Research Article

Abdulaziz Samkari, David W. Farris, and Haitham M. Baggazi*

Activation of Ad Damm shear zone, western Saudi Arabian margin, and its relation to the Red Sea rift system

<https://doi.org/10.1515/geo-2022-0343>
received May 25, 2021; accepted January 20, 2022

Abstract: The Ad Damm shear zone (ADSZ) is a major mylonitic right-lateral structure that bounds the Jeddah terrane to the north from the Asir terrane to the south. High-resolution field mapping coupled with petrological and geochemical analyses indicate that Jeddah terrane is characterized by heterogeneous magmatism with extensive meta-basalt intruded by silicic plutons of varying size. South of the ADSZ, Asir terrane is characterized by larger scale granitic batholiths. A younger generation of Eocene–Miocene basaltic dikes cut the mylonitic shear zone at a high angle. Petrographic analyses of the ADSZ mylonitic rocks indicate dynamic recrystallization and grain-size reduction, suggesting high-temperature recrystallization. Field observations also found a lack of low-temperature fault zone rocks (e.g. gouge) except for isolated brittle slickensides. Spider diagrams of Jeddah, Asir terranes, and ADSZ rocks are characterized by an arc-related signature, which related to the amalgamation of Jeddah and Asir terranes and defined ADSZ as Neoproterozoic structure. In contrast, Eocene–Miocene basaltic dikes and southern basaltic flow are represented by a rift-related signature, which associated with the development of the Red Sea rift system. Offshore, south of the ADSZ, the Red Sea rift exhibits well-developed linear magnetic anomalies and large topographic escarpment perpendicular to the rift margin, but they are not present north of it. In addition, recent seismicity recorded along the ADSZ and differences in the

crustal thickness and characteristics of Asir and Jeddah terranes, collectively, make ADSZ acted as an active crustal boundary and still influence the ongoing tectonic evolution of the Red Sea rift.

Keywords: Red Sea rift system, Ad Damm shear zone, Precambrian reactivation, satellite image processing, spider diagrams, crustal thickness variation

1 Introduction

Over the last few decades, the coastal margin of Saudi Arabia has experienced earthquakes recorded by 89 stations and monitored by the National Center of Earthquakes and Volcanoes of Saudi Arabia [1]. Major historical earthquakes on the Arabian Peninsula, including the Gulf of Aqaba earthquake in 1995 with a magnitude of 7.3, are located along the Red Sea rift axis and inboard on the ancient Neoproterozoic structures of Arabian shield (e.g. Klinger et al. [2]). Such observations indicate that the areas considered to be of highest potential risks are located along the Red Sea. Thus, it is very crucial to better understand the opening of the Red Sea and to place constraints on the geologic and structural elements in the western Saudi Arabian margin.

1.1 Tectonic history of the Arabian shield

Most of rock units exposed on the flanks of the Red Sea are Neoproterozoic in age and recognized as part of the Arabian and Nubian shields (ANS) on the eastern and western margins of the Red Sea [3,4]. The ANS has been shaped by the amalgamation of different terranes and divided into nine terrains, which are separated by faults or suture zones [5] (Figure 1). Earliest terranes include Jeddah (870–740 Ma; [6]) and Asir (850–750 Ma; [7]). Middle age terrane covers Midayan (780–710 Ma; [8]) and younger terranes include Al-Ryan (>670 Ma; [9]) and

* **Corresponding author: Haitham M. Baggazi**, Structural Geology and Remote Sensing Department, Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Saudi Arabia, e-mail: hbagazi@kau.edu.sa, tel: +966-540084084

Abdulaziz Samkari: Structural Geology and Remote Sensing Department, Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Saudi Arabia; Department of Geology, University of Leicester, UK

David W. Farris: Department of Geological Sciences, Washington and Lee University, Lexington, VA, USA

Figure 1: Tectonic map of the western central part of the Arabian shield, displaying the boundaries and ages of several terranes (modified after Stoesser and Frost [18]). Focal mechanism solution recorded along ADSZ by an earlier study [14].

Ad Dawadimi (674 ± 6 Ma; [10]). Most of these terranes are interpreted to have formed in supra-subduction zone environments and were subsequently amalgamated through collisional processes [5]. Although the radiometric-ages range is wide across the Arabian Shield (e.g. 870–674 Ma), there appears a general agreement that basement rocks are all Precambrian in age. Previous geochemical work indicates that the Arabian Shield has been subjected to two significant events of volcanic activities in response to the development of the Red Sea and Gulf of Aden rift system (Bohannon et al. [11]). The first major event occurred during late Oligocene, followed by the second event during Late-Miocene. Both episodes involve intense volcanic eruptions and uplifting. Although seafloor magnetic anomalies south of Arabian Shield is well observed, it does not correlate with north part of Arabian plate [12] (Stern and Johnson). The southern segment of the Red Sea is affected by the upwelling of Afar plume. However, the northern part of the Red Sea is influenced by its connection with the Dead Sea transform fault [13] (Lazar et al.).

1.2 Geological and structural background

One of the large-scale, terrane bounding features in the Arabian Shield is the Ad Damm shear zone (ADSZ), located at the central-western part of Saudi Arabia and defined as NE-trending right-lateral strike-slip fault [3,4] (Figures 1 and 2). The ADSZ is thought to act as a tectonic boundary between Asir terrane to the South and Jeddah terrane to the North and is topographically expressed as a linear zone of mylonitic to highly sheared granite (e.g. Al-Saud [14]). North of the ADSZ, Jeddah terrane is characterized by heterogeneous composition. In contrast, south of the ADSZ exists the Asir terrane, which is composed of large silicic plutons and mainly of sheared to granite gneiss that believed to be a syntectonic intrusion during the deformation of the volcanic and the sedimentary rocks [15].

Structurally [3], simplified the deformation history in the ADSZ into three phases: NW-SE contractional regime (D1) which led to NE-trending thrust faults and tight-

Figure 2: Simplified geological map and cross-section of the study area, display major geologic units and cross-cutting relationships (after an earlier study ref. [4]).

overturned folds, followed by NE-SW compressional episode (D2). The last phase of deformation (D3) represented by NE-SW dextral transcurrent shear zone which led to the formation of ADSZ. Tertiary and younger geologic activity was subjected to multiple generations of normal

faults, with a NNW-NW strike, due to the opening of the Red Sea at approximately 25 Ma [5,16,17]. Furthermore, such recent faults are thought to be responsible for geographic relief differences between the northern and southern part of ADSZ. For instance, on land, the ADSZ

Figure 3: ASTER satellite image using decolouration stretch and band ratio (7/6, 6/5, 6/4) in RGB. Field localities are also shown in red dots.

bounds a large topographic escarpment perpendicular to the rift axis with higher elevation to the south. In this study, high-resolution field mapping coupled with petrographic and geochemical analyses are integrated to investigate whether ADSZ was solely a Neoproterozoic structure or if it has been reactivated during Cenozoic. The selected methods presented here help to constrain the effect of the Red Sea opening on the ADSZ by carefully characterize the Neoproterozoic structures from more recent Cenozoic-age structures.

2 Methods

High-resolution field mapping was used to define the significant geologic and structural characteristics of ADSZ, Jeddah and Asir terranes, and its relation to the Red Sea rift-related structures. Microstructural studies were conducted to interpret the quartz-crystal evolution and deformation mechanism across the ADSZ. Whole-rock geochemistry analyses were used to distinguish between Neoproterozoic units from more recent Cenozoic intrusions [4].

Figure 4: Displays some of prominent large-scale structures: (a) dextral sense of shear in mylonitic granite, (b) mylonitic fabrics of ADSZ rocks, (c) cross-section of large-scale syn-form drag folds in Jeddah terrane, and (d) NNW-NW Oblique normal faults cut across basement rocks.

3 Results

3.1 Satellite image processing

Advanced spaceborne thermal emission and reflection radiometer (ASTER) satellite image was carefully selected to construct lithological discrimination map. In addition, four software packages were later used to process and layout satellite images (Arc map (Environmental System Research Institute, USA), ENVI (Environment for Visualising Images software, USA), ERDAS (Earth Resources Data Analysis System IMAGINE), and Global Mapper (Blue Marble Geographics, USA)). Processing of ASTER imagery included resampling the spatial resolution of the 30 m six-bands of short wave infrared to correlate with the three-bands of 15 m visible and near-infrared to produce nine bands with a spatial resolution of 15 m. Thereafter, the decorrelation stretch technique was applied to enhance differences in colour by stretching the image pixels. Next, the band ratio technique is applied using (7/6, 6/5, 6/4) ratios because it efficiently separates different geologic features and lithologic

compositions (Figure 3). The Ad Damm narrow valley and other minor valleys are well defined in white colour due to the presence of quartz rich sand. In comparison, the dark blue colour represents amphibolite and metabasalt, which are more abundant in the Jeddah terrane and along the ADSZ. The dull green colour displays the unstrained granite (Asir terrane), and the reddish-brown colour symbolizes Jeddah terrane (heterogeneous granite). Basalt flows of the Harrat Ad Damm are clearly shown in a dark brown colour [4].

3.2 Field mapping

ADSZ is dominated by a right-lateral strike-slip mylonitic shear zone that strikes NE-SW and separates between the Asir to the south and Jeddah terranes to the north (Figure 2). The sense of shear and mylonitic fabrics have been identified in many localities and measured as a dextral slip (Figure 4a and b). North of ADSZ, the Jeddah terrane is characterized by heterogeneous magmatism (amphibolite

Figure 5: Petrographic analysis of mineral-forming rocks in the study area: (a) relative mineral compositions of Jeddah terrane, (b) relative mineral composition of Asir terrane, (c) eutectic minimum melt composition shows lower crystallization temperature in Asir terrane, and (d) dynamic recrystallization of mylonitic granite in ADSZ rocks.

to greenschist), intruded by several felsic to basaltic dikes) and North Northeast-Northeast striking foliation and mineral lineation. Such units are later folded in large-scale drag folds and overprinted by shear indicators (Figure 4c). In contrast, the Asir terrane is defined by massive granitic batholiths that include sheared to highly foliated granite, located adjacent to ADSZ, and granitic gneiss to granodiorite away from the shear zone. Subsequently, the western margin was intruded by a number of Eocene to Miocene mafic and silicic dikes, associated with NW to North North-west (NNW)-striking faults that are interpreted to be related with the opening of the Red Sea (Figure 4d).

3.3 Petrographic and microstructural analyses

The petrographic study shows Jeddah terrane composed of a mixture of quartz, K-feldspar (microcline), and plagioclase

with more than 25% of biotite and hornblende (Figure 5a). Asir terrane contains abundant of quartz, K-feldspar (microcline), plagioclase, and occasionally biotite (Figure 5b and c). ADSZ rocks exhibit a high degree of recrystallization and are composed of quartz, K-feldspar, plagioclase feldspar, microcline, and occasionally biotite and hornblende (Figure 5d).

The microstructural study indicates dynamic recrystallization in the mylonitic granites of the ADSZ (Figure 6a). Dominant processes include sub-grain rotation recrystallization and grain boundary migration. Grain-size reduction and triple junction formation suggest high-temperature recrystallization (Figure 6a). A few kilometres away from ADSZ, the intensity of the dynamic recrystallization decreases, and samples are governed by recovery process, which involves the gradual evolution of sub-grains and deformation bands with undulose extinction (Figure 6b). About 10 km away from ADSZ, the crystals are very coarse in size, nearly strain-free, and display magmatic features suggesting an igneous origin (Figure 6c and d).

Figure 6: Microstructural analysis across ADSZ: (A) high-temperature dynamic recrystallization and grain-size reduction of quartz in ADSZ rocks, (B) gradual evolution of sub-grains and deformation bands with undulose extinction adjacent to ADSZ, (C and D) coarse crystalline, dominated by magmatic texture suggest plastic deformation, away from ADSZ.

Table 1: Whole-rock geochemistry for 26 samples (in wt%)

Sample	Description	SiO ₂	Al ₂ O ₃	FeO	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	MnO	P ₂ O ₅
Locality no.	Rock unit	%	%	%	%	%	%	%	%	%	%	%
St. 32A	Granitic Pluton (Jeddah terrane)	69.7	14.55	2.72	3.02	2.32	0.82	4.18	4.21	0.52	0.05	0.16
St. 33A	Granitic Pluton (Jeddah terrane)	75.7	14.15	0.77	0.86	1.02	0.05	4.13	5.43	0.03	0.01	0.009
St. 40	Granitic Pluton (Jeddah terrane)	77.3	13.15	0.93	1.03	0.54	0.1	3.6	5.63	0.1	0.01	0.01
St. 42B	Granitic Pluton (Jeddah terrane)	56.5	15.75	7.28	8.09	7.03	4.35	3.62	1.55	0.71	0.18	0.27
St. 44 (1)	Granitic Pluton (Jeddah terrane)	59.5	15.5	6.37	7.08	6.41	3.86	3.56	2.28	0.68	0.15	0.26
St. 52	Granitic Pluton (Jeddah terrane)	74.3	13.95	1.69	1.88	1.83	0.39	3.78	4	0.2	0.05	0.12
St. 60C	Meta-Basalt, Amphibolite (Jeddah terrane)	50.5	17.15	8.40	9.33	8.49	6.34	3.59	1.02	0.96	0.15	0.34
St. 62B	Meta-Basalt, Amphibolite (Jeddah terrane)	45.7	16.1	13.05	14.5	8.64	5.63	3.24	0.83	1.81	0.23	0.44
St. 46	ADSZ Rocks	59.5	18.1	4.63	5.15	5.33	1.52	7.01	1.05	0.73	0.12	0.2
St. 47	ADSZ Rocks	70.5	15.55	0.83	0.92	0.57	0.21	3.22	8.01	0.13	0.01	0.02
St. 49	ADSZ Rocks	73.1	14.4	1.44	1.6	0.82	0.32	3.27	4.67	0.24	0.02	0.07
St. 54	ADSZ Rocks	74.2	14.05	1.58	1.76	1.26	0.32	3.98	3.85	0.21	0.02	0.05
St. 50	Granitoid Rock (Asir Terrane)	71.5	14.7	1.82	2.02	1.64	0.51	3.77	4.78	0.33	0.03	0.08
St. 51	Granitoid Rock (Asir Terrane)	71.8	13.5	2.23	2.48	1.56	0.59	3.59	4.09	0.39	0.03	0.1
St. 57	Granitoid Rock (Asir Terrane)	71.8	14.55	1.91	2.12	1.83	0.54	3.63	4.5	0.33	0.03	0.09
St. 65	Granitoid Rock (Asir Terrane)	70.7	15.6	2.56	2.85	2.47	0.85	4.44	3.18	0.47	0.03	0.16
St. 67	Granitoid Rock (Asir Terrane)	72.7	14.45	1.76	1.96	1.6	0.42	3.78	4.64	0.25	0.02	0.07
St. 68	Granitoid Rock (Asir Terrane)	72.4	14.1	2.05	2.28	1.31	0.48	3.69	4.78	0.25	0.05	0.1
St. 60A	Folded silicic dike-AD damm drag fold	76.6	11.9	1.62	1.8	0.22	0.09	4.29	3.93	0.1	0.04	0.01
St. 62A	Folded silicic dike-AD damm drag fold	77.1	12	1.11	1.23	0.82	0.03	4.05	4.13	0.05	0.01	0.009
St. 64A	Folded silicic dike-AD damm drag fold	78.9	11.05	2.18	2.42	1.24	0.37	3.74	3.35	0.18	0.07	0.01
St. 63C	Folded basaltic dike-AD damm drag fold	49.9	14.8	10.89	12.1	5.54	3.78	4.33	2	2.43	0.19	0.45
St. 39	Eocene-Miocene Ad Damm Dikes complex	47.5	16.75	9.58	10.65	11.8	9.24	2.14	0.18	0.7	0.19	0.09
St. 33C	Eocene-Miocene Ad Damm Dikes complex	47.5	13.7	12.15	13.5	9.26	5.07	2.29	0.4	2.66	0.2	0.36
St. 64C	Eocene-Miocene Ad Damm Dikes complex	45	15.5	13.32	14.8	8.74	6.35	3	0.4	2.04	0.23	0.36
St. 69	Southern basalt flow	48.3	17.15	8.58	9.54	9.7	7.06	2.53	0.29	1.14	0.16	0.19

3.4 Whole rock geochemistry

The main purpose of using whole rock geochemistry is to give a proper classification of rock units (using major elements; Table 1) and to determine whether or not the rock samples within the study area are arc-related and, therefore, potentially related to Neoproterozoic in age, or rift-related, and thus, most likely related to the Red Sea rift system during Cenozoic time (Table 2). The radiometric ages available for the rock units of the ADSZ and Jeddah/Asir terranes appears to be Precambrian in age. However, Asir and Jeddah terranes lithological units are distinctively older (e.g. 804 ± 8 to 895 ± 173 Ma; [19]) comparing to those collected from the ADSZ (e.g. 542 ± 23 Ma; [20]).

3.4.1 Major elements

Total Alkaline Silicate (TAS) chart [21] indicates that the granitoid bodies of the Jeddah terrane, Asir terrane, and

ADSZ rocks have similar and high concentration of SiO₂ vs K₂O, and Na₂O (Figure 7). Eocene–Miocene Ad Damm dikes complex is mainly basaltic in composition with SiO₂ concentrations range between 50 and 45 wt% (Figure 7). The K₂O vs SiO₂ classification diagram of an earlier study [21] illustrates that most of the granitic rock units of Asir, Jeddah, ADSZ, and folded silicic dikes of Ad Damm drag folds are characterized as high-*K* calc-alkaline in composition (Figure 8). Several samples of the Jeddah terrane are characterized as medium-*K* calc-alkaline, which reflects the heterogeneous composition of Jeddah terrane. The mafic group, which includes meta-basalt, amphibolite (Jeddah terrane host rock), Eocene–Miocene Ad Damm dikes complex basalt, folded basaltic dikes, plots in the low to medium-*K* calc-alkaline fields. Finally, Harker variation diagrams (Figure 9) show a strong correlation between most of the major elements of the different geologic units versus SiO₂. CaO, MgO, MnO, FeO, Fe₂O₃, TiO₂, and P₂O₅ decrease with increase SiO₂ whereas K₂O and the sum of K₂O and Na₂O increase dramatically with the increase of

Table 2: Average calculation of trace elements for different lithologic units (in ppm)

Rock Unit	Cs	Rb	Ba	Th	U	Nb	Ta	K	La	Ce	Sr	Nd	Zr	Hf	Sm	Eu	Ti	Tb	Dy	Yb	Lu
Granitic Pluton (Jeddah terrane)	0.38	61.92	772.73	3.16	0.89	3.57	0.40	31960.78	19.67	42.42	401.77	21.35	110.83	3.50	4.25	1.07	2218.57	0.44	2.45	1.34	0.20
Meta-Basalt, Amphibolite (Jeddah terrane)	0.27	14.40	179.50	0.37	0.09	1.70	0.10	6890.25	8.70	23.50	599.00	20.30	76.00	2.30	5.82	1.85	10756.11	0.87	5.44	2.95	0.39
Basaltic Dikes (Jeddah terrane)	0.14	8.00	255.00	2.59	0.70	18.10	1.10	3320.60	21.70	48.90	450.00	29.70	210.00	5.40	7.21	2.32	15807.32	1.06	6.35	3.02	0.37
ADSZ Rocks	0.91	96.08	1155.25	8.43	1.54	4.38	0.30	36485.09	32.33	56.18	319.13	26.80	156.50	5.00	4.51	1.13	1946.20	0.46	2.53	1.62	0.25
Granitoid Rock (Asir Terrane)	0.93	106.60	1368.33	10.93	1.49	5.07	0.33	35931.66	35.30	66.00	438.83	24.90	201.83	5.55	3.69	0.79	2000.68	0.28	1.35	0.60	0.09
Folded silicic dike-AD damm drag fold	0.19	56.80	662.67	6.93	2.34	11.93	0.73	31573.37	34.87	91.63	69.30	58.10	324.00	11.90	15.25	1.09	653.69	2.69	16.90	11.53	1.70
Folded basaltic dike-AD damm drag fold	0.18	36.05	440.00	1.34	0.41	10.85	0.70	12535.27	14.15	34.05	607.00	21.80	149.00	4.15	5.39	1.68	10072.71	0.90	5.26	2.91	0.39
Eocene-Miocene Ad Damm Dikes complex	0.18	4.45	152.00	0.22	0.10	2.40	0.15	2407.44	4.90	13.80	298.00	12.25	71.00	2.30	3.62	1.32	8141.36	0.77	5.07	2.98	0.45
Southern basalt flow	0.06	3.60	226.00	0.56	0.21	3.00	0.20	2407.44	6.90	16.40	496.00	11.50	84.00	2.40	3.26	1.20	6774.56	0.55	3.48	1.80	0.30

SiO₂. Such observations indicate a clear fractionation pattern. The percentage of Al₂O₃ remains almost constant with a slight increase during the formation of the basaltic dikes.

3.5 Trace elements

Samples are divided on the basis of their lithological difference and field relation into six main groups as follows: Jeddah terrane, Asir terrane, ADSZ rocks, Eocene–Miocene basaltic dikes, southern basalt flow, and folded Silicic-basaltic dikes (in the Ad Damm drag folds; Table 2). Multi-element diagrams show that all six groups are defined by high abundance of large ionic lithophile elements (LILEs; Cs, Rb, K, Ba, and Sr) compared to the high field strength elements (HFSEs; Th, U, Ce, Ti, Nb, Ta, Zr, and Hf) and heavy rare earth elements (HREEs). However, the Neoproterozoic rocks are characterized by a large negative Nb–Ta anomaly, suggesting an arc origin consistent with that of an earlier study [22] (Figure 10). In contrast, the Cenozoic groups (Ad Damm dike complex and the southern basaltic flow) exhibit significantly reduced negative Nb–Ta anomaly that is consistent with a rift origin (Figure 11). In detail, the spider diagrams suggest that both the Jeddah and Asir terranes, and ADSZ rocks have broadly similar trace element patterns, which suggests that they may have originated in similar tectonic environments. Normalized multi-element diagrams indicate that LILEs are elevated in composition. In contrast, HFSE are depleted. The plutonic and volcanic groups listed above are characterized by an arc-related signature (Figure 10). The rare earth element pattern is defined by sharp slop where the average of light rare earth elements to HREEs (Ce/Yb) n ranging between 2 and 28 and the average of LILE to HFSE ranges between (K/Ta) 15 and 8. The highest LREE/HREE and LILE/HFSE average content belongs to Asir terrane where (Ce/Yb) $n = 28$ and (K/Ta) $n = 20$. Lower trace element ratios and LILE/HFSE values are found in the folded basaltic and silicic dikes and amphibolite of Jeddah terrane where (Ce/Yb) $n = 2$ and (K/Ta) $n = 8$. Overall, the trace element signature in both the Jeddah and Asir terranes is consistent with a volcanic arc, subduction-related origin. In contrast, Eocene–Miocene basaltic dikes and southern basaltic flow are distinguished from the other groups by a significantly reduced Nb–Ta anomaly, which is consistent with a rift-related environment. The rare earth element pattern is defined by the slop between LREE/HREE (Ce/Yb) n ranging between 2.1 and 2.3 and the average of LILE to HFSE fluctuated (K/Ta) between 1.1 and 2.2. LIL elements have a slight enrichment

Figure 7: TAS chart of Jeddah and Asir terrane, ADSZ rocks, folded silicic/basaltic dykes, Eocene–Miocene basaltic-dykes, and southern basaltic flow [21].

content (Cs, Rb, Ba, K, and Sr) relative to the older groups; whereas, HFS elements have relatively less depletion in their content (Nb, Ta, U, Zr, Hf, and Ti).

4 Discussion

Overall, findings presented here (e.g. the recorded shear indicator) support the hypothesis that the ADSZ is solely a Neoproterozoic structure. Current interpretations show essentially a small number of fault displacements and low temperature-brittle deformation features (e.g. fault gouge) are associated with active faulting. However, it is suggested that the ADSZ still influences the modern tectonic of the Red Sea margin via inherited differences in crustal characteristics between the Jeddah and Asir terranes. For example, the seismicity recorded along the Ad Damm area (Figure 1) as well as crustal topographic variation between the Asir and Jeddah terranes imply the area is tectonically active (Figure 12) [4,14,24]. Moreover, rift-related dikes are propagated obliquely with respect to

extensional stress axes of the Red Sea, suggesting pre-existing structure controls the geometry of rift architectures [25]. Furthermore, the Red Sea rift exhibits well-developed linear magnetic anomalies located south of the ADSZ, but north of it, they are not present [17]. On land, the ADSZ bounds a large topographic escarpment perpendicular to the rift margin, with higher elevations to the south (Figure 12). Hence, the interpretive question of how can such conflicting data sets be reconciled [26] represents seismically based estimates of crustal thickness in the Arabian plate. This study was carried out using seismic receiver functions to image and estimate Moho's depth. The study conclude that Jeddah terrane is 30–35 km thick, whereas the Asir terrane is 35–41 km thick, and that this change in thickness occurs at the ADSZ [4,26].

Trace element data has been used in arc systems to estimate crustal thicknesses. The method of Mantle and Collins [27] for estimating arc crustal thicknesses using trace element geochemical data was applied to determine the difference in the crustal thickness between the Asir and Jeddah terranes. The ratio of LREE to HREE increases

Figure 8: SiO_2 vs K_2O classification of Jeddah and Asir terrane, ADSZ rocks, folded silicic/basaltic dykes, Eocene–Miocene basaltic-dykes, and southern basaltic flow [21].

Figure 9: Harker variation diagram of major elements from Jeddah and Asir terrane, ADSZ rocks, folded silicic/basaltic dykes, Eocene–Miocene basaltic-dykes, and southern basaltic flow.

Figure 10: Multi-element diagram of average samples of Jeddah terrane (granitic plutons, silicic and basaltic folded dikes, and amphibolite/meta-basalt), Asir terrane, ADSZ rock. Data normalized to Normal Mid-Ocean Ridge Basalt (N-MORB) [23].

Figure 11: Multi-element diagram of average samples of Eocene–Miocene Ad Damm Dykes complex and southern Basaltic flow. Data normalized to N-MORB [23].

with increasing arc crustal thickness due to the deeper crystallization of minerals such as garnet and hornblende that preferentially absorb HREE [24] calibrated this relationship using the Ce (as LREE) and Y (as HREE) ratio. Therefore, arc Moho depth can be calculated by using this equation:

$$\text{Arc Moho depth (km)} = \ln((\text{Ce/Y})/0.3029)/0.0554.$$

Application of this formula suggests that the Jeddah terrane has thickness of approximately 30 km and the Asir terrane is approximately 8 km thicker, which is well-correlated with seismic data sets from earlier studies [26,28]. The crustal thickness variations and topographic differences suggest greater uplift of the Asir terrane during opening of the Red Sea. Such crustal thickness variations will produce a significant isostatic effect; therefore, the

Figure 12: Elevation profile across Jeddah, Ad Damm shear (ADSZ), and Asir terranes, as indicated by white line. Data derived from Geomap App.

inherited crustal characteristics of the Jeddah and Asir terranes may explain the observed difference in elevation across the ADSZ (Figure 12). Such interpretation is further supported by the observed obliquity of Cenozoic-age dike sets at the ADSZ. The NE-striking basaltic dikes are emplaced along pre-existing structures and parallel to the ADSZ, suggests rift-related structures and dikes inherit geometry from Neoproterozoic ADSZ during the opening of the Red Sea.

5 Conclusions

- 1- Significant differences in lithological characteristics across Jeddah and Asir terranes, and ADSZ observed by satellite image processing and field observations.
- 2- Microstructure analyses indicate a gradual spatial evolution from sub-grains of quartz with undulose extinction (away from ADSZ) to dynamic recrystallization and grain-size reduction, suggesting high-temperature recrystallization along ADSZ.
- 3- Trace element data indicate the Jeddah and Asir terranes and ADSZ rocks have similar arc-related signatures.

In contrast, Eocene–Miocene basaltic dikes and basalt flows are characterized by a rift-related signature that lacks this anomaly.

- 4- Crustal thickness variation between the Asir and Jeddah terranes allow the ADSZ to act as an active crustal boundary and may still influence the neotectonics of the Red Sea.

Acknowledgements: A special thanks of gratitude to King Abdulaziz University for the logistic and financial support. In addition, the authors would like to thank the Saudi Arabian Cultural Mission for all kinds of help during the field works of this study.

Author contributions: Abdulaziz Samkari: lead author, data collection, data processing and interpretation, writing manuscript. David W. Farris: structural and geochemical analyst. Haitham M. Baggazi: recognition field trip, structural data analyst, manuscript reviewing and editing.

Conflict of interest: Authors state no conflict of interest.

References

- [1] Roobol MJ, Kadi KA. Cenozoic faulting in the Rabigh area, central west Saudi Arabia (including the sites of King Abdullah Economic City and King Abdullah University for Science and Technology). Saudi Geol Surv Technical Rep SGS-TR-2008-6. Vol. 1; 2008. p. 250.
- [2] Klinger Y, Rivera L, Haessler H, Maurin J. Active faulting in the Gulf of Aqaba: new knowledge from the Mw 7.3 earthquake of 22 November 1995. Bull Seismological Soc Am. 1999;89(4):1025–36.
- [3] Hamimi Z, El-Sawy E, El-Fakharani A, Matsah M, Shujoon A, El-Shafei M. Neoproterozoic structural evolution of the NE-trending Ad-Damm shear zone, Arabian shield. Saudi Arabia. J Afr Earth Sci. 2014;99:51–63.
- [4] Samkari A. Structural evolution of Ad Damm shear zone, Western Saudi Arabian margin and its relation to Red Sea rift system. Master Thesis. USA: Florida State University; 2015.
- [5] Johnson PR. Explanatory notes to the map of Proterozoic geology of western Saudi Arabia. Saudi Geological Survey Technical Report SGS-TR-2006-4; 2006. p. 62.
- [6] Abdelsalam MG, Stern RJ. Sutures and shear zones in the Arabian-Nubian Shield. J Afr Earth Sci. 1996;23(3):289–310.
- [7] Johnson PR, Woldehaimanot B. Development of the Arabian-Nubian Shield: perspectives on accretion and deformation in the northern East African Orogen and the assembly of Gondwana. Vol. 206. Issue 1. London: Geological Society, Special Publications; 2003. p. 289–325.
- [8] Ali KA, Stern RJ, Manton WI, Kimura J, Whitehouse MJ, Mukherjee SK, et al. Geochemical, U–Pb zircon, and Nd isotope investigations of the Neoproterozoic Ghawjah

- metavolcanic rocks, northwestern Saudi Arabia. *Lithos.* 2010;120(3–4):379–92.
- [9] Stoeser DB, Stacey JS. Evolution, U–Pb geochronology, and isotope geology of the Pan-African Nabitah orogenic belt of the Saudi Arabian Shield. In the Pan-African belt of Northeast Africa and adjacent areas: tectonic evolution and economic aspects of a late proterozoic Oregon. Jiddah, Kingdom of Saudi Arabia: Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources; 1988. p. 227–88.
- [10] Coleman RG. Geological evolution of the Red Sea. Oxford Monographs on Geology and Geophysics. New York: Oxford University Press; 1993. p. 186.
- [11] Bohannon RG, Naeser CW, Schmidt DL, Zimmermann RA. The timing of uplift, volcanism, and rifting peripheral to the Red Sea: a case for passive rifting. *J Geophys Research: Solid Earth.* 1989;94(B2):1683–701.
- [12] Stern RJ, Johnson PR. Constraining the opening of the Red Sea: evidence from the Neoproterozoic margins and Cenozoic magmatism for a volcanic rifted margin. Geological setting, palaeoenvironment and archaeology of the Red Sea. Cham: Springer; 2019. p. 53–79.
- [13] Lazar M, Ben-Avraham Z, Garfunkel Z. The Red Sea—New insights from recent geophysical studies and the connection to the Dead Sea fault. *J Afr Earth Sci.* 2012;68:96–110.
- [14] Al-Saud M. Seismic characteristics and kinematic models of Makkah and central Red Sea regions. *Arab J Geosci.* 2008;1(1):49–61.
- [15] Johnson P. Tectonic map of Saudi Arabia and adjacent areas. Saudi Arabia: Ministry for Mineral Resources; 1997.
- [16] Bosworth W, Huchon P, McClay K. The Red Sea and Gulf of Aden Basins. *J Afr Earth Sci.* 2005;43(1):334–78.
- [17] Stern RJ, Johnson P. Continental lithosphere of the Arabian Plate: a geologic, petrologic, and geophysical synthesis. *Earth-Science Rev.* 2010;101(1–2):29–67.
- [18] Stoeser DB, Frost CD. Nd, Pb, Sr, and O isotopic characterization of Saudi Arabian shield terranes. *Chem Geol.* 2006;226(3–4):163–88.
- [19] Pallister JS. Reconnaissance geologic map of the Harrat Tuffil quadrangle sheet 20/39. Saudi Arabian Deputy Minist. Miner. Resour., Open File Rep., USGS-OF-03-33, scale 1:100,000; 1982.
- [20] Fleck RJ, Hadley DG. Ages and strontium initial ratios of plutonic rocks in a transect of the Arabian Shield. Saudi Arabia: Ministry of Petroleum and Mineral Resources; 1985.
- [21] Le Maitre RW. A classification of igneous rocks and glossary of terms. Recommendations of the international union of geological sciences subcommission on the systematics of igneous rocks. Cambridge University; 1989. p. 193.
- [22] Rollinson HR. Using geochemical data: evaluation, presentation, interpretation. UK: Routledge; 2014.
- [23] Klein EM. Geochemistry of the igneous oceanic crust. *Treatise Geochem.* Vol. 3. Amsterdam: Elsevier; 2014. p. 433–63.
- [24] Fnais M, Al-Amri A, Abdelrahman K, Abdelmonem E, El-Hady S. Seismicity and seismotectonics of jeddah-makkah region. West-Central Saudi Arabia *J Earth Sci.* 2015;26(5):746–54.
- [25] Dixon TH, Stern RJ, Hussein IM. Control of Red Sea rift geometry by Precambrian structures. *Tectonics.* 1987;6(5):551–71.
- [26] Al-Damegh K, Sandvol E, Barazangi M. Crustal structure of the Arabian plate: new constraints from the analysis of teleseismic receiver functions. *Earth Planet Sci Lett.* 2005;231(3–4):177–96.
- [27] Mantle GW, Collins WJ. Quantifying crustal thickness variations in evolving orogens: Correlation between arc basalt composition and Moho depth. *Geology.* 2008;36(1):87–90.
- [28] Al-Amri A, Gharib AA. Lithospheric seismic structure of the eastern region of the Arabian Peninsula. *J Geodynamics.* 2000;29(1–2):125–39.