithos.2016.01.031>
- Krienitz, K., & Haase, K. (2011). The evolution of the Arabian lower crust and lithospheric mantle – Geochemical constraints from southern Syrian mafic and ultramafic xenoliths. *Chemical Geology*, 280(3–4), 271–283. <https://doi.org/10.1016/j.chemgeo.2010.11.015>

- Krienitz, M., Haase, K., Mezger, K., & Shaikh-Mashail, M. (2007). Magma genesis and mantle dynamics at the Harrat Ash Shamah volcanic field (Southern Syria). *Journal of Petrology*, 48(8), 1513–1542. <https://doi.org/10.1093/petrology/egm028>
- Krienitz, M., Haase, K., van den Bogaard, P., Thiemann, V., & Shaikh-Mashail, M. (2009). Tectonic events, continental intraplate volcanism, and mantle plume activity in northern Arabia: Constraints from geochemistry and Ar-Ar dating of Syrian lavas. *Geochemistry, Geophysics, Geosystems*, 10(4), Q04008. <https://doi.org/10.1029/2008GC002254>
- Lambart, S., Laporte, D., & Schiano, P. (2009). An experimental study of pyroxenite partial melts at 1 and 1.5 GPa: Implications for the major-element composition of Mid-Ocean Ridge Basalts. *Earth and Planetary Science Letters*, 288(1–2), 335–347. <https://doi.org/10.1016/j.epsl.2009.09.038>
- Le Roux, V., Dasgupta, R., & Lee, C. (2011). Mineralogical heterogeneities in the Earth's mantle: Constraints from Mn, Co, Ni and Zn partitioning during partial melting. *Earth and Planetary Science Letters*, 307(3–4), 395–408. <https://doi.org/10.1016/j.epsl.2011.05.014>
- Le Roux, V., Lee, C., & Turner, S. (2010). Zn/Fe systematics in mafic and ultramafic systems: Implications for detecting major element heterogeneities in the Earth's mantle. *Geochimica et Cosmochimica Acta*, 74(9), 2779–2796. <https://doi.org/10.1016/j.gca.2010.02.004>
- Lyakhovsky, V., Segev, A., Schattner, U., & Weinberger, R. (2012). Deformation and seismicity associated with continental rift zones propagating towards continental margins. *Geochemistry, Geophysics, Geosystems*, 13(1), Q01012. <https://doi.org/10.1029/2011GC003927>
- McKenzie, D., & Bickle, M. (1988). The volume and composition of melt generated by extension of the lithosphere. *Journal of Petrology*, 29(3), 625–679. <https://doi.org/10.1093/petrology/29.3.625>
- Medlin, J., Suhr, N., & Bodkin, J. (1969). Atomic absorption analysis of silicates employing LiBO₂ fusion. *Atomic Absorption Newsletter*, 8(2), 25–29.
- Mengel, K., & Green, D. (1986). Experimental study of amphibole and phlogopite stability in metasomatized peridotite under water-saturated and water-undersaturated conditions. *International Kimberlite Conference: Extended Abstracts*, 4(1), 193–195. <https://doi.org/10.29173/ikc1115>
- Moufti, M., Moghazi, A., & Ali, K. (2012). Geochemistry and Sr-Nd-Pb isotopic composition of the Harrat Al-Madinah volcanic field, Saudi Arabia. *Gondwana Research*, 21(2–3), 670–689. <https://doi.org/10.1016/j.gr.2011.06.003>
- Moufti, M., Moghazi, A., & Ali, K. (2013). ⁴⁰Ar/³⁹Ar geochronology of the Neogene-Quaternary Harrat Al-Madinah intercontinental volcanic field, Saudi Arabia: Implications for duration and migration of volcanic activity. *Journal of Asian Earth Sciences*, 62(30), 253–268. <https://doi.org/10.1016/j.jseaes.2012.09.027>
- Murcia, H. (2015). *Monogenetic volcanism in the western Arabian Peninsula: Insights from late quaternary eruptions in northern Harrat Rahat, Kingdom of Saudi Arabia*. Doctor of Philosophy Dissertation. The University of Auckland.
- Murcia, H., Lindsay, J. M., Németh, K., Smith, I. E. M., Cronin, S. J., Moufti, M. R. H., et al. (2016). Geology and geochemistry of Late Quaternary volcanism in northern Harrat Rahat, Kingdom of Saudi Arabia: Implications for eruption dynamics, regional stratigraphy and magma evolution. *Geological Society, London, Special Publications*, 446(1), 173–204. <https://doi.org/10.1144/sp446.2>
- Murcia, H., Németh, K., Moufti, M., Lindsay, J., El-Masry, N., Cronin, S., et al. (2014). Late Holocene lava flow morphotypes of northern Harrat Rahat, Kingdom of Saudi Arabia: Implications for the description of continental lava fields. *Journal of Asian Earth Sciences*, 84(15), 131–145. <https://doi.org/10.1016/j.jseaes.2013.10.002>
- Murris, R. (1980). Middle East stratigraphic evolution and oil habitat. *AAPG Bulletin*, 64, 597–618. <https://doi.org/10.1306/M35439C20>
- Musil, A. (1926). The Northern Hegaz, A topographical itinerary. In J. Wright (Ed.), *American geographical society oriental explorations and studies No. 1*.
- Omar, G., & Steckler, M. (1995). Fission track evidence on the initial rifting of the Red Sea: Two pulses, no propagation. *Science*, 270(5240), 1341–1344. <https://doi.org/10.1126/science.270.5240.1341>
- Paton, C., Hellstrom, J., Paul, B., Woodhead, J., & Hergt, J. (2011). Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry*, 26(12), 2508–2518. <https://doi.org/10.1039/C1JA10172B>
- Patton, T., Moustafa, A., Nelson, R., & Abdine, A. (1994). Tectonic evolution and structural setting of the Suez Rift. In S. M. Landon (Ed.), *Interior rift basins* (Vol. 59, pp. 7–55). American Association of Petroleum Geologists Memoir.
- Pertermann, M., & Hirschmann, M. (2003). Partial melting experiments on a MORB-like pyroxenite between 2 and 3 GPa: Constraints on the presence of pyroxenite in basalt source regions from solidus location and melting rate. *Journal of Geophysical Research*, 108(B2), 2125. <https://doi.org/10.1029/2000JB000118>
- Pillet, S., Baker, M., & Stolper, E. (2008). Metasomatized lithosphere and the origin of alkaline lavas. *Science*, 320(5878), 916–919. <https://doi.org/10.1126/science.1156563>
- Pitcavage, E., Furman, T., Nelson, W., Graham, D., Shirey, S., Kulyanying, P., & Barifajio, E. (2023). Geochemical constraints on the origin of primitive potassic lavas in the eastern Virunga Volcanic Province. *Geochemistry, Geophysics, Geosystems*, 24(6), e2023GC010950. <https://doi.org/10.1029/2023gc010950>
- Powers, R., Ramirez, L., Redmond, C., & Elberg, E. (1966). *Sedimentary geology of Saudi Arabia. Geology of the Arabian Peninsula, Professional paper 560-D*, US Geological Survey.
- Putirka, K. (2008). Thermometers and barometers for volcanic systems. *Reviews in Mineralogy and Geochemistry*, 69(1), 61–120. <https://doi.org/10.2138/rmg.2008.69.3>
- Roobol, J., & Stewart, I. (2018). Cenozoic faults and seismicity in Northwest Saudi Arabia and the Gulf of Aqaba region. *From Geological Setting, Paleoenvironment and Archaeology of the Red Sea*, 275–305.
- Rooney, T., Nelson, W., Ayalew, D., Hanan, B., Yirgu, G., & Kappelman, J. (2017). Melting the lithosphere: Metasomes as a source for mantle-derived magmas. *Earth and Planetary Science Letters*, 461(1), 105–118. <https://doi.org/10.1016/j.epsl.2016.12.010>
- Sack, R., Walker, D., & Carmichael, I. (1987). Experimental petrology of alkalic lavas: Constraints on cotectics of multiple saturation in natural basic liquids. *Contributions to Mineralogy and Petrology*, 96, 1–23. <https://doi.org/10.1007/bf00375521>
- Salter, V., & Stracke, A. (2004). Composition of the depleted mantle. *Geochemistry, Geophysics, Geosystems*, 5(5), Q05B07. <https://doi.org/10.1029/2003GC000597>
- Schaen, A., Jicha, B., Hodges, K., Vermeesch, P., Stelten, M., Mercer, C., et al. (2020). Interpreting and reporting ⁴⁰Ar/³⁹Ar geochronologic data. *GSA Bulletin*, 133(3–4), 461–487. <https://doi.org/10.1130/B35560.1>
- Sebai, A., Zumbo, V., Féraud, G., Bertrand, H., Hussain, A., Giannerini, G., & Campredon, R. (1991). ⁴⁰Ar/³⁹Ar dating of alkaline and tholeiitic magmatism of Saudi Arabia related to the early Red Sea rifting. *Earth and Planetary Science Letters*, 104(2–4), 473–487. [https://doi.org/10.1016/0012-821X\(91\)90223-5](https://doi.org/10.1016/0012-821X(91)90223-5)
- Segev, A., & Rybakov, M. (2011). History of faulting and magmatism in the Galilee (Israel) and across the Levant continental margin inferred from potential field data. *Journal of Geodynamics*, 51(4), 264–284. <https://doi.org/10.1016/j.jog.2010.10.001>
- Shaw, J., Baker, J., Menzies, M., Thirlwall, M., & Ibrahim, K. (2003). Petrogenesis of the largest intraplate volcanic field on the Arabian Plate (Jordan): A mixed lithosphere-asthenosphere sources activated by lithospheric extension. *Journal of Petrology*, 44(9), 1657–1679. <https://doi.org/10.1093/petrology/egg052>

- Sobolev, A., Hofmann, A., Kuzmin, D., Yaxley, G., Arndt, N., Chung, S., et al. (2007). The amount of recycled crust in sources of mantle-derived melts. *Science*, 316(5823), 412–417. <https://doi.org/10.1126/science.1138113>
- Sobolev, A., Hofmann, A., Sobolev, S., & Nikogosian, L. (2005). An olivine-free mantle source of Hawaiian shield basalts. *Nature*, 434(7033), 590–597. <https://doi.org/10.1038/nature03411>
- Stelten, M., Downs, D., Champion, D., Dietterich, H., Calvert, A., Sisson, T., et al. (2020). The timing and compositional evolution of volcanism within northern Harrat Rahat, Kingdom of Saudi Arabia. *GSA Bulletin*, 132(7–8), 1381–1403. <https://doi.org/10.1130/B35337.1>
- Stelten, M., Downs, D., Dietterich, H., Mahood, G., Calvert, A., Sisson, T., et al. (2018). Timescales of magmatic differentiation from alkali basalt to trachyte within the Harrat Rahat volcanic field, Kingdom of Saudi Arabia. *Contributions to Mineralogy and Petrology*, 173(8), 68. <https://doi.org/10.1007/s00410-018-1495-9>
- Stern, R. (1994). Arc assembly and continental collision in the neoproterozoic East African Orogen: Implications for the consolidation of Gondwanaland. *Annual Review of Earth and Planetary Science*, 22(1), 319–351. <https://doi.org/10.1146/annurev.ea.22.050194.001535>
- Stockli, E., & Bosworth, W. (2019). Timing of extensional faulting along the magma-poor Central and Northern Red Sea rift margin—Transition from regional extension to necking along a hyperextended rifted margin. In *Geological setting, palaeoenvironment and Archaeology of the Red Sea* (pp. 81–111). Springer Link.
- Stracke, A., Hofmann, A., & Hart, S. (2005). FOZO, HIMU, and the rest of the mantle zoo. *Geochemistry, Geophysics, Geosystems*, 6(5), Q05007. <https://doi.org/10.1029/2004GC000824>
- Sun, S., & McDonough, W. (1989). Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In A. Saunders & M. Norry (Eds.), (eds), *Magmatism in the ocean basins*. Geological Society Special Publication (Vol. 42, pp. 313–345).
- Szymanski, E. (2013). *Timing, kinematics and spatial distribution of Miocene extension in the central Arabian margin of the Red Sea rift system*. PhD thesis. University of Kansas.
- Szymanski, E., Stockli, D., Johnson, P., & Hager, C. (2016). Thermochronometric evidence for diffuse extension and two-phase rifting within the Central Arabian margin of the Red Sea. *Tectonics*, 35(12), 2863–2895. <https://doi.org/10.1002/2016TC004336>
- Valentine, G., & Gregg, T. (2008). Continental basalt volcanoes – Processes and problems. *Journal of Volcanology and Geothermal Research*, 177(4), 857–873. <https://doi.org/10.1016/j.jvolgeores.2008.01.050>
- Vogt, K., Dohmen, R., & Chakraborty, S. (2015). Fe-Mg diffusion in spinel: New experimental data and a point defect model. *American Mineralogist*, 100(10), 2112–2122. <https://doi.org/10.2138/am-2015-5109>
- Wan, Z., Coogan, L., & Canil, D. (2008). Experimental calibration of aluminum partitioning between olivine and spinel as a geothermometer. *American Mineralogist*, 93(7), 1142–1147. <https://doi.org/10.2138/am.2008.2758>
- Wang, K., Plank, T., Walker, J., & Smith, E. (2002). A mantle melting profile across the Basin and Range, SW USA. *Journal of Geophysical Research*, 107(B1), ECV-5. <https://doi.org/10.1029/2001JB000209>
- Weinstein, Y., Navon, O., Altherr, R., & Stein, M. (2006). The role of lithospheric mantle heterogeneity in the generation of Plio-Pleistocene alkali basaltic suites from NW Harrat Ash Shaam (Israel). *Journal of Petrology*, 47(5), 1017–1050. <https://doi.org/10.1093/petrology/egl003>
- Woodhead, J. D., Hellstrom, J., Hergt, J. M., Greig, A., & Maas, R. (2007). Isotopic and elemental imaging of geological materials by laser ablation inductively coupled plasma-mass spectrometry. *Geostandards and Geoanalytical Research*, 31(4), 331–343. <https://doi.org/10.1111/j.1751-908x.2007.00104.x>
- Yang, Z., & Zhou, J. (2013). Can we identify source lithology of basalt? *Scientific Reports*, 3(1), 1856. <https://doi.org/10.1038/srep01856>