Journal of Volcanology and Geothermal Research 260 (2013) 103–116

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Timing and composition of volcanic activity at Harrat Lunayyir, western Saudi Arabia

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ARTICLE INFO

Article history:
Received 14 January 2013
Accepted 14 May 2013
Available online 26 May 2013

Keywords:
Continental volcanism
$^{40}Ar/^{39}Ar$ age determinations
Trace elements
Mantle melting

ABSTRACT

Harrat Lunayyir is an alkali basaltic, continental volcanic field in NW Saudi Arabia. Lava flows and cinder cones are basanite to alkali olivine basalt to trachy-basalt in composition. The field contains about 50 volcanic cones fed by fissures through Precambrian crystalline rocks along a N–S axis, lying about 200 km east of the Red Sea spreading center. One of cones erupted as recently as the 10th century AD. Analysis of a recent earthquake swarm (2007–2009) indicates a ~10-km, NW-trending cluster of events at both shallow and deep crustal locations, concentrated in regions of higher velocity material. Six volcano-stratigraphic units are identified, based on super-position and morphology (degree of erosion). New $^{40}Ar–^{39}Ar$ incremental heating age determinations indicate that the entire volcanic history occurred within the last 600 ka, with eruption rate decreasing with time. Major and minor element compositional variations are due almost entirely to crustal level fractionation (of mainly olivine, plagioclase, and clinopyroxene), or small differences in mantle partial melting. Primitive liquid composition, estimated by adding olivine to parental magma compositions, is consistent with ~10% melting of an upper mantle peridotitic source in the depth range of spinel to garnet stability (80–60 km). There is no evidence for crustal assimilation. Trace element variations (in Dy/Yb, Ce/Yb) are consistent with shallowing of the asthenospheric melting region with time. Regional variations in trace element compositions among other harrats indicate a strong influence of the lithosphere–asthenosphere boundary in controlling mantle melting.

1. Introduction

Extensive Cenozoic basaltic lava fields occur in the western part of the Arabian peninsula (Fig. 1), forming one of the largest alkali basalt provinces in the world (area: 180,000 km^2). These young volcanic fields (called “harrats”) lie within 300 km of the NW-trending eastern margin of the Red Sea. There is no counterpart to these volcanic centers on the western margin (African Plate) of the Red Sea. Likewise, topography is more elevated and rugged on the Arabian side, compared with the African side (Bohannon et al., 1989). In contrast to the tholeiitic basalts of the Red Sea spreading system, lava compositions in this province include tholeiites but are predominantly basanite to alkali olivine–basalt to hawaiite, with minor more evolved compositions. Within several large centers, volcanic activity began (>12 Ma) with tholeiitic to transitional compositions, then became more alkalic for younger eruptions (<12 Ma) (Camp and Roobol, 1992). The older period of activity includes dikes and eruptive centers close to and aligned with the NW–SE Red Sea margin, while the younger volcanic centers are distributed over a 200 km swath and display N–S alignment. The most voluminous centers form a prominent N–S volcanic axis, the Makkah–Madinah–Nafud (MMN) line. This lineament is aligned with the Ha'il–Rutbah Arch axis of uplift of the Arabian shield, a Late Cretaceous–Early Tertiary structure that was reactivated ~15 Ma (Coleman, 1993).

Harrat Lunayyir is one of the smaller and younger volcanic fields, lying ~100 km east of the Red Sea margin and on the western edge of the escarpment. It is located NW of Al-Madinah Al Munawwarah, north of Yanbu and in the immediate vicinity of the town of Al Ays between latitudes 24°50'N to 25°29'N and longitudes 37°28'E to 38°04'E., occupying a surface area of about 3575 km^2 (Fig. 2). This study was initiated because Harrat Lunayyir experienced multiple seismic swarms in the period 2007–2009. Recent studies (e.g. Pallister et al., 2010) have indicated that these swarms are associated with magma that has risen to shallow levels beneath Harrat Lunayyir, potentially increasing the likelihood of a volcanic eruption. It is estimated that at least twenty-one different eruptions have occurred in western Arabia over the past 1500 yr (Camp et al., 1987), including one within Harrat Lunayyir about 1000 yr ago. The Harrat Lunayyir area is characterized by geothermally warm groundwater where temperatures up to 32 °C were measured in April 2007 before the earthquake swarm began. Farmers in the Harrat Lunayyir area reported seeing steam in many places on cold winter mornings, while geothermal anomalies and

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0377-0273/$ – see front matter
http://dx.doi.org/10.1016/j.jvolgeores.2013.05.006

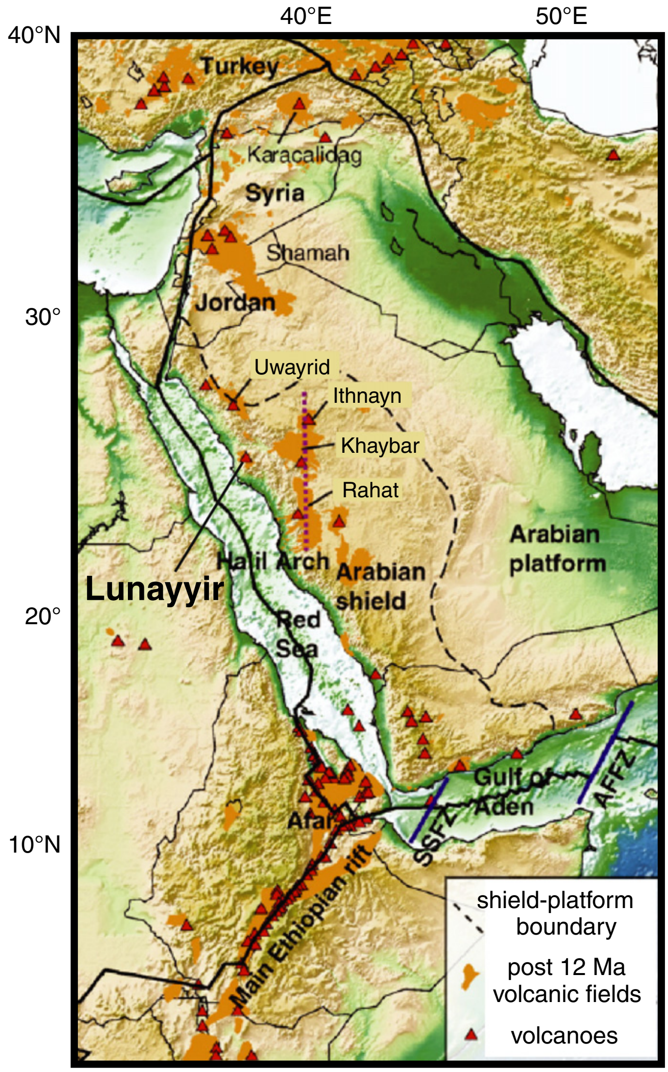

Fig. 1. Location map for volcanic fields ('harrats') in western Saudi Arabia (from Chang and van der Lee, 2011). Individual harrats lie within 300 km of the Red Sea margin, but eruptive centers/fissures are aligned predominantly N–S. The most voluminous provinces fall within the region indicated by dotted red line (Ha'il Arch), also called the Makkah–Medinah–Nafud (MMN) lineament. Harrat Lunayyir is a relatively small province that lies between the MMN line and the Red Sea.

reports of stream were first noted by Saudi Geological Survey staff in 2001. The current phase of Harrat Lunayyir activity is therefore considered to have begun at least 10 yr ago.

Various ideas have been proposed for the origin of the aligned volcanic fields of western Saudi Arabia. The timing and proximity to the Red Sea spreading system have led some researchers to favor plate extension and lithospheric thinning, increasing from east to west (Bertrand et al., 2003; Shaw et al., 2003). The triple junction to the south, formed by Red Sea, Gulf of Aden and East African Rift plate separation, has been proposed to have initiated at the onset of Afar hotspot activity (~32 Ma) (Schilling, 1973; Courtillot et al., 1984; Hill et al., 1992; Baker et al., 1995, 1997; Debayle et al., 2001). Radial flow of upper mantle material from the underlying mantle plume may have reached the base of the lithosphere beneath the Arabian shield, leading to excess heat, thinning, uplift and melting (Camp and Roobol, 1992; Krienitz et al., 2009). A separate mantle plume, upwelling beneath the Arabian shield, has been implicated from the distribution of the volcanic activity (Moufti and Hashad, 2005) and seismic imaging (Chang and van der Lee, 2011).

The main objective of this paper is to report new age determinations that define the timing and duration for the Harrat Lunayyir volcanic activity, and describe the petrology and geochemical characteristics of the lavas. We then compare Harrat Lunayyir compositions with neighboring fields and discuss possible models for dynamic controls on the timing and composition of the regional volcanic activity.

2. Geologic mapping and volcanic stratigraphy

The Cenozoic to recent basaltic lava fields of western Saudi Arabia rest directly on rocks of the stable Precambrian Arabian shield (Fig. 1). These older rocks are upper Proterozoic metavolcanics and plutons of mainly granitic composition. They rise as rugged hills around and within the lava field. Harrat Lunayyir is constructed from a series of volcanic eruptions that took place along related fissures, producing ~50 cinder cones that form N–S and NW–SE trends and cover an area of about 3600 km^2. Flow morphology is predominantly a'a type, and thicknesses are typically 3–5 m. Scoria cones are typically 400–500 m in diameter and 100–200 m in height.

A geological map has been prepared (Fig. 2, after Al-Amri et al., 2012), and determined from field investigation, geomorphologic data, satellite imaging and petrographic examination. Precambrian rocks of Pan-African mobile belt age occupy the northern and the southern parts, and also the eastern periphery of the mapped area. In the central zone the Precambrian rocks form isolated inliers. During volcanic eruptions the relief of the Precambrian rock was apparently great enough to hinder the lavas flowing westwards. Field observations lead to the identification of the following volcanic units (young to old), based primarily on degree of erosion, saturation with wind-blown dust, and relative stratigraphic position (Al-Amri et al., 2012), based on the characteristics used by Camp et al. (1989):

Q5 — Historic to late Prehistoric lava flows.
Q4 — Prehistoric lava flows and scoria cones.
Q3 — Non-eroded lava flows and scoria cones.
Q2 — Eroded lava flows and scoria cones.
Q1 — Eroded lava flows without scoria cones.
Unconformity (thin, intermittent soil horizon).
T "Tertiary" basalt.

There are no systematic changes in the composition of the lava flows among the volcanic units.

Based on the Al-Amri et al. (2012) map, we have estimated erupted volumes for each of the volcanic units from areal extent and observed thicknesses, assuming that older units continue beneath younger units. These are: Q5 (7.2 km^3), Q4 (11.5 km^3), Q3 (16.1 km^3), Q2 (4.3 km^3), Q1 (13.7 km^3), and T (18.0 km^3). When divided by the estimated duration of each unit's activity (Age determinations by ^{40}Ar/^{39}Ar incremental heating section below) we derive eruption rate estimates.

3. Seismicity and earthquake locations

Recently, Hansen et al. (in press) observed two linear NW-trending clusters of ~1300 seismic events (Fig. 3). The northern cluster is approximately 5 km long and the southern cluster is about 3 km long. At the south end of the swarm there is a dense cluster of earthquake locations beneath a volcanic center. The earliest events are intermediate depth (5–9 km) along the northern linear swarm, as well as deep events (>9 km) beneath the southern volcanic center. As the swarm continued up to July 2009, the second linear swarm developed. This cluster of earthquakes defines a steeply dipping plane that connects the deeper region of seismicity with that closer to the surface. Most of the seismicity, across the entire depth range, is concentrated in regions of higher velocity material. The planar dipping