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

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ABSTRACT

The volcanism in the western Arabian plate extends from the Red Sea through the Harrat Ash Shaam system to western Syria, as far north as the Bitlis suture in the Taurides. The Harrat Ash Shaam volcanic system in Jordan consists of northwest-trending dikes and a volcanic field that together encompass a width of 220 km. In terms of width, direction, and age of the main volcanic phases, the system is similar to the Red Sea dike belt. About 130 new K-Ar age determinations show that the ages of the Harrat Ash Shaam system (dikes and flows) range from Oligocene to Quaternary. However, there is a distinct gap in the ages between ~22 and 13 Ma. This gap coincides with an apparent decrease in volcanism in the Red Sea region from around 20 to 12 Ma. We interpret this 9 m.y. gap as a quiescent period interrupting the volcanic activity in the region and suggest that from ~22 to 13 Ma, tectonic activity in the Arabian plate was mainly restricted to the Red Sea region. A renewal of volcanism along the western margins of the Arabian plate at 13 Ma was very likely associated with the sinistral movement along the north-trending Dead Sea transform. This renewal of volcanism and tectonic activity may reflect the emergence of upper-mantle upwelling beneath the western Arabian plate at that time.

Keywords: basalts, K-Ar age determinations, Harrat Ash Shaam, Jordan, Red Sea, Dead Sea transform.

INTRODUCTION

Opening of continental rifts is commonly associated with magmatic events. The magmas are injected along fissures to form dikes, vents, central volcanoes, and in some cases, large basaltic fields. Since the Oligocene and repeatedly in the Miocene, Pliocene, and Pleistocene, the western Arabian and northern African plates have undergone rifting, faulting, and volcanism. During this period, a basaltic dike belt and volcanic fields of basalt flows and pyroclastic rocks were emplaced along the eastern borders of the Red Sea rift and its seafloor-spreading axis. The associated Red Sea dike system consists of a belt of elongated, northwest-trending tholeiitic dikes intruding basement rocks. The width of the belt in the northwestern part of Saudi Arabia is ~220 km (Fig. 1; Garfunkel, 1989). The dike system is best defined and concentrated along the northeast border of the Red Sea, where it is associated with several volcanic fields (Fig. 1; Camp and Roobol, 1989). The continuation of the belt in the sedimentary cover is marked by long, linear, narrow grabens that are pierced by small, isolated dikes or plugs. These features suggest a generic relationship between the volcanic and tectonic activities.

A similar relationship between volcanic features and structural positions of dikes and faults can be seen in the Harrat Ash Shaam volcanic field (Fig. 1). This field is one of the largest in the Arabian plate, extending over 50 000 km^2 and covering parts of Syria, Jordan, and Saudi Arabia (Ibrahim, 1996). Its principal features include volcanic centers, dikes, ring dikes, and fault trends subparallel to the Red Sea system. Southwest of the Harrat Ash Shaam field is the Sirhan depression, a 30–50-km-wide graben-like structure that extends for several hundred kilometers, also trending in a northwest direction (Basha, 1982; Al-Laboun, 1986; Ibrahim, 1996). To the east, a set of northwest-trending fractures delineates the dikes that are covered by the Harrat Ash Shaam basalt flows (Garfunkel, 1989). Despite its significance in the regional geologic framework and its apparent relationship to the well-studied Red Sea system, only a few studies have focused specifically on the Harrat Ash Shaam field (Bender, 1974; Ibrahim, 1993, 1996). These include the K-Ar age determinations by Barberi et al. (1979) and Moffat (1988) that yielded dates between 13.7 and 0.1 Ma for the volcanism.

The age range of the volcanic fields along the Red Sea in Saudi Arabia is from ca. 30 Ma to Holocene (Fig. 2; Camp and Roobol, 1992). K-Ar dating of volcanic dikes from Saudi Arabia, Sinai (Egypt), and Israel yielded ages between 25 and 18 Ma (Blank, 1977; Steinitz et al., 1978, 1981; Pallister, 1987). On the basis of $^{40}Ar/^{39}Ar$ dating of feeder dikes and lava flows of the alkalic massif of Harrat Hadan (Saudi Arabia), Sebai et al. (1991) concluded that the early activity of alkalic volcanic fields in western Saudi Arabia started at ca. 28–27 Ma. Nevertheless, the main volcanic phase of the Red Sea region, including a >1700-km-long narrow zone of tholeiitic rocks along the coast, occurred from 24 to 21 Ma. The southward-increasing volume of 30–20 Ma magmatic rocks indicates that the Afar triple junction was the major site of Oligocene-Miocene magmatism. The distribution of a dike belt and volcanic fields to the north, along the entire northwest side of the Red Sea, indicates a contemporaneous period of Red Sea rifting. All these volcanic fields show evidence of at least 2.5 km of uplift, indicating invasion of asthenosphere-derived magmas into the lithosphere (Camp and Roobol, 1991).

The age of the volcanic activity along the Red Sea is also based on fission-track evidence (Omar and Steckler, 1995). According to these authors, the Red Sea initially opened simultaneously along its entire length in two main pulses. The first pulse began in the late Eocene to early Oligocene, at 34 Ma. The second phase started in the late Oligocene to early Miocene, from 25 to 21 Ma, and marked the start of the main phase of extension of the Red Sea. Omar and Steckler (1995) suggested that the rifting and volcanism in the Red Sea region occurred nearly simultaneously, not se-

Geology; February 2001; v. 29; no. 2; p. 171–174; 2 figures; Data Repository item 200119.

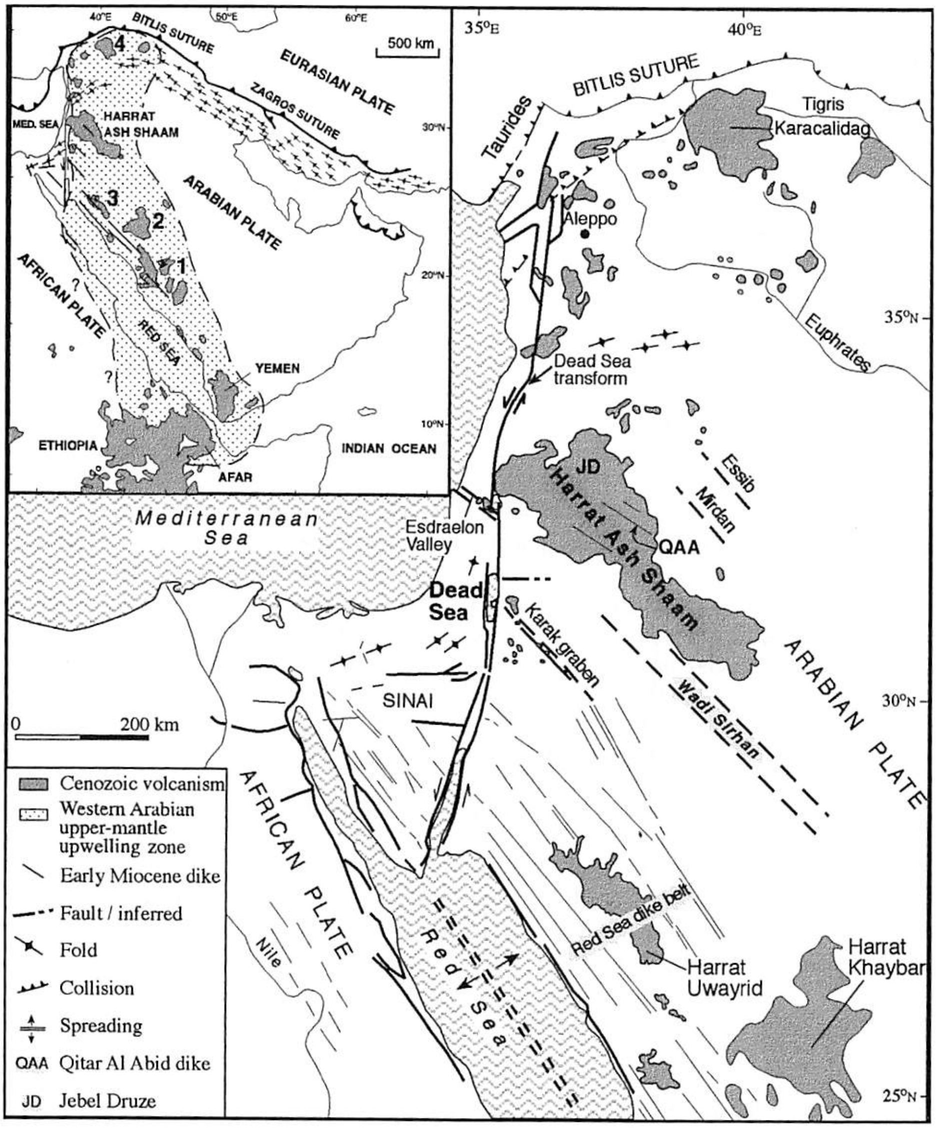

Figure 1. Location map of volcanic fields along western Arabian plate (after Garfunkel, 1989; Camp and Roobol, 1989) and suggested upper-mantle upwelling zone. 1—Harrat Hadan, 2—Harrat Khaibar, 3—Harrat Uwayrid, 4—Karacalidag.

quentially as previously proposed. However, on the basis of magnetic anomalies in the Gulf of Aden, the extension in the Red Sea and Gulf of Aden occurred after 10 Ma (Bonatti, 1985; Cochran, 1983). This age is consistent with the results of Camp and Roobol (1991), who suggested that most of the volcanic fields in the western Arabian plate began to form after 10 Ma.

Our investigation is the first to systematically date the Harrat Ash Shaam field and to study its volcanic evolution. We use new K-Ar ages to examine the close relationship between tectonic configuration and duration of volcanic activity in the Harrat Ash Shaam and in the Red Sea systems. The results of this study can shed light on the span and duration of the upper-mantle upwelling beneath the western Arabian plate. This was made possible by a recently enacted Memorandum of Understanding between the Geological Survey of Israel and the Natural Resources Authority of the Hashemite Kingdom of Jordan.

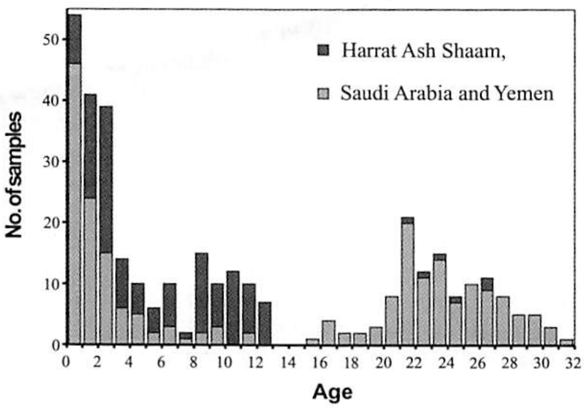

Figure 2. Age histogram of basalt samples from Harrat Ash Shaam (this study only) northeast Jordan ($n = 132$). Also represented are samples from Saudi Arabia and Yemen compiled by Camp and Roobol, 1992 ($n = 223$).

DATING THE HARRAT ASH SHAAM BASALT FIELD

The basalt flows in the Harrat Ash Shaam volcanic field in northeastern Jordan are mostly olivine basalts with pyroxene. The mineral assemblages include different combinations of labradorite, olivine and/or iddingsite, pyroxene, and iron oxides. (Tarawneh et al., 2000).

Fresh samples ($n = 132$) for K-Ar age dating were collected at various locations. Each sample was crushed and sieved to 80–100-mesh size fractions, followed by the separation of secondary minerals (calcite, zeolite, etc.) using the Franz magnetic separator. Samples were dissolved in lithium meta-borate, and K concentrations were determined by using a Perkin Elmer Optima 3300 instrument ICP-AES at the Geological Survey of Israel. The Ar analysis, performed on whole-rock samples, used the standard-isotope dilution procedures (K-Ar) of the geochronological laboratory at the Geological Survey of Israel (Steinitz et al., 1983; Kotlarsky et al., 1992). Hot blank and air measurements were determined at the beginning and end of each measurement day. The air value was used in determining the mass-spectrometer background, and the age was calculated following the procedure outlined by Kotlarsky et al. (1992). Results of the analysis are presented in Table 1[1] and shown in Figure 2.

The K-Ar dating indicates that the basalt field was formed during three main episodes: Oligocene to early Miocene (26–22 Ma), middle to late Miocene (13–8 Ma), and late Miocene to Pleistocene (7 Ma to more recently than 0.5 Ma) (Fig. 2). The youngest age (<0.5 Ma) reflects the limit of detection of the dating method; however, field evidence implies that the volcanic activity continued into the Quaternary. An important result is that none of the samples dated yielded ages between ~22 and 13 Ma. This gap suggests a quiescent interlude in volcanic activity of ~9 m.y. from the early Miocene to the middle Miocene.

The results also show a correlation between

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[1] GSA Data Repository item 200119, K-Ar ages from the Harrat Ash Shaam volcanic field, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

the age and the distribution of basalt flows in Harrat Ash Shaam. Oligocene and middle Miocene basalt flows, dikes, and volcanoes are exposed mostly in the southern parts of the volcanic field in Jordan. In the north, near Jebel Druze, these flows are probably covered by Pliocene-Quaternary volcanic rocks. Oligocene–early Miocene (26–22 Ma) basalts are exposed within "windows" in younger basalt units (32°04.88′N, 37°16.34′E) and at the eastern margin of the volcanic field (31°51.68′N, 38°01.58′E). These basalts form an elongated northwest-trending ridge that extends for several kilometers in the central part of the study area. The ridge, which is probably a relict of a fissure eruption, is ~100 m wide at its base and rises up to 40 m above its surroundings. Within the Harrat Ash Shaam are several dikes trending northwest. The most prominent is the Qitar Al Abid dike (QAA, Fig. 1), which yielded ages of ~10 and ~3 Ma.

DISCUSSION

The main faults and volcanic lines within the Harrat Ash Shaam volcanic field strike northwest; this is known as the Red Sea trend (Sebai et al., 1991). Furthermore, the duration and pattern of volcanism determined from the K-Ar dating are within the range of the Red Sea volcanism. These similarities imply a common origin for the Harrat Ash Shaam and the Red Sea systems.

Similarity between Harrat Ash Shaam and Other Volcanic Fields in Saudi Arabia

The similarity between the Harrat Ash Shaam and volcanic fields in Saudi Arabia lies in two aspects: (1) timing of volcanic activity and (2) association between volcanic field and dike system. The oldest basalts in the Harrat Ash Shaam area were extruded between ~26 and 22 Ma, probably during the main volcanic phase and at the same time (25–18 Ma) that the Red Sea dike belt was emplaced. The quiescence in volcanic activity between 22 and 13 Ma in the Harrat Ash Shaam system coincides with an apparent decrease in volcanism within other volcanic fields along the Red Sea region from 20 to 12 Ma (volcanic activity along the Red Sea stopped completely between 15 and 12 Ma (Camp and Roobol, 1992). It is possible that the main opening phase of the Red Sea started at 22 Ma, when volcanism ceased in the Harrat Ash Shaam region and significantly decreased in Saudi Arabia. This is in agreement with the time attributed to the opening of the Red Sea by Hempton (1987).

The exposure of northwest-trending dikes of Oligocene–early Miocene age in windows within the central and southeastern parts of the Harrat Ash Shaam volcanic field suggests that younger basalt flows cover the western part of the dike belt. The average width of the Harrat Ash Shaam field is ~100 km. Garfunkel (1989) noted the presence of dikes associated with grabens northeast of the Harrat Ash Shaam. It is important to note that these features trend northwest. If indeed the young basalts cover an old dike belt, then the total width of the dike belt associated with the Harrat Ash Shaam field from the northeastern margins of the Sirhan depression to the Essib fault zone is about 220 km. This is similar to the Red Sea dike belt dimensions (Fig. 1). Similar relationships between dike belt and volcanic field exist elsewhere in the Arabian plate, such as at Harrat Uwayrid volcanic field and the Red Sea dike belt in northern Saudi Arabia (Fig 1; Camp and Roobol, 1989).

Asymmetric Location of Magmatism and Tectonism

Dixon et al. (1989) showed that magmatism and tectonism are distinctly asymmetric around the Arabian-African plate boundary. Whereas within the eastern African plate there are only restricted dikes and lava fields, the Arabian plate northeast of the plate boundary contains numerous large basaltic dikes and lava fields. This asymmetry appears to be replicated throughout the western margin of the Arabian plate (Fig. 1). For example, the dike belt in the Red Sea region, which was emplaced at the same time or shortly before the plate separation along the Red Sea and the Suez rift (Omar and Steckler, 1995; Sebai et al., 1991), is located northeast of the plate boundary. Similarly, the Harrat Ash Shaam volcanic field is located northeast of the Wadi Sirhan depression, which is an extensional feature analogous to the Red Sea rift. These examples demonstrate that throughout the African-Arabian plate boundary, volcanism is consistently northeast of tectonism.

Another noticeable feature in the western Arabian plate is the common orientation of the Oligocene-Pleistocene magmatic and tectonic elements. Many dikes and volcanic fields as well as the rifts and faults, consistently strike northwest (Fig. 1). This orientation is attributed to northeast horizontal extension and is most likely associated with the sinistral displacement along the Dead Sea transform and the opening of the Red Sea. This interpretation is in broad agreement with the study of Eyal (1996), who investigated mesostructures and macrostructures adjacent to the Dead Sea transform and in the northern Arabian plate from the middle Miocene to recent time. Similarly, Shaliv (1991) suggested that the Esdraelon Valley in northern Israel (Fig. 1) was formed as a graben some 13 m.y. ago with an initial northwest trend. This valley might be a continuation of the Sirhan feature, displaced by sinistral movement along the Dead Sea transform. In addition, Freund at al. (1968) and Zak and Freund (1981) argued that the last 40–45 km of the sinistral movement along the Dead Sea transform most likely occurred less than 12 m.y. ago. According to Bartov et al. (1980), the total movement of ~105 km along the Dead Sea transform occurred after middle Miocene time. Thus, the renewal of volcanism in the Harrat Ash Shaam and in other volcanic fields northeast of the Red Sea Basin is coeval with the movement along the Dead Sea transform.

Span of Upper-Mantle Upwelling

Volcanic activity in the Arabian plate since 13 Ma has been spread over a wide region northeast of the Red Sea and east of the Dead Sea transform, including areas such as the Harrat Ash Shaam field, and volcanic fields in western Syria and the region near the Bitlis suture in the Taurides. Similar K-Ar ages were determined for exposures in western Syria (Sharkov et al., 1994), although several ages were within the range of ~20 to 16 m.y. (Mouty et al., 1992). This trend in the volcanic fields is found only along the western margins of the Arabian plate, close to but not necessarily in contact with the Dead Sea transform. The alignment of these volcanic fields and the trend of the Dead Sea transform clearly do not follow the previously existing northwest trends and appear to define a new weakness orientation within the western margins of the Arabian plate. In addition, some of the magmas younger than 13 m.y. were emplaced along northwest-trending preexisting fissures. This spatial coincidence may indicate that these lineaments were weak zones during the middle Miocene to Pliocene and that melting due to the emplacement of an upper-mantle upwelling beneath the western Arabian plate was partially aided by extension (Weinstein, 1998).

The northward movement of the Arabian plate relative to the African plate is expressed in the volcanic and tectonic activity as follows: (1) All the volcanic fields located in the western margins of the Arabian plate became active simultaneously after ~13 Ma. (2) This age is in agreement with the initiation or renewal of lateral movement along the Dead Sea transform since the middle Miocene, noted by Bartov et al. (1980), Freund et al. (1968, 1970), and Zak and Freund (1981). However, Sneh (1996) expressed doubt that a major lateral slip occurred after the late Miocene.

According to Camp and Roobol (1992), the magmatic phase since ~12 Ma is contemporaneous with crustal uplift, producing the Western Arabian swell. This swell is presumed to be thermally supported by hot, upwelling asthenosphere, extending as a long lobe from the Ethiopian mantle plume in the south. On the basis of Nd versus Sr isotopic compositions of basalts, Weinstein (1998) suggested that the strongest plume-type geochemical signature in the African-Arabian volcanic areas, including the Afar plume, is found in Arabia, and not in Yemen and northern Ethiopia, as expected from the thickness of volcanic rocks in that region. He suggested that the Arabian magmas were mainly produced by conductive heating as a result of plume impingement at the base of the lithosphere. In agreement with Camp and Roobol (1992), we suggest that the volcanic fields were formed above upper-mantle upwelling that extended northward to the Aleppo region in northwestern Syria and the Karacalidag volcanic field in southern Turkey (Fig. 1). Furthermore, we speculate that the existence of such upwelling along the western part of the Arabian plate since ~13 Ma accelerated the sinistral movement of the Arabian plate relative to the African plate, along the Dead Sea transform.

CONCLUSIONS

The Harrat Ash Shaam system is a basaltic field related to the volcanism along the western margins of the Arabian plate, which extends from the eastern coast of the Red Sea Basin to western Syria and north to the Taurides. On the basis of basalt age determinations, extent and geometry of the volcanic fields, and orientation of the volcanic and tectonic features, we infer that the volcanism and tectonism are closely associated in this region. The volcanism in the Harrat Ash Shaam field lasted from ~26 to 22 Ma and occurred simultaneously with the volcanism along the Red Sea. From ~22 to 13 Ma, the Harrat Ash Shaam field was quiescent. The simultaneously active volcanic fields in the western Arabian plate, especially since ~13 Ma, are associated with the northward motion of the Arabian plate relative to the African plate along the Dead Sea transform.

ACKNOWLEDGMENTS

We are grateful to F. Hirsch and M. Abelson for helpful remarks, and to C. Dallal, P. Kotlarsky, and D. Stieber for performing the age analyses. We thank reviewers F. Gomez and R.J. Stern for their helpful comments.

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Manuscript received July 24, 2000
Revised manuscript received November 6, 2000
Manuscript accepted November 7, 2000

Printed in USA