



Post–east African Orogen dilation and magmatism: development of a conjugate-style of dolerite dike swarm in the northwestern Arabian shield

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Abstract

The Al Madinah area bimodal dike swarms underwent detailed field mapping, measurements of dikes' attitudes, structural analyses, remote sensing data interpretation, and petrology study. The oldest rock unit is a greenish intermediate dioritic unit that varies in its petrologic composition between microdiorite and andesite porphyry which is intruded by alkali granite. The dioritic and alkali granite units have been cut by intermediate to mafic dikes, ranging in texture and composition from micromonzodiorite and micromonzonite to microgabbro, microdolerite, and basalt or basaltic andesite, as revealed by thin-section work. A stereographic projection and rose diagrams of the mafic dikes formed a regional conjugate dike system, following probably a typical andersonian style, consisting of three major sets, namely, the WNW set which trends between N295 and N330, E-W set between N265 and N270, and finally the ENE (N065) set. The WNW set has its own local system, but it is considered as a set in the overall regional conjugate dike system. The WNW and E-W sets are the conjugate pair of the WNW Najd fault system maximum horizontal shearing, where the ENE set reflects the minimum regional horizontal shearing stress of the Najd system. The interpretation of this dike system is a WNW-ESE sinistral faulting and NE-SW dilation that formed Wadi Al-Hamd Ediacaran continental basin, bounded by two Najd faults and Thurwah–Bir Um suture. The study area underwent final thrust faulting that tilted the dikes towards the east. For the consequent magmatisms during the Neoproterozoic period, followed by Cenozoic volcanism, the Al Madinah area is considered a large igneous province.

Keywords Dike swarms · Western Arabian shield · Conjugate style · Najd fault system · Al Madinah Al Munawarah · Dolerite

Introduction

The East African Orogen (EAO) belt represents an assemblage of fragments of the former Rodinia supercontinent during opening and closing of the Mozambique Ocean between East and West Gondwana (Stern 1994; Meert 2003; Meert and Lieberman 2008). The East African orogeny resulted in Transgondwanan Supermountain, which was more than 8000 km long and 1000 km wide; the sedimentary deposition from this mountain chain exceeded 1,000,000 km³ and lasted for 260 million years, coinciding with the [Cambrian explosion](#), the

sudden radiation of life on Earth 550 Ma; these unprecedented sedimentary depositions probably made the evolution of early life possible (Squire et al. 2006).

The Arabian Nubian Shield (ANS) is considered the northern extension of the EAO; it underwent three tectonic levels, from island through volcanic to continental arcs, where each level has a significant geochemical and mineral composition and consists of layered (volcanic and clastic) rocks associated with an intrusive rock suite (Al-Shanti, 1993). The ANS development involved the formation of ophiolites ranging between 900 and 740 Ma, then suturing and arc accretions between 750 and 650 Ma and orogenic extension and exhumation of core complexes, followed by Molasse basin formation between 620 and 580 Ma (Abd El-Naby and Frisch 2006, and references therein). The ANS underwent late crustal and lithospheric reworking during the Ediacaran time between the 600 and 550; at that time, dike swarms were developed, part of a dilational event, followed by bimodal magmatism (Stern and Voegeli 1987; Stern et al. 1988; Jarrar et al. 1992;

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Blasband et al. 2000; Genna et al. 2002; Avigad and Gvirtzman, 2009; Johnson et al. 2011; Zaineldeen, 2013).

The dike swarms are bounded by the Najd Fault System (NFS), which is a NW-SE sinistral strike-slip fault system within the Arabian Shield (Fig. 1). The NFS includes two master Ruwah and Rika faults, extends for 1100 km, and reaches up to 300 km in width, with a total length that reaches up to 2000 km, covering the ANS and surrounding Phanerozoic rocks (Delfour, 1979, 1980; Moore 1979). The system was probably active during the late Ediacaran up to the Cambrian (530 Ma) time and involved in transpressional movement and gneiss doming, positive and negative flower structure development, and deposition of the Jibalah Group in the Arabian Plate, as well as the dike swarms (Genna et al. 2002; Johnson and Kattan 2001; Johnson et al. 2011). Stern (1985) realized variations in deformational style along this fault system from the north to the south. Individual faults of the Najd system have a maximum left-lateral displacement of 65 km in the middle of the Shield (Cole and Hedge 1986), in a cumulative displacement of 240 km (Abdelsalam and Stern 1996).

The two NW trending master faults (Fig. 1) are exposed in Southeastern Arabian Shield (Johnson 1996). The eastern master fault, Rika fault zone, includes the shear zones of Kirsh, An Nakhil, Wajiyah, and Qazaz, where Ruwah fault includes Hamadat and Ajaj, and Qazaz shear zones (Fig. 1), from south to north (Mogren et al. 2008). The Rika fault probably affected Madinah by two diagonal NW and NE fault sets (Fig. 2), but the main fault trace (Nakhil-Wajiyah) is exposed 200 to the east of Madinah (Fig. 1), near Harrat Khayber.

At the beginning of 25 Ma, the Arabian and Nubian Shields were separated after the development of the Red Sea and Gulf of Aden rifts (e.g., Johnson et al. 2011), and the East African rift system evolved complexly along the preexisting EAO structures to the south of the Red Sea–Gulf of Aden opening system (Aulbach et al., 2011). After that, large volcanic provinces known as harrats extruded and overlain the Precambrian rocks, which is several monogenic eruptions of Tertiary and Quaternary basaltic lava flow rocks (Brown 1960; Brown et al. 1963a,b; Brown 1972; Blank and Sadek 1983; Coleman et al. 1983; Camp et al. 1987; Camp and Roobol 1989; Camp and Roobol, 1991; Mirza 2008; Moufti et al., 2013; Murcia et al., 2015; Murcia et al., 2017; Smith and Meth 2017).

Pellaton (1981) compiled and mapped dike swarms as part of the Al Madinah 1:250,000 geologic map and reported several types of dikes. Field investigation has confirmed the appearance of rhyolite, andesite, trachyte, and mafic dikes, which occupy in the western part of Al Madinah City, and it is geologically situated in the northwestern Arabian Shield. This study focuses on the mafic dikes for their clear structural relationship with older intruded rocks and their fresh-looking outcrops, which indicate that they are the youngest rocks of the late Neoproterozoic rocks of the Arabian Shield. Dike

swarms near Madinah have not been studied in detail. Therefore, the main aim of this study is to provide a petrological description of dike swarm rocks and the major trend of the mafic dike swarms, as well as to interpret the tectonic setting in relation to the NFS development.

Geological setting

The Al Madinah area geologically overlies the Hijaz Terrane, northwest of the Neoproterozoic Arabian Shield (900–550 Ma), which covers one third of the Arabian plate, bound to the west by the Red Sea and surrounded by Arabian shelf rocks in the north, south, and east (e.g., Johnson 1998). Two major Cryogenian–Ediacaran layered rock units are dominant in the study area, namely, the Al Ays Group (743–725 ma) and the unconformably overlying Furayh Group, in ascending order (Al-Shanti 1993; Johnson, 2006; Johnson et al. 2013). The Al Ays Group comprises three formations, namely, the Farashah, Urayfi, and Difayrah formations (Kemp 1981; Pellaton 1981). The Farashah Formation is mainly composed of andesitic lava and pyroclastic rocks. The Urayfi Formation is generally silicic volcanic epiclastic rock with silicic lava and rhyolitic tuff, intercalated with detrital sedimentary rocks. Finally, the Difayrah Formation is composed of rhyolitic and sedimentary rocks (Pellaton 1981). The Al Ays Group was intruded by intermediate igneous rocks, such as diorite, granodiorite, and monzogranite, which are part of the Dulu intrusion that is partly associated with second diorite series. The intermediate igneous rock is present in the study area, namely the dioritic unit. The overlying Furayh Group is composed of basal conglomerate and sandstone of Murayr Formation, overlain by andesitic basaltic lava with pyroclastic and detrital sedimentary rocks of Qidrah Formation, as well as Dawnak Formation that is composed of mature sedimentary rock deposited in a subsiding basin. Furayh Group was intruded by the alkali granite, microgranite, and syng granite rocks, and finally by gabbro and associated dike swarms. The alkali granite-microgranite-syng granite unit is present in the study area, extruded by the mafic dike swarms. The intermediate igneous suit of intrusive rocks association with layered Al-Ays and Furayh groups rocks suggest involvement during the second level of evolution, the volcanic arc tectonic setting (e.g., Al-Shanti 1993).

The two Precambrian volcanoclastic units and igneous rocks underwent greenschist metamorphism and two generations of folds, specifically N-S folds (F1) and E-W folds (F2), that are cut by the NFS (i.e., Pellaton, 1981; Kemp, 1981; Bamousa, 2013). Figure 2 shows the effect of the F1 fold and Najd system faults. The Al Madinah area was then covered by Cambro-Ordovician rocks and Harrat of Tertiary and Quaternary basalts (Kemp 1981; Pellaton 1981). Cenozoic N-S normal faults, cut by E-W transtensional faults related to the Red Sea rifting, have also affected the study area and formed a

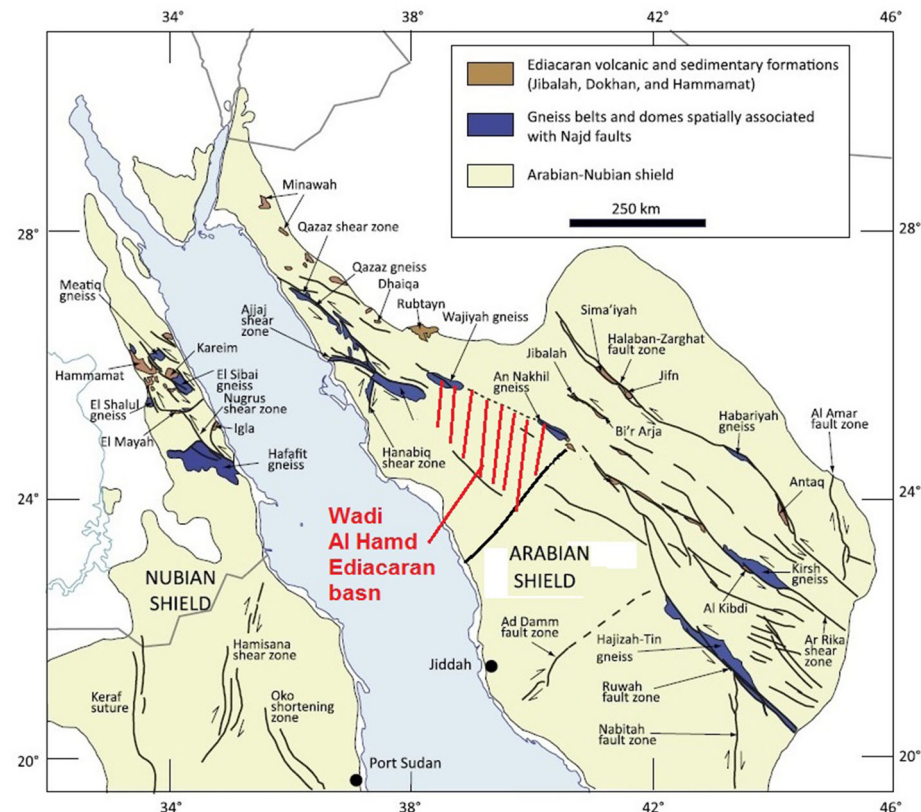
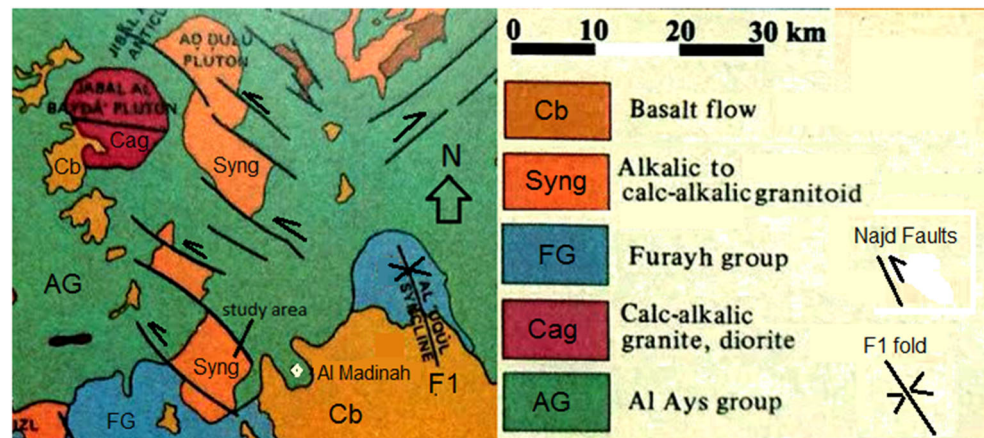


Fig. 1 Drainage map of Wadi Al Hamd showing location of Al Madinah City (the black rectangle), modified after Lehner et al. (2008) and Lehner and Grill (2013)

Fig. 2 Tectonic map showing the major rock units in the Al Madinah quadrangle, after Pellaton 1981



relief inversion geomorphology in which Tertiary lava flows are at the top of the high mountains in the west of Madinah, such as the Jammah and Ayr Mountains (Bamousa et al. 2013).

Methodology

This work comprises detailed field investigation, measurements of dikes' attitudes (strike, dip, and dip direction) using a Brunton compass, and structural analysis via remote sensing data. Dikes' attitudes were plotted on a lower sphere stereographic projection, as well as on an azimuth-frequency (A-F) rose diagram using Stereonet 10 and GeoRose. In study area I (Fig. 3), detailed geological mapping, petrology study, and structural analysis in the vicinity of the Taibah University Campus was performed. World View III imageries were used for their high spatial resolution, which reaches 0.31 m, to discriminate the mafic dikes from country rock (Fig. 4). Moreover, a larger area (study area II) was selected west of Madinah City using a digital globe image available from Google Earth, plotted on an A-F rose diagram. Study area III and IV were selected further to the west, to find other representative trends of the mafic dike swarms and show a relationship with older rock units (Figs. 5 and 6). Nine samples of the dioritic and dike swarm units are collected from study area I and examined first by hand lenses, and then standard thin section was prepared. Microscopic examination was undertaken in transmitted light using polarizing microscope Leica DMRX. Micro-photographs were taken using digital camera Leica DFC-320, attached to the microscope.

Results

The results of the petrologic study of the nine samples show 3 collected samples from oldest dioritic unit as microdiorite and andesite porphyry, under a microscope. The other 6 samples

are from the dike swarms which are micromonzodiorite and micromonzonite, latite, microgabbro (two samples), microdolerite, and basalt-basaltic andesite. The dike swarms are mostly mafic in composition; therefore, they are called dolerite dike swarm unit in the detailed geological mapping, analyzed and synthesized structurally.

Structural analyses and synthesis

Study area I was 10 by 20 km² in the vicinity of Taibah University; 89 dikes were mapped in detail and measured (Fig. 4). The detailed mapping and petrology study showed that the oldest rock unit was a greenish intermediate igneous rock that varied in petrological composition between microdiorite and andesite porphyry, which is named in the detailed geologic map as dioritic units. Al Jammah Mountain alkali granite to syngranite (Gougazeh et al. 2018) intruded the dioritic unit in the study area as continuous laccolith bodies in one almost horizontal layer and cut by the intermediate and mafic dikes (Fig. 7). Figure 8 shows a cross-section where a latite dike was emplaced and divided by a dolerite dike that intruded the older dioritic and granitic units. Thus, it reflects the mechanism of emplacement and suggests a tectonic history that will be discussed below. Stereographic projection of the mafic dikes shows the main range of direction between N300 and N330, with the mean frequency in the N315 direction (Fig. 4c). Poles to 85 dike attitudes show that they tend to dip steeply SW and NE, suggesting a conjugate system (Fig. 9). The N300 - N330 frequency has a typical andersonian style with a 30° difference, where the mean N315 trend represents the overall regional WNW Najd system. Finally, the study area underwent the last compressional event after emplacement of the dike swarms, as suggested by NE-trending and W-dipping thrust faults and tilting rock units towards the west (Fig. 9).

Study area I does not represent all dikes' orientations; therefore, a larger area, study area II, was selected (Fig. 5a). An A-F rose diagram reveals a major trend of N085 and

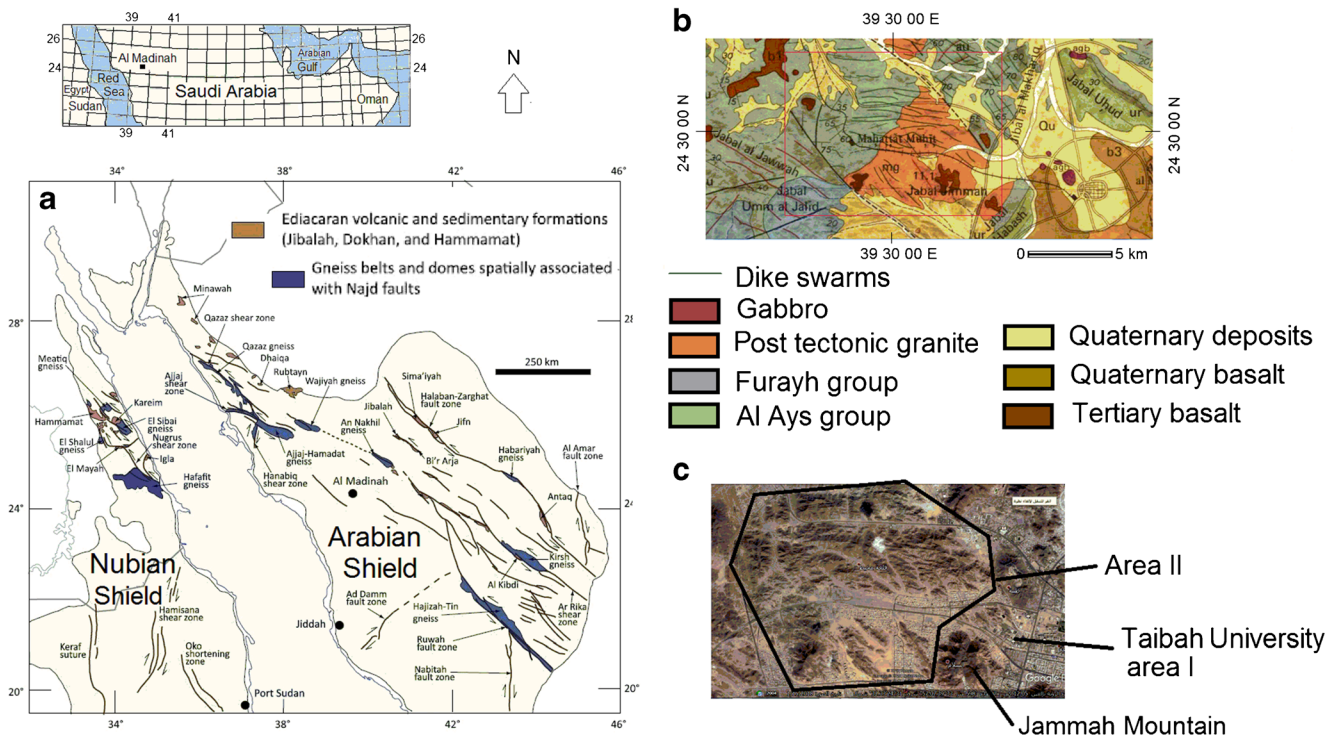


Fig. 3 Location of Al Madinah City in relation to the NW Arabian Shield and Najd Fault System (NFS). Geological map showing lithologic units underlying Al Madinah City, highlighting dike swarms mapped by Pellaton (1981)

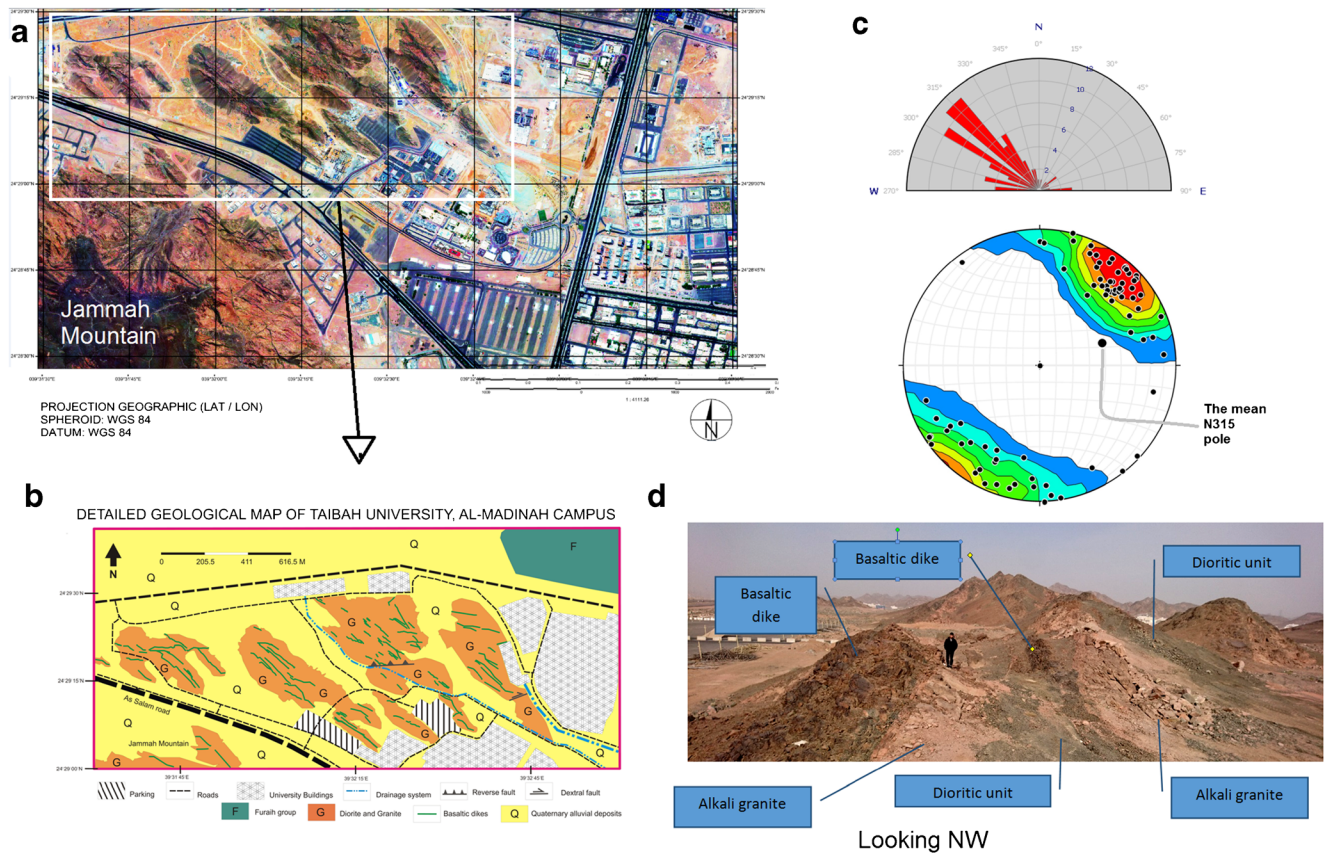


Fig. 4 Decorrelation stretch of true color composite imagery of World View III and detailed geological mapping. Results of the structural analysis and field photo showing geological relationships

Fig. 5 Structural analysis and rose diagrams of area II and area III

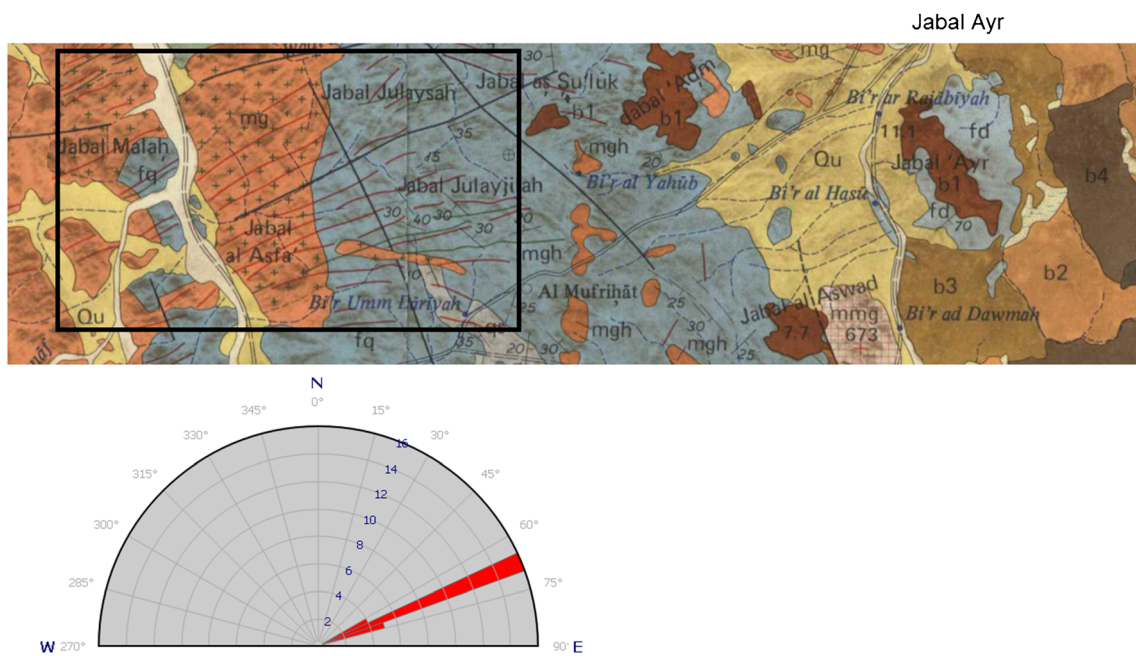
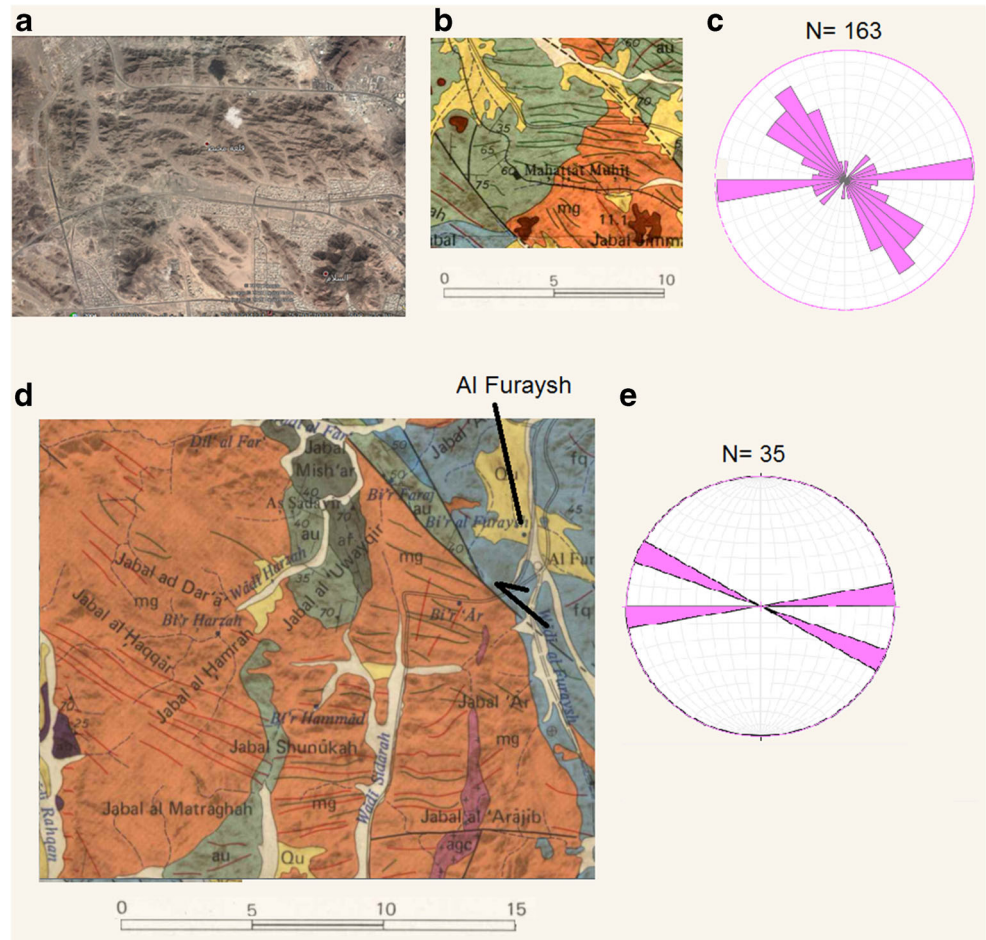


Fig. 6 Structural analysis and rose diagram of area IV

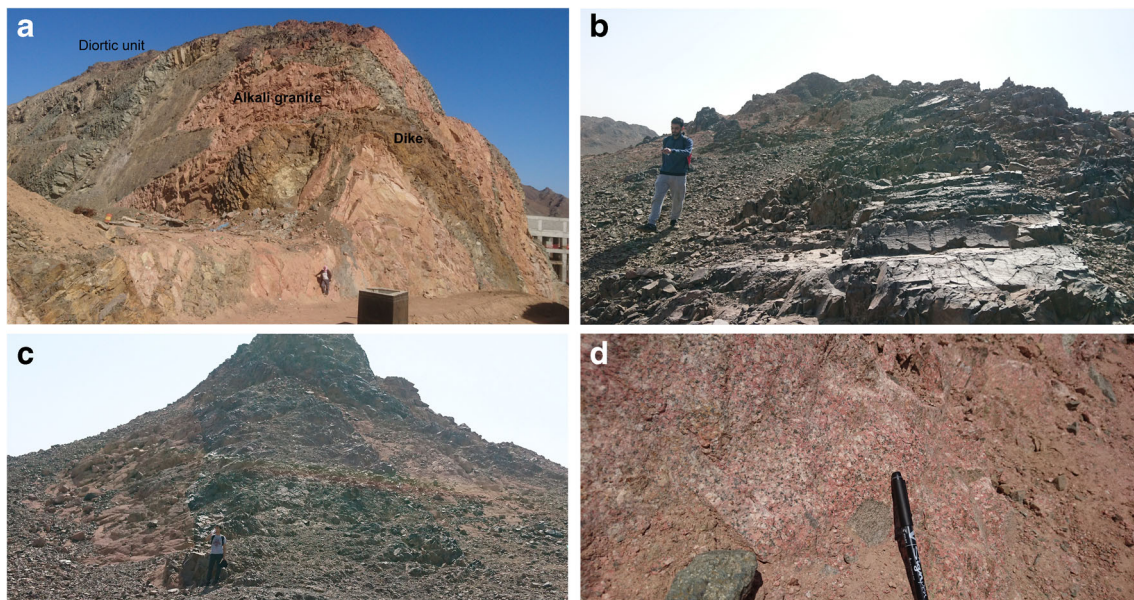


Fig. 7 **a** Three igneous dioritic, alkali granite, and dolerite dikes. The alkali granite has a series of laccoliths showing horizontal emplacement. **b** Dolerite dike intruding the dioritic unit. **c** Dolerite dike

intruding in the alkali granite only. **d** Closer look at the xenolith of the dioritic unit contained in the alkali granite

N300–330 for the 163 dolerite dike swarm (Fig. 5c), which is similar to the results in area I. In addition, near Al Furaysh Town, about 50 km to the west of Al Madinah, both mafic and felsic dikes are present, subparallel to a major NFS zone, suggesting an association of the dikes with strike-slip faults (Fig. 5d, e). Structural analysis and rose diagram of Pellaton's (1981) map suggests two main directions, N295 and E-W direction (Fig. 5e), which can be grouped to the frequency trends in study area I, II, and III. Analysis of the Al Madinah geologic map (Pellaton 1981) shows that the Jabal Al Asfa' area south of Al Madinah contains a felsic dike swarm, trending in an average direction of N065 (Fig. 6).

The different dike swarm trends in the four study areas can be synthesized into three major sets. The N295 with the N300–N330 may be considered as the first major WNW set and occurred in study areas I, II, and III. The second group of dikes is likely the E-W set, when looking at the trend N085 as N265, composed of the N265–270 in study areas I, II, and III. The last more clear group or set of dikes is likely the N065 set in area IV, which is part of study area IV, and represents the ENE set. These three sets reflect a dike swarm system, discussed in detail in the discussion section.

Microdiorite and andesite porphyry

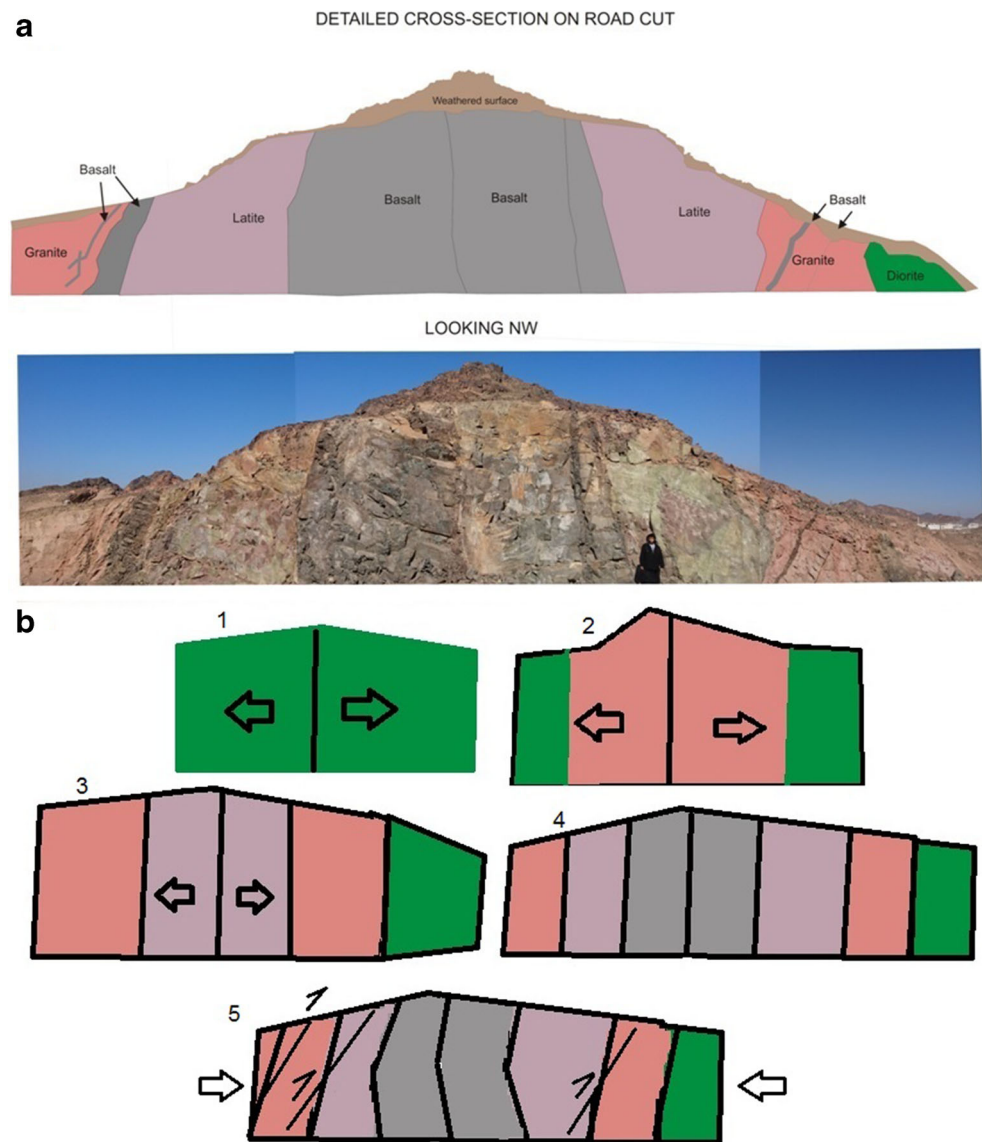
This rock unit is chiefly plagioclase together with secondary chlorite probably after primary amphibole alteration, accessory quartz, and opaques (Fig. 10). In addition secondary epidote is also identified locally replacing and forming intergrowth over plagioclase. Plagioclase is fine-grained,

subhedral with platy grain morphology and displays random orientation. The intergranular spaces are commonly occupied by secondary chlorite and locally by quartz. Chlorite is fine-grained, flaky in habit, and mostly aggregates at the intergrain spaces of plagioclase. Quartz is very fine-grained, anhedral in form, and occurs in scattered disseminations. The rock is affected by mild hydrothermal alteration which is marked by turbidity among plagioclase (probably due to sericite and kaolin alteration). In addition, chlorite predominantly replaces ferromagnesian minerals (amphibole/biotite) and epidote replaces and forms intergrowth over plagioclase.

Micro-monzodiorite or micromonzonite

The rock is partially to moderately altered and is comprised essentially of plagioclase and alkali feldspar together with subordinate amounts of chloritized amphibole, quartz, accessory apatite, and opaques (Fig. 10). In addition, secondary chlorite \pm epidote is also recorded. Feldspars in general is fine-grained, dominantly subhedral, and platy in habit and occurs in random orientation. The intergrain spaces of feldspars are mostly occupied by green chlorite (probably after amphibole) and locally by quartz. Amphibole (actinolite-tremolite variety) is fine-grained, prismatic in habit, and dominantly altered to chlorite. Epidote is fine-grained and granular in habit; it replaces and forms intergrowth over plagioclase. Quartz is very minor; it is fine-grained, anhedral in form, and locally occupies intergrain spaces of plagioclase. The rock is affected by mild to moderate propylitic alteration. The alteration minerals identified consists of chlorite and epidote.

Fig. 8 Cross-section shows the emplacement mechanism and the final thrust faults



Latite

The latite is distinguished in two main components: rock mesostasis and phenocrysts (Fig. 11). The rock mesostasis is partially altered; it is fine-grained and comprised dominantly of feldspars (including both alkali feldspar and plagioclase) together with subordinate amounts of amphibole, secondary chlorite, epidote, carbonate, accessory quartz, and opaques. Feldspars (alkali feldspar and plagioclase) are fine-grained, subhedral with stubby grain morphology, and commonly cloudy in appearance. Amphibole is fine-grained and dominantly occurs in prismatic slender laths with random orientation. Chlorite is fine-grained, flaky in habit, and occurs in scattered patches or filling micro-cavities. It is probably formed after amphibole alteration. Epidote is also fine-grained and occurs in scattered aggregates probably formed after

plagioclase and amphibole. Carbonate is very scarce; it is fine-grained and subhedral to anhedral in form. The rock is affected by mild propylitic alteration; the alteration mineral identified consists in order of abundance chlorite, epidote, and carbonate.

Microgabbro

The rock is differentiated into two parts: rock groundmass and phenocrysts (Fig. 12). Rock groundmass is finely crystalline and comprised chiefly of microlites of plagioclase with random orientation where pyroxene and accessory opaques fill their intergrain spaces. The groundmass commonly encloses phenocrysts of plagioclase and pyroxene ± olivine. Plagioclase phenocrysts are fine- to medium-grained, generally subhedral in form, with platy crystal morphology. Locally, plagioclase phenocrysts occur in

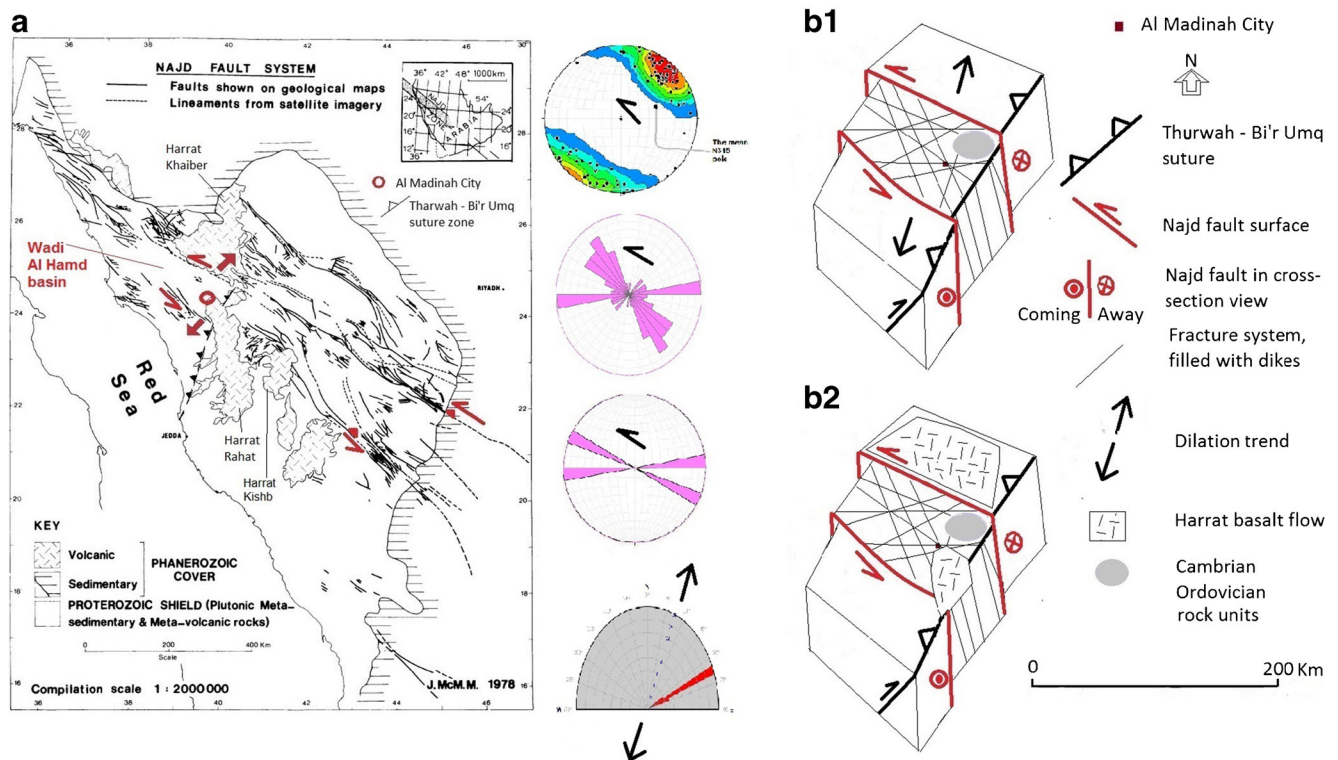


Fig. 9 Model of the dilational area developed by two master NFS fault zones. Late thrusting events affecting dolerite dikes, suggesting that they are more recent, representing the final tectonic event

clusters forming glomerocrysts. Pyroxene occurs both as groundmass constituent and in the form of phenocrysts. Pyroxene phenocrysts are fine- to medium-grained, subhedral to anhedral in form, and it locally also aggregates forming glomerocrysts. The rock in general is fresh and unaltered except slight turbidity among plagioclase (probably due to very fine sericite \pm kaolin alteration) and mild chlorite alteration of pyroxene documented.

Microdolerite

The chief component of the rock is plagioclase and pyroxene together with accessory opaques and secondary chlorite. Plagioclase is fine- to medium-grained, subhedral with platy grain morphology, and shows random orientation, where secondary chlorite fills plagioclase intergrain spaces. Plagioclase generally also displays subophitic interrelationship with pyroxene. Pyroxene (augite variety, pale pinkish in color) is also fine to medium, subhedral to anhedral in form, and generally partially to moderately encloses plagioclase laths giving subophitic to ophitic fabric to the rock assemblage (Fig. 12). Secondary chlorite (green in color) is fine-grained, flaky in habit, and mostly occupies intergrain spaces of plagioclase. The rock is affected by chlorite alteration of pyroxene.

Basalt and basaltic andesite

The rock is comprised of microcrystalline groundmass and phenocrysts of plagioclase and pyroxenes. The groundmass is extremely fine-grained with intergranular texture and partially affected by chlorite alteration. It is comprised of microlites of plagioclase that shows random orientation. The intergranular spaces of plagioclase are occupied by very fine-grained pyroxene and accessory opaques. The groundmass commonly encloses phenocrysts of plagioclase and pyroxene. Plagioclase phenocrysts are fine- to medium-grained, subhedral with platy crystal morphology. Pyroxene phenocrysts are dominantly fine-grained, subhedral to locally euhedral in form, locally occur in clusters, and show boundary association with plagioclase. The rock is partially affected by hydrothermal alteration. The alteration is marked by turbidity among plagioclase phenocrysts probably due to very fine sericite \pm kaolin alteration. Groundmass pyroxene is partially to moderately affected by chlorite alteration.

Discussion

Although the older granite and diorite unit fracture systems have some joints filled with some dolerite dike swarms (Fig. 13), the intrusive event dated between 600 and 550 Ma (Jarrar et al. 1992) is likely associated with the NFS event,

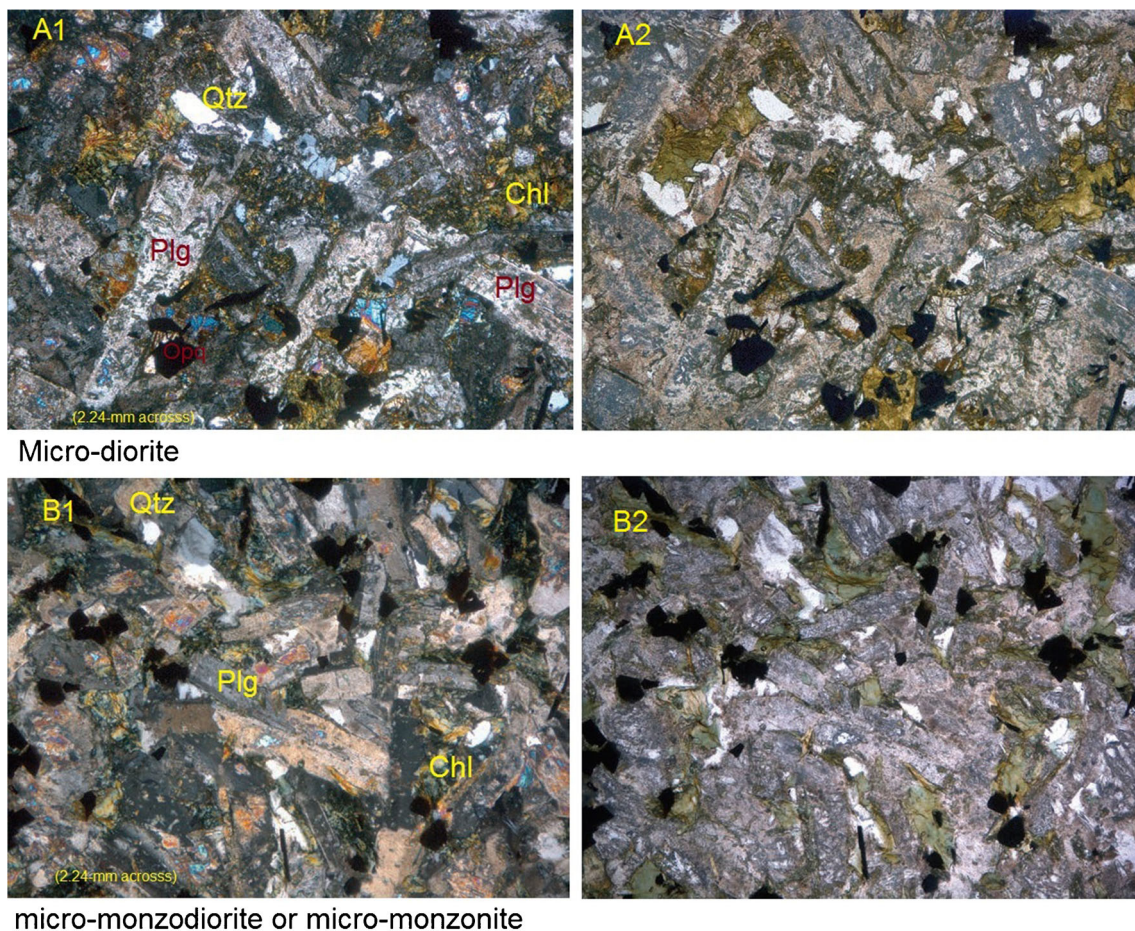


Fig. 10 Thin-section photos of the dioritic unit and micromonzodiorite to micromonzonite rock

which occurred during the 630–530 Ma period (e.g., Genna et al. 2002; Johnson and Kattan 2001; Johnson et al. 2011). Mafic dike swarms which are excellent time markers and paleostress indicators can be used to reconstruct paleostresses during their development. Each parallel trajectory of one set (group) of dikes may fit parallel to the maximum horizontal shearing stress orientations (Pollard 1987; Hou et al. 2006). Field and regional observations as well as structural syntheses suggest at least three major WNW, E-W, and ENE dike sets, associated with the NFS. The 300 to N330 range in study area I represents probably a typical 30° difference of the andersonian style, formed due to WNW (N315) maximum horizontal principal stress and vertical neglected intermediate stress. Even though the N300–N330 frequency has its own local andersonian dike system, it includes the N295 frequency in area III representing a regional WNW set. The N265–N270 frequency is the second main E-W set formed obliquely to horizontal stress, representing with WNW set, the conjugate pair of the maximum horizontal shearing stresses of the transcurrent NW Najd system. The ENE (N065) set reflects the opposite minimum regional NE extension stress in the andersonian style, perpendicular to the WNW shearing. Thus, there is a new dike swarm system (more than one set)

developed, the conjugate system, to be added to the other parallel, radiating, and arcuate dike swarms (Halls and Fahrig 1987; Ernst et al. 1995; Hou et al. 2006).

The conjugate system formed probably when the two master transcurrent NFS, Ruwah and Rika, released, stepped-over, and formed a dilation and extension (Busby and Azor 2012). This basin development was carried out towards the NE–SW obliquely to the WNW–ESE trend of the NFS (Figs. 1 and 2). The fault near the Al Furaysh town, shown in Fig. 5b, is likely a master fault and a representative sector of Ruwah, which bound the Wadi Al Hamd basin to the west of Madinah. This dilation area may represent an earlier regional continental basin formed during the late Precambrian time, bound by the two Najd faults and by the Thurwah–Bi'r Umq suture to the south (Fig. 9). This basin model would probably explain the deposition and outcropping of Cambrian Ordovician rocks to the east of Al Madinah. It may also explain the distribution of harrats around Madinah, in which the northern Harrat Rahat is outcropping SE of the Al Madinah area and Harrat Khaiber is an outcropping to the east, away from the dilation area (Fig. 9b). This regional dilational basin is called Wadi Al Hamd basin in this study, for the geographic contemporaneous of the two features (Fig. 1).

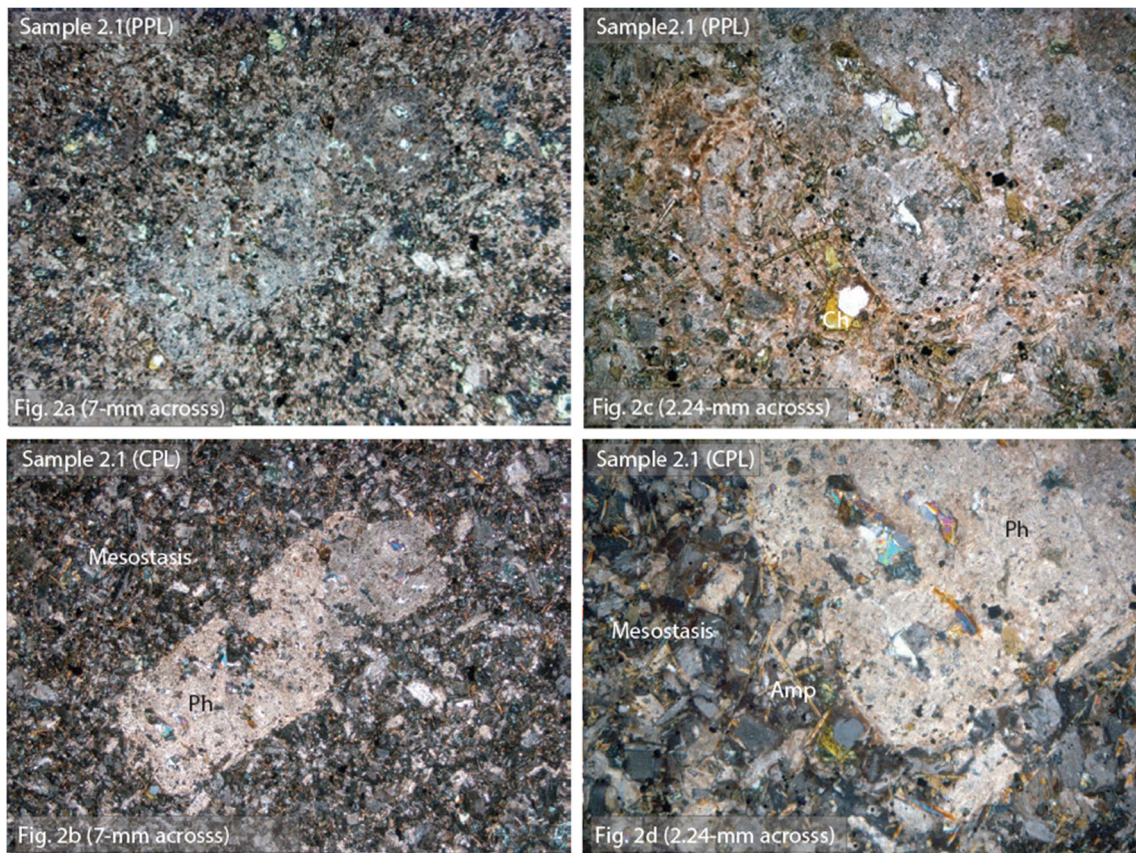


Fig. 11 Microphotographs of the latite dike, under microscope

The NFS is still active because of the rifting of the Red Sea, controlling the harrats’ basalt flows, drainage pattern, and wadis flow directions in the Madinah area (Bamousa et al., 2013). Consequently, the intersection of Red Sea faults and the reactivated NFS formed the Al Madinah basin, which is a later orthorhombic Cenozoic basin that affected Al Madinah City (op. cit.).

One of the results showed that the dioritic unit was intruded by the granite, which was emplaced by an intermediate dike that split by dolerite dike swarms (Fig. 8). After this emplacement mechanism, it seems that the original mafic magma coming from the upper mantle was still hot and emplaced along the same fracture, splitting the felsic and intermediate bodies into two dikes bounding a dolerite dike and forming

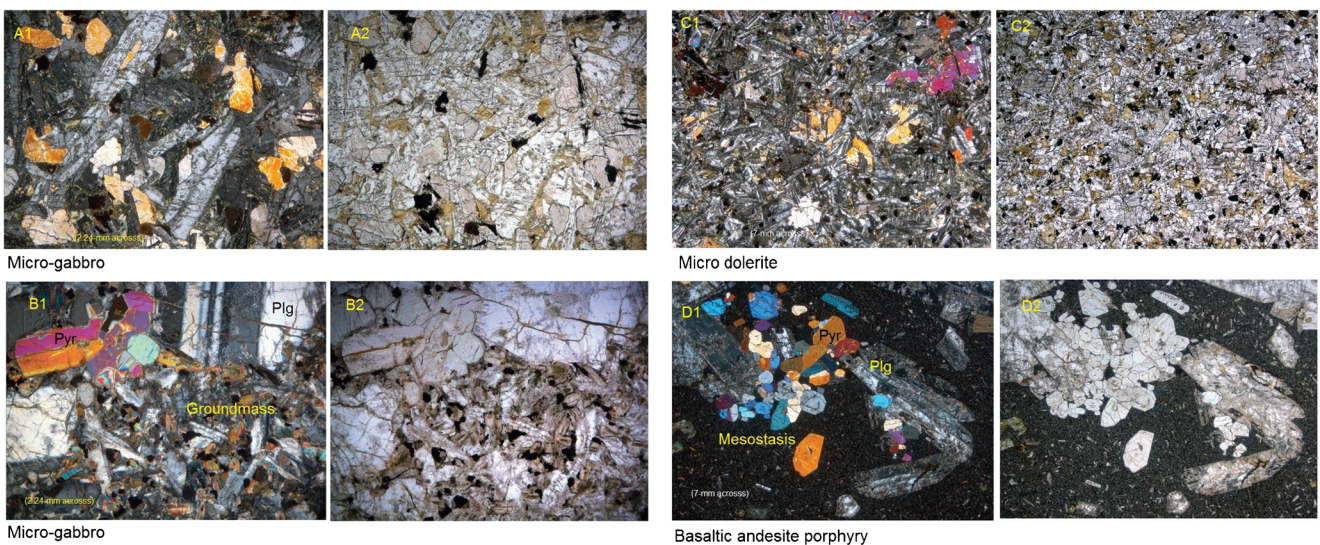


Fig. 12 Thin-section photos of dolerite dike swarms

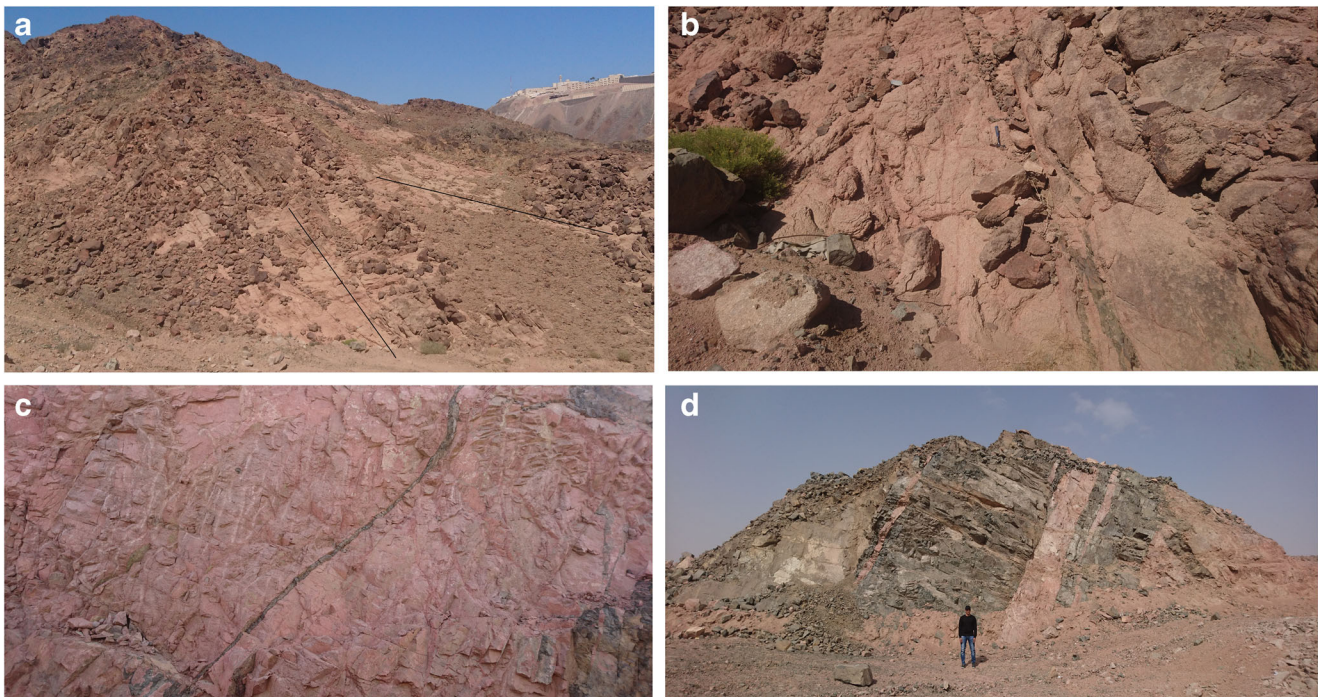


Fig. 13 Fracturing system in granite rocks before (a, b). Fractures in the granite filled with dike are almost parallel (c, d)

the bimodal dikes. The larger dikes may be built up incrementally by numerous small injections of magma (Platten 2000). Speight et al. (1982) suggest that swarms are generally densest in the vicinity of the central complexes, where smaller sub-swarms of varying trends also occur and where the dikes commonly exhibit considerable compositional diversity. Therefore, intrusion of the dike swarms causes pronounced local crustal dilation. However, distribution of the dike swarms controlled by a regional east-northeast–west-southwest extensional stress field, and the over-riding control on the orientation of the swarms are considered as the orientation of lower crustal intrusions that fed the dikes (op. cit.); therefore, dikes intrude a range of pre-existing fractures, for magma pressure varying and regional stress.

Previous workers realized different structural features such as folding and doming suggesting transpressional component of the NFS (Moore, 1979; Johnson and Kattan 2001; Johnson et al. 2011, Mogren et al., 2008, Fig. 1). However, the study area, Hijaz Terrane (in Al Madinah), has witnessed dilation (e.g., Genna et al. 2002). Therefore, this suggests partitioning of deformation, in which the NFS zone has a major transpression system, with a minor transtensional system and a relatively large area of dilation between fault zones in the Wadi Al-Hamd area (Fig. 1). Moreover, 1100 km width of the NFS in the southeastern end of the fault zone gets narrower, and faults near Harrat Kishb and Rahat in the west bend towards the east, where Thurwah-Bi'r Umq suture is exposed. This may suggest that the Thurwah-Bi'r Umq suture may act as an accommodation zone that switches the displacement from transpressional to transtensional (Fig. 4a). Notice that

all gneiss belts domes are to the south and east of Al Madinah area (Johnson et al. 2011, Fig. 1a) and appear again to the north near another suture zone known as Yanbu Suture.

Conclusion

The rock assemblage reveals different magmatism and the development of magma composition from intermediate to felsic, after which it returned to a mafic, during the late Precambrian to early Tertiary periods. Therefore, the Al Madinah area is considered as a large igneous province. Moreover, the structural features vary in origin, in which it shows dike swarms which are evidences of dilation, faulted by thrust faults which suggest compression. One famous tectonic feature of structural geology that can bring extension and compression together is strike-slip faults. NFS as strike-slip affinity is not just one tectonic style and represents a final post-amalgamation of EAO that was broken into different realms, due to the inhomogeneity of the crust components of the Arabian Shield. In addition, the style changed from transpressional to transtensional where older pre-existing suture zones acted as accommodation zone. The NW-SE trend of the NFS is still controlling younger features and rocks. The dikes were then thrust faulted against the granite that was tilted towards the NE, which probably suggests that it could be the final pulse of transpression of the Najd System after extension and intrusion of the dike swarms. This study recommends further work on the thrust faulting analysis and relationship with NFS age dating and geochemistry to further elucidate

these processes, and further investigation should deal with Paleozoic rock deposition in the central part of the Arabian Shield, east of Madinah.

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