Spatio-temporal position of the Ediacaran Thalbah Basin in the Najd Fault System, Arabian Shield

Moujahed Al-Husseini

ABSTRACT

This paper starts with a bibliographic review of the lithostratigraphy and radiometric dating of the Ediacaran Thalbah Group in the northwestern Arabian Shield, Saudi Arabia. It seeks to establish the spatio-temporal position of the group in the ongoing compilation and correlation of Ediacaran–Cambrian sedimentary time-rock units in the Middle East Geologic Time Scale (Al-Husseini, 2010, 2011, 2014). The group is defined and described in the Thalbah Basin, which crops out in the Al Wajh Quadrangle, and is approximately 100 km (NW-SE) by 40 km (SW-NE) in extent (Davies, 1985). The basin is situated within the approximately (ca.) 300 km-long, NW-trending Qazaz Fault Zone of the Najd Fault System.

The Thalbah Group consists of three siliciclastic units: Hashim Formation (ca. 1,050–1,300 m thick) and likely coeval Zhufar Formation (ca. 600–1,400 m thick), and the younger Ridam Formation (ca. 1,000 m thick). Recently published U-Pb dating of detrital zircons gave ages of ≤ 596 ± 10 Ma for the Hashim Formation, and ≤ 612 ± 7 Ma for the Zhufar Formation (Bezenjani et al., 2014). The maximum depositional ages of the Hashim and Zhufar formations indicate they are approximately coeval to the lower part of the sedimentary and volcanic rocks of the Jibalah Group (≤ 605 ± 5 and ≥ 525 ± 5 Ma). The latter group was deposited in pull-apart basins along the ca. 600 km-long Rika and several other extensive fault zones of the NW-trending Najd Fault System in the northern and eastern parts of the Arabian Shield.

The Qazaz Fault Zone left-laterally dislocated ophiolites of the NE-trending Yanbu Suture Zone (≥ 700 Ma) by about 100 km. The strike of the Qazaz Fault Zone projects into the Rika Fault Zone, along which five major pull-apart basins contain the Jibalah Group. The Rika Fault Zone dislocated by about 100 km the NS-trending ophiolite outcrop belts of the Ad Dafinah and Hulayfah fault zones (sometimes interpreted as parts the Nabitah Suture Zone, 680–640 Ma). Based on the time correlation of the Thalbah and Jibalah groups, and the highlighted structural features, the Rika and Qazaz fault zones are interpreted as a continuous 30 km-wide, 1,200 km-long, N63°W-striking fault zone, the “Rika-Qazaz Fault Zone”, which left-laterally dislocated the Arabian Shield by approximately 100 km after 605 ± 5 Ma and before 525 ± 5 Ma.

INTRODUCTION

Understanding the geologic evolution of the Middle East during the Ediacaran Period (635–541 Ma, Knoll et al., 2006) continues to be a challenge with important implications for the academic and industrial geosciences in and beyond the region. It was the time in Afro-Arabia when accretionary and collisional plate-tectonic events switched at approximately (ca.) 630–605 Ma to an intracontinental extensional and sinistral (left-lateral) shear phase that may have lasted until 525 ± 5 Ma in the early Cambrian. During the later phase (ca. 605 to possibly 525 Ma) siliciclastics, carbonates, evaporites, and volcanic rocks, altogether several kilometers thick, were deposited in numerous extensional basins as well as the pull-apart basins along the Najd Fault System (also known as the...
“Najd Shear Zone”; Figures 1 and 2; Al-Husseini, 2000, 2011, 2014). Farther east, Ediacaran–lower Cambrian marine sedimentary rocks constitute the oldest-known petroleum system of the Middle East, the Huqf Supergroup of Oman (Al-Siyabi, 2005; > 635 to 525 ± 5 Ma, Forbes et al., 2010, and references therein).

The rock units that were deposited along the Najd Fault System are known as the Jibalah Group. They crop out in several isolated, pull-apart basins mainly along the Rika and Halaban fault zones, and are reliably dated in just a few localities (Figure 2, Table 1; e.g. Vickers-Rich et al., 2010; Kennedy et al., 2010, 2011a, b; Johnson and Kattan, 2012; Johnson et al., 2013; Nettle et al., 2014). Therefore maintaining an up-to-date compilation and synthesis of this limited chronostratigraphic dataset is an important task that is being presented in the Ediacaran–Cambrian Middle East Geologic
Figure 2: Map of the Arabian Shield showing outcrops of the Jibalah and Thalbah groups, Yanbu and Ad Dafinah–Hulayfah sutures, and Najd Fault System (NFS, after Delfour, 1977; Hadley, 1974; Brown et al., 1989; Al-Husseini, 2000, 2014).
# Table 1

**Dating of Rock Units in NW Arabian Shield**

Age in million years before present (Ma) and rounded to integer

<table>
<thead>
<tr>
<th>Unit or Complex</th>
<th>Rock Type (Sample)</th>
<th>Age</th>
<th>Method</th>
<th>Reference</th>
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<td><strong>Metamorphic Group</strong></td>
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<tr>
<td>Zaam Group</td>
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<td>705 ± 4</td>
<td>U-Pb SHRIMP</td>
<td>Kennedy et al. (2011a)</td>
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<td>Zaam Group</td>
<td>gritstone (SA09-21)</td>
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<td>U-Pb detrital zircons</td>
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<td>Bayda Group</td>
<td>volcanicleastic (BY-2)</td>
<td>700–660</td>
<td>U-Pb SHRIMP</td>
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<td>Abu Suar Complex</td>
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<td>626 ± 4</td>
<td>U-Pb SHRIMP</td>
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<td>Ash Shab Complex</td>
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<td>U-Pb SHRIMP</td>
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<td>Baladiyah Complex</td>
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<td>Hedge (1984)</td>
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<td>Buwaydah Complex</td>
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<td>Dabbagh Complex</td>
<td>granite</td>
<td>777 ± 4</td>
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<td>Habd Complex</td>
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<td>Imdan Complex</td>
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<td>660 ± 4</td>
<td>U-Pb TIMS</td>
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<td>Imdan Complex</td>
<td>granodiorite (FK 26/1)</td>
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<td>Sadr Complex</td>
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<td>K-Ar</td>
<td>Gettings and Stoeser (1981)</td>
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### Table 1 (continued)

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<td>Ajjaj Shear Zone</td>
<td>weakly foliated granite (AJ-2)</td>
<td>≤ 575.1 ± 9.6</td>
<td>U-Pb SHRIMP</td>
<td>Kennedy et al. (2011a)</td>
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<td>Ajjaj Shear Zone</td>
<td>lamprophyric dike (AJ-1)</td>
<td>≤ 573.1 ± 5.2</td>
<td>U-Pb SHRIMP</td>
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<td>Burj Formation</td>
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<td>509</td>
<td>Biostratigraphy</td>
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<td>Dhaiqa Formation</td>
<td>carbonate</td>
<td>≤ 560 ± 4</td>
<td>U-Pb detrital zircon</td>
<td>Vickers-Rich et al. (2010)</td>
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<td>Hashim Formation</td>
<td>siliciclastics</td>
<td>≤ 596 ± 10</td>
<td>U-Pb detrital zircon</td>
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<td>≤ 609 and ≥ 560</td>
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<td>Muwaylih Dike Swarm</td>
<td>quartz syenite</td>
<td>575 ± 5</td>
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<td>Siq Sandstone Formation</td>
<td>siliciclastics</td>
<td>≤ 525 ± 5 and ≥ 509</td>
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</tr>
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<td>Sub-Jibalah Unconformity</td>
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<td>605 ± 5</td>
<td>Rb/Sr</td>
<td>Al-Husseini (2014)</td>
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<tr>
<td>Sub-Siq Unconformity</td>
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<td>525 ± 5</td>
<td>Rb/Sr</td>
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<td>Estimate</td>
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<td>Thalbah Group</td>
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<td>605–?575</td>
<td>Estimate</td>
<td>This Study</td>
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<td>Wadi Thalbah Andesite Dike</td>
<td>andesite</td>
<td>618 ± 4</td>
<td>U-Pb SHRIMP</td>
<td>Kennedy et al. (2011b)</td>
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<td>Zhufar Formation</td>
<td>siliciclastics</td>
<td>≤ 612 ± 7</td>
<td>U-Pb detrital zircon</td>
<td>Bezenjani et al. (2014)</td>
</tr>
</tbody>
</table>

**Time Scale** (Al-Husseini, 2010, 2011, 2014). The Thalbah Group, which is reviewed in this paper, adds an important data point that clarifies several regional tectono-stratigraphic aspects of the Najd Fault System, and in particular the relationship between the Qazaz and Rika fault zones of the system (Figure 2). It also provides another keystone for attempting correlations with similar sequences across Saudi Arabia, eastern Egypt and Jordan (Powell et al., 2014, 2015).

The bibliographic review of the group’s lithostratigraphy is mainly based on the published map and accompanying explanatory notes of the Al Wajh Quadrangle by Davies (1985, Figures 1 to 5), who cites various reports and maps by authors from Saudi Arabia’s Director General Mineral Resources (DGMR), Saudi Arabia’s Deputy Ministry for Mineral Resources (DMMR), and France’s geologic survey, the Bureau de Recherches Géologiques et Minières (BRGM). The present review highlights significant contradictions between the original mapping of the formations of the Thalbah Group by these sources, and subsequent publications (e.g. Johnson and Kattan, 2012; Johnson et al., 2013). Accordingly, the original maps and descriptions are reproduced here for the benefit of those readers that do not have access to them. Another key development for this compilation is the extensive collection of new U-Pb zircon ages for the Thalbah and other Ediacaran rock units.

The present paper also documents and reinterprets the radiometric dating of time-rock units in Al Wajh and nearby quadrangles that constrain the age of the Thalbah Group as probably younger than 605 ± 5 Ma (Hedge, 1984; Kennedy et al., 2010, 2011a, b; Johnson and Kattan, 2012; Bezenjani et al., 2014), and to therefore be coeval with the lower part of the Jibalah Group (≤ 605 ± 5 and ≥ 525 ± 5 Ma, Al-Husseini, 2014). This interpretation differs significantly from other estimates for the depositional age of the Thalbah Group between 660 and 634–621 Ma (Hedge, 1984; Johnson et al., 2011; Johnson and Kattan, 2012), or 620–595 Ma (Johnson et al., 2013). The correlation of the Thalbah and Jibalah groups provides evidence for interpreting the Rika and Qazaz fault zones of the Najd Fault System as a continuous 30 km-wide, 1,200 km-long, N63°W-striking fault zone, the “Rika-Qazaz Fault Zone” (RQFZ), which left-laterally dislocated the Arabian Shield by about 100 km after 605 ± 5 and before 525 ± 5 Ma (Figure 2). Most geoscientists familiar with the region think that tectonic movements were completed by about 570–560 Ma (P.R. Johnson and R.J. Stern, written communications, 2014).
Davies (1985) and Davies and Grainger (1985) attribute the definition of the Thalbah Group to Frets (1977), who named it after Wadi Thalbah (Wadi Thalibah) in the 1:100,000-scale geologic map of the Wadi Thalbah Quadrangle, and its revised definition to Davies (1981a) at the same locality. Davies (1983) compiled available geologic reports, including the two 1:100,000-scale reconnaissance geologic maps by BRGM (Alabouvette and Khateib, 1979; Alabouvette and Pellaton, 1979), three 1:100,000-scale geologic maps prepared by DGMR (Davies, 1981a; Davies et al., 1981; Frets et al., 1981), and structural geologic investigations of the Precambrian rocks between 26°N and 28°N (Davies, 1981b, 1982). He used this compilation as the basis for publishing in 1985 the 1:250,000-scale geologic map of the Al Wajh Quadrangle (26°N to 27°N, and Red Sea coast near 36°E to 37°30'E). The present paper is mainly based on the explanatory notes and map of the Al Wajh Quadrangle (Davies, 1985; Figures 1–5), and adjoining quadrangles (Figures 1, 2 and 7 to 9).

Figure 3: Simplified geological map of the Al Wajh Quadrangle (reproduced from the 1:1,000,000-scale Structural Sketch Map relating to the 1:250,000-scale map of the Al Wajh Quadrangle, Davies, 1985). Dating of rock units are from Hedge (1984), Kennedy et al. (2010, 2011a, b, MT-39, 40 and 43) and Bezenjani et al. (2014). The map has been modified to show the outcrop of the interpreted Jibalah Group ("j"), which crops out southeast of the Warid Complex in the northwestern part of the quadrangle. P1 to P4 are thermobarometric samples collected from the Qazaz Dome (Meyer et al., 2014), which together with the Qazaz Complex are referred to as the "Greater Qazaz Complex" in this paper. The fault shown as heavy red line that crosses the map diagonally is traced from figure 5 of Davies (1985). It is here interpreted as the main fault of the Rika-Qazaz Fault Zone (RQFZ).
Figure 4: Geological map of the Thalbah Basin showing the outcrops of the Hashim ("th"), Zhufar ("td") and Ridam ("tr") formations of the Thalbah Group, and the swarm of dikes cutting (red lines with dots) the Thalbah Group in the northwestern part of the basin (reproduced from 1:250,000 geologic map of Al Wajh Quadrangle, Davies, 1985; see Figures 1 to 3 for location). Cross-section AA' is shown in Figure 5.

Figure 5: NE-SW cross-section of Thalbah Basin (see Figure 4 for location), reproduced from the structural section AA' published in the 1:250,000 Al Wajh Quadrangle (Davies, 1985). The Zhufar Formation ("td") of the Thalbah Group overlies the volcaniclastic Zaam Group ("zk" and "zn"). In the eastern part of the Thalbah Basin the Zhufar Formation is overlain by the Ridam Formation ("tr") over a distance of ca. 7 km. The unit "gm" to the northeast is an unassigned monzogranite pluton. Its age and the nature of its boundary with the Thalbah Group are not known.
Type Locality of the Thalbah Group

The group is defined in Wadi Thalbah, where a detailed section is exposed in the upper part of the wadi (Davies, 1985; Figure 4). The Thalbah Basin is incorrectly named as the “Jabal Liban Basin”, and briefly described in Kusky and Matsah (2003, number 1 in their figure 3). It is shown in the map of the Arabian Shield of Brown et al. (1989), but labeled with the letters “mh” for the Hadiyah Group.

Boundaries of the Thalbah Group

The Thalbah Group unconformably overlies the metasediments and metavolcanics of the Zaam and Bayda groups (Davies, 1985); the lower boundary is here referred to as the “Sub-Thalbah Unconformity”. To the north the Thalbah Group is in fault contact with the Cretaceous Azlam Formation sedimentary rocks in Wadi Azlam (Wadi az Zalm, Figure 4). The Azlam Basin is approximately 80 km long (NW-SE) and 8–15 km wide (NE-SW). Based on a geophysical survey and shallow drill holes it contains a maximum of about 2,000 m of Cretaceous and Cenozoic sedimentary rocks (Arabian Geophysical and Surveying Company, 1976).

Sub-Divisions of the Thalbah Group

Davies (1985) divided the Thalbah Group into the Hashim (“th”), Ridam (“tr”) and Zhufar (“td”) formations (Figure 4), and listed them in this consecutive order in the explanatory notes and its table of contents, and in the legend of the geologic map of the Al Wajh Quadrangle. In the explanatory notes, he reported that the Ridam Formation disconformably to unconformably overlies the Hashim Formation. In the structural section AA’, which crosses the quadrangle diagonally (Figures 4 and 5), he showed the Ridam Formation (“tr”) overlying the Zhufar Formation (“td’”). The Hashim (“th”) and Zhufar (“td”) formations are not in contact anywhere at outcrop in the Thalbah Basin (Figure 4), and their stratigraphic relationship is not explicitly discussed by Davies (1985).

The stratigraphic positions of the Hashim and Zhufar formations on the Sub-Thalbah Unconformity and below the Ridam Formation suggests the former pair may be lateral equivalents and approximately coeval (Figure 6). Several authors, however, report that the Hashim, Ridam and Zhufar formations occur in ascending stratigraphic order and are separated by unconformities (Genna et al., 2002; Johnson et al., 2013; Bezenjani et al., 2014). This apparent misunderstanding may be due to their adopting the order of presentation given by Davies (1985), which is not chronostratigraphic with regards to the Hashim and Zhufar formations.

Upon seeking clarification regarding discrepancies in the stratigraphic order of the formations, P.R. Johnson wrote back to the present author in March 2014: “there are many facies variations in the Thalbah Basin and the present-named formations do not do justice to the complexity of deposition in an active sedimentary basin.” R.N. Bezenjani added in May 2014 that he believes the maps are not reliable and they should be revised with further fieldwork. Neither P.R. Johnson nor R.N. Bezenjani had the opportunity to do fieldwork so as to revise the map of Davies (1985). Based on the extensive mapping and fieldwork done by the geological surveys (see “Authors” above), the present paper adopts the stratigraphic order in Figure 6, as interpreted from the map and cross-section of Davies (1985).

Hashim Formation, Thalbah Group

Author: Davies (1985).

Nomenclature and Type Locality (Davies, 1985): The Hashim Formation is named after Wadi Hashim, a tributary of Wadi Thalbah (Figure 4), where a detailed section of about 1,800 m is exposed in the NW corner of the Al Wajh Quadrangle. The formation crops out about 5 km north of Wadi Thalbah and east of Khawr Dukhan Plateau. The outcrop occurs in a highly faulted area.
Lithology and Thickness (Davies, 1985): The formation consists of conglomerate, overlain by well-bedded purple and green litharenite and siltstone. It starts with a basal polymict conglomerate that is from 50 to 300 m thick and comprises clast-supported, subrounded pebbles and cobbles (5–10 cm in diameter) of sandstone, andesite, rhyolite, quartz diorite and granodiorite, in a purple siltstone matrix. A few purple siltstone beds, 5–20 cm thick, are intercalated with the conglomerate. The conglomerate is overlain by a 1,000 m-thick unit comprising well-bedded brown and purple litharenite, subordinate siltstone, and intra-formational conglomerate.

Boundaries (Davies, 1985): The Hashim Formation lies with a distinct angular unconformity on folded sedimentary rocks of the Umm Ashsh Formation volcanoclastics and Nuwaybah Formation sedimentary rocks of the Zaam Group. To the east and south, the Hashim Formation is disconformably to unconformably over-stepped by conglomerates of the Ridam Formation. R.N. Bezenjani (written communication, 2014) adds that satellite images show the Hashim Formation as mapped by Davies (1985), is limited by fault zones both in the east and south.
Zhufar Formation, Thalbah Group

Author: Davies (1985).

Nomenclature and Type Locality (Davies, 1985): The Zhufar Formation is named after Jabal Zhufar (Jabal Zufr, Figure 4). Rocks of this formation are exposed in the cores of a major syncline and anticline, extending in a northerly direction about 100 km across the west center of the Al Wajh Quadrangle.

Lithology and Thickness (Davies, 1985): The lower part of the formation consists of well-bedded litharenite and pebble conglomerate; siltstone becomes dominant toward the top. The thickness of the formation increases eastward from 600 m around Wadi Thalbah to as much as 1,400 m in the area north of Jabal Liban (Figures 3 and 4), where it consists dominantly of thinly bedded shale and minor litharenite and conglomerate beds. The formation thins eastward from the Jabal Liban area. To the south, beds of litharenite containing abundant angular clasts of rhyolite, 1–5 mm in diameter, become common.

Boundaries: In cross-section AA’, which traverses the Al Wajh Quadrangle, Davies (1985) shows the Ridam Formation (“tr”) overlying the Zhufar Formation (“td”; Figures 4 and 5). In the 1:250,000 map of the quadrangle, along traverse AA’, the Zhufar Formation overlies the Zaam Group in the west, strikes NW and dips to the east where it passes below the Ridam Formation (Figure 4).

Ridam Formation, Thalbah Group

Author: Davies (1985).

Type Locality (Davies, 1985): The Ridam Formation is named after Wadi ar Ridam (Figure 4). It is exposed south of the junction of Wadi as Sirr and Wadi Thalbah over a 10 km-wide, N-striking belt, and also in the central part of the Al Wajh Quadrangle (Figure 4).

Lithology and Thickness (Davies, 1985): The Ridam Formation is as much as 1,000 m thick in the center of the Al Wajh Quadrangle, but thins to the northwest, toward Wadi Thalbah. In the northern part of the quadrangle the lower 200 m of the formation consists of poorly sorted, crudely bedded pebble conglomerate, with sporadic large granitic boulders as much as 2 m across. The pebbles and boulders are generally subrounded, but the smaller pebbles are more angular. More than half of the fragments consist of granite, granodiorite, and diorite. Clasts of gray granodiorite and red granite are predominant and probably were derived from local Liban and Kara Dakha complexes (Figures 3 and 4). Other pebbles are rhyolite porphyry, andesite, sandstone, and quartz. The matrix of the conglomerate consists of sand-sized feldspar and quartz crystal fragments and grains of volcanic rock. Stratigraphically higher conglomerates within the formation have clasts with diameters of 1–15 cm and are interbedded with pebbly sandstone and shale. Cobbles and boulders of granite are common in the higher units and occur over the whole area of exposure.

Boundaries (Davies, 1985): North of Wadi Thalbah the basal conglomerate of the Ridam Formation overlies disconformably to unconformably the Hashim Formation. To the south the conglomerate overlies rocks of the igneous and metamorphic rocks of the Bayda Group. In cross-section AA’, which traverses the Al Wajh Quadrangle, Davies (1985) shows the Ridam Formation overlying the Zhufar Formation (Figures 4 and 5).

Structural and Depositional Setting

The Thalbah Basin is situated in a major NW-trending sinistral shear system, the Najd Fault System, which formed as the Arabian-Nubian Shield began to stabilize in Ediacaran time (Stern, 1985; Figure 2). The system has many strands with many different names; the Thalbah Basin is situated in a broad region of NW-trending faults originally referred to as the “Ajaj Shear Zone” by Davies (1985). He used this term as follows: “NW-trending belt of distinctively styled shearing and has a consistent sinistral [left-lateral] sense of displacement. The southern boundary of the
zone is situated south of the Al Wajh Quadrangle, and its northern boundary, 90–100 km away, is
the wrench fault running between the Ash Shab Complex and the Warid Complex” (Figure 3). In
subsequent publications by the Saudi Geological Survey (e.g. Kennedy et al. 2010, 2011a, b; Johnson
and Kattan, 2012) the term “Ajaj Shear Zone” is given to the approximately 10 km wide, E-W fault
zone passing south of the Baladiyah and Imdan complexes (Figure 3).

In this paper the term “Qazaz Fault Zone” is used to name the corridor that passes through the
Thalbah and Azlam basins, and farther southeast through the dislocation of the outcropping
ophiolites of the Yanbu Suture Zone (Figure 2). This zone has also been referred to as “Abu
Masaraib Zone”, “Al Muwayilih Shear Zone” and “Duba Zone” (Sultan et al., 1998, 1993). In the
region where the Yanbu Suture is dislocated by the Qazaz Fault Zone, Johnson and Kattan (2012,
their figure 6-3) name three distinct NW-trending shear zones (here referred to as faults); from
southwest to northeast: (1) Dhawrah Fault; (2) Durr Fault, and (3) Da’ban Fault. The Durr and
Da’ban faults correspond to the NE and SW edges of the linear corridor depicted as the “Rika-
Qazaz Fault Zone” (RQFZ) in Figure 2.

The Thalbah Group was deposited in a continental setting and its outcrop has a shape consisting
of distinct NS and NW trends and an areal extent of about 100 km (NW-SE) by 40 km (SW-NE)
(Figures 3 and 4). The NW trend is parallel to the Qazaz Fault Zone. The NS-trending outcrops
extend beyond the confines of the Rika-Qazaz Fault Zone (Figure 2) and are parallel to the Dead
Sea Transform Fault, which may have been a failed rift basin during the Ediacaran (Al-Husseini,
2000). The structural significance of the NS trends remains to be determined.

The Thalbah Basin is the largest Neoproterozoic sedimentary basin in the Qazaz Fault Zone. The
structural setting of the basin and surrounding region was discussed by Davies (1985), Genna et
al. (2002), Johnson et al. (2013) and Meyer et al. (2014). The sediments of the Thalbah Group are
moderately folded with a NS-axis with beds dipping between 10° and 70° and, in places, are
overturned near the northwestern side of the basin (Figure 4; Davies, 1985). According to Johnson et
al. (2013) the rocks are barely metamorphosed except in the northeast adjacent to the Qazaz Dome
(Figure 3), where clasts are stretched and the rocks are metamorphosed to paragneiss.

South of Wadi Thalbah, a swarm of NE-trending dikes that is at least 25 km long (NW-SE) and
13 km wide (NE-SW) intrudes rocks of the Zaam and Thalbah groups (Davies, 1985; Figure 4).
The dikes are sub-vertical, 50–100 m apart, and occupy up to 50 percent by volume of the exposed
rocks; individual dikes are as much as 10 km long. The dikes do not intrude the Cretaceous
Azlam Formation. Margin irregularities and dike-offsets indicate sinistral displacements across
the margins of many dikes. About 75 percent of the dikes consist of andesite porphyry with large
oligoclase phenocrysts about 1 cm long. The remaining 25 percent are composed of pale-gray
porphyritic microgranite and cut the andesite porphyry dikes. No other volcanic rocks have been
identified in the Thalbah Basin (Figure 4).

Greater Qazaz Complex

The Qazaz Gneiss Complex is situated to the northeast of the Azlam Graben and continues
on-trend to the southeast into the “Qazaz Dome” (named “Jarash Antiform” in Johnson and
Kattan, 2012), a triangular-shaped anticline that was mapped as an unassigned gneissic granite
and granodiorite complex (“um” in Figure 3 and “gg” in Figure 4) by Davies et al. (1985). The
two features are here referred to as the “Greater Qazaz Complex” (Figure 3). Meyer et al. (2014)
presented a new interpretation whereby the Greater Qazaz Complex is attributed to EW-directed
compression and NW-directed transpressional sinistral shearing. They consider the structural
development of this feature to be coeval to the deposition of the Thalbah Group, which based on the
literature, they suggest may be ca. 630–580 Ma (see “Age of Greater Qazaz Complex” below).

Meyer et al. (2014) collected four samples and analyzed them using mineral exchange
thermobarometers to calculate peak metamorphic conditions and maximum depths of burial
(Figure 3, Table 2). They indicate that amphibolite-facies rocks dominate the core of the Qazaz
Dome (Sample P1); its periphery is amphibolite overprinted to greenschist (P2), and sheared rocks
that bound the southwestern edge of the dome are schists (P3). The depth of burial and subsequent exhumation for these three samples varies from 15.5 to 28 km (Table 2). Sample P4 was taken from the base of the Thalbah Group (Zhufar Formation) at a distance of ca. 120 m from Sample P3, and indicates greenschist metamorphic facies and a burial depth of 1.5–3.5 km. Meyer et al. (2014) in their figure 3a show the Thalbah Group sediments to the southwest of the Azlam Basin are not metamorphosed. They conclude that the local metamorphic gradient is telescoped with significant uplift of the Qazaz Dome with respect to the Thalbah Group due to movement on the shear zones.

The evolution of the Greater Qazaz Complex, and other gneiss complexes such as the Baladiyah Complex (Figure 3), with respect to the pull-apart basins along the Najd Fault System remains unclear for several reasons. Firstly, the Jibalah Group sedimentary rocks in the Najd pull-apart basins are folded but not metamorphosed. Secondly, the metamorphism of the gneiss domes and sediments deposited in the Najd pull-apart basins are not proven to be coeval (see “Age of Greater Qazaz Complex” below). Thirdly, the present author finds it difficult to reconcile the abrupt change in just 120 m from the calculated depth of 15.5–17.5 km for the schist in the SW shear zone of the Qazaz Dome (P3), to just 1.5–3.5 km in the Thalbah Group sediments (P4). The depth of burial for the basal Thalbah sediments is essentially the thickness of the group. However, R.J. Stern (written communication, 2014) believes that this may be possible in a region of active tectonics. Fourthly, the study by Meyer et al. (2014) does not discuss the relationship between the unmetamorphosed Thalbah Group sediments that crop out to the southwest of the Azlam Basin.

AGE OF THE THALBAH GROUP

The age of the Thalbah Group was first estimated by Hedge (1984) who concluded that it was deposited after 660 Ma and prior to 625 Ma. He arrived at this conclusion because the group overlies the igneous Imdan Complex dated 660 ± 4 Ma (Hedge, 1984), and its supposedly correlative volcano-sedimentary “Thalbah group” situated further north in Al Muwaylih Quadrangle, is intruded by the igneous Shar Complex dated 625 ± 5 Ma (Hedge, 1984; Table 1, Figures 6 and 7). Based on age assignations interpreted in the present paper, the “Thalbah group” situated north of and outside of the Thalbah Basin is believed to be much older and to differ from the sedimentary Thalbah Group in the Thalbah Basin. Accordingly, it is distinguished with quotation marks as the “Thalbah group” (see further explanation below).

The depositional age of the Thalbah Group was modified to 660–635 Ma in several subsequent publications implying it is exclusively Cryogenian (e.g. Johnson and Kattan, 2012). It was revised to 620–595 Ma in the Ediacaran Period (Johnson et al., 2013) when an andesite dike that supposedly intrudes the Thalbah Group was dated 617.7 ± 4.4 Ma (Kennedy et al., 2011b; see “Wadi Thalbah Andesite Dike” below), and detrital zircons from the Hashim and Zhufar formations gave maximum depositional ages of ≤ 596 ± 10 Ma and ≤ 612 ± 7 Ma, respectively (Bezenjani et al., 2014). The most recent interpretation of the group’s depositional age is between 635 Ma to younger than 596 Ma; the older limit of 635 Ma is based on assuming the igneous Liban Complex, as dated by Hedge (1984), intrudes the Thalbah Group (R.N. Bezenjani, written communication, 2014). The contact relationship between the Liban Complex and Thalbah Group, however, remains to be established in the field. In this section the database upon which these various and in many cases contradictory age estimates are based is reviewed and re-interpreted (Figure 6, Table 1).
Age of the Hashim Formation: \( \leq 596 \pm 10 \text{ Ma} \)

Sample MT-132 (26°51.518’N, 36°16.185’E; Bezenjani et al., 2014) was collected from the outcrop belt of the Hashim Formation according to the geological map of Davies (1985; Figure 4). According to Bezenjani et al. (2014) these sediments are barely deformed despite being close to the Najd Fault System, and consist of fine-grained, laminated, reddish-brown sandstone with well-preserved ripple marks. A total of 125 zircon grains were handpicked and of these 74 were analyzed; after data processing 54 were included in the final synthesis. A maximum depositional age for the sample, defined by the youngest grain present, is 596 ± 10 Ma (Table 1 and Figure 6). The sample has numerous peaks from approximately 595–1,067 Ma, with notable clusters at approximately 700, 728, 815, 852, 926, and 978 Ma. Five grains yield pre-Neoproterozoic \( ^{207}\text{Pb}/^{206}\text{Pb} \) ages of 1,814 ± 12, 1,740 ± 10, 1,264 ± 7, 1,068 ± 6 and 1,040 ± 6 Ma.

Age of the Zhufar Formation: \( \leq 612 \pm 7 \text{ Ma} \)

Sample SA09-11 (26°25.143’N, 36°37.208’E; Bezenjani et al., 2014) is fine- to medium-grained, red and brown laminated sandstone and represents the lower part of the Zhufar Formation (Figure 4). A suite of 125 zircon grains was handpicked and of these 60 were analyzed; after data processing 37 were included in the final synthesis. The analytical results indicate a maximum depositional age for the sample, defined by the youngest concordant grain present, is 612 ± 7 Ma (Table 1 and Figure 6). The sample is dominated by a peak at approximately 695 Ma, but also contains smaller clusters at approximately 713 and 733 Ma. Four grains yield pre-Neoproterozoic \( ^{207}\text{Pb}/^{206}\text{Pb} \) ages of 2,480 ± 17, 2,396 ± 15, 2,081 ± 14 and 1,025 ± 5 Ma.

Age of Wadi Thalbah Andesite Dike: 617.7 ± 4 Ma

Kennedy et al. (2011b) obtained Sample SA-64 (26°46’54.5”N, 36°16’17.6”E) from an andesite dike in Wadi Thalbah. Johnson et al. (2013, their figure 19) depicted the stratigraphic position of the dike at approximately 450 m above the base of the Hashim Formation of the Thalbah Group. R.N. Bezenjani (written communication, 2014), however, reported that the andesite dike cuts the Zaam Group, but not the Hashim Formation. He added that Sample SA-64 was taken from the Zaam Group at a location that is at least 800 m to the west of the well-recognized Zaam/Thalbah boundary.

Kennedy et al. (2011b) recovered 22 zircon grains from Sample SA-64, and of these, the results of 18 \( ^{206}\text{Pb}/^{238}\text{U} \) SHRIMP analyses were used to establish its age distribution between 559 and 720 Ma. The youngest date is based on just one zircon grain dated 559 ± 18 Ma. It has a high uranium content (1,732 ppm) and the date is discordant (+18%) leading R.N. Bezenjani (written communication, 2014) to conclude it is an unreliable age for the dike. Kennedy et al. (2011b) chose the next-oldest five zircon grains from Sample SA-64 with dates that cluster between 612 and 622 Ma to estimate its age as 617.7 ± 4 Ma, and concluded this to be the minimum (youngest) age for the Thalbah Group.

If the dike does not cut the Hashim Formation, as explained by R.N. Bezenjani (written communication, 2014), then the age of 617.7 ± 4 Ma does not represent the Hashim Formation. Instead it implies that the base of the Hashim Formation is younger than about 618 Ma, which would bracket the Sub-Thalbah Unconformity between approximately 618 and 596 Ma.

Age of the Zaaam Group: 763 ± 25 to 660 ± 4 Ma

The Hashim and Zhufar formations of the Thalbah Group overlie the Zaaam Group (Davies, 1985), which according to Hedge (1984) is the oldest group in the Al Wajh and Al Muwaylih quadrangles (Figures 1, 3 to 7, Table 1). The maximum known age of the group was obtained by Ali et al. (2010) who reported a weighted mean \( ^{206}\text{Pb}/^{238}\text{U} \) age of 763 ± 25 Ma zircon age for Zaaam metavolcanic rocks in Wadi Sawawin (27°50’N, 35°50’E) to the north of the Thalbah Basin. These metavolcanics are intruded by a diorite, which gave a U-Pb zircon age of 661.5 ± 2.3 Ma (Ali et al., 2010).
Al-Husseini

The Zaam Group is intruded by several igneous complexes that are dated by Hedge (1984) between 725 ± 4 Ma and 660 ± 4 Ma (Table 1, Figures 3, 6 and 7). The minimum age of the Zaam Group is based on dating of the youngest intrusive Imdan Complex: U-Pb TIMS zircon crystallization age of 660 ± 4 Ma (Hedge, 1984) and U-Pb zircon SHRIMP age of 676 ± 6 Ma (Kennedy et al., 2011a; Table 1, Figures 3 and 6).

Additional dating of the Zaam Group gave ages of approximately 705–700 Ma. Kennedy et al. (2011a) dated Sample FK 26/4-48 (26°07'55.8"N, 36°59'10.5"E) at 705 ± 4 Ma from an interstratified orthogneiss within the Zaam Group. Bezenjani et al. (2014) collected Sample SA09-21 (26°46.987'N, 36°16.776'E) from the volcaniclastics of the Umm Ashsh Formation of the Zaam Group (Figures 3 and 4). The detrital zircons were collected from a highly oxidized, coarse-grained siliceous sandstone (gritstone) from just below the red-oxidized unconformity between the Zaam Group and the Hashim Formation of the Thalbah Group. Sample SA09-21 gave a date of ≤700 ± 4 Ma (Table 1 and Figure 6).

**Age of the Bayda Group: 700–660 Ma?**

The Thalbah Group lies unconformably on the metasediments and metavolcanics of the Bayda Group. Two samples from this group (Samples BY-1 and BY-2, Kennedy et al., 2011a) were taken from outcrops within a few meters of each other and unexpectedly gave results that are completely different. The results led Kennedy et al. (2011a) to caution that Sample BY-1 (26°25'36.3"N, 37°08'12.2"E) may have been contaminated during processing by zircons from an earlier study of samples from Australia. The results from Sample BY-2 suggest that the Bayda Group may have formed between 700 and 660 Ma, but again Kennedy et al. (2011a) suggest caution pending further investigation. The ages of the Zaam and Bayda groups only constrain the Thalbah Group as younger than approximately 660 Ma.
Interpreted Age of the Thalbah Group

The dating of the detrital zircons by Bezenjani et al. (2014) is here believed to be the most reliable estimate for the maximum (oldest) depositional ages of the Hashim ($\leq 596 \pm 10$ Ma) and Zhufar ($\leq 612 \pm 7$ Ma) formations. Their maximum ages overlap within their error bounds in the interval 606–605 Ma ($612 - 7 = 605$ Ma; $596 + 10 = 606$ Ma), which coincides closely with the maximum estimated age for the Jibalah Group (i.e. Sub-Jibalah Unconformity: $605 \pm 5$ Ma; see Al-Husseini, 2014).

When cast in the proposed stratigraphic order for the formations of the Thalbah Group (Davies, 1985), the Hashim and Zhufar formations are here interpreted to be approximately coeval and probably younger than $605 \pm 5$ Ma. The youngest Ridam Formation is $\leq 596 \pm 10$ Ma, and it may be older than $575 \pm 5$ Ma, the age of a dike swarm located outside the Thalbah Basin (see “Age of Muwaylilh Dike Swarm” and “Age of Ajjaj Shear Zone” below).

CHRONOSTRATIGRAPHIC MODEL OF THE NORTHWESTERN ARABIAN SHIELD

The here-proposed potential correlation of the Thalbah Group with the Jibalah Group provides an opportunity to determine if and how several other Ediacaran–lower Cambrian time-rock units in the northwestern and central Arabian Shield correlate (see Introduction). In the northwestern Arabian Shield the Jibalah Group has only been identified and so-named in the Sahl Al Matran Quadrangle (Hadley, 1974, 1986; Figure 8), and Al Wajh Quadrangle (Miller et al., 2008; Vickers-Rich et al., 2010, Figure 3; see summary in Al-Husseini, 2014).
In the Mashhad area in the Sahl Al Matran Quadrangle (Hadley, 1974, 1986, Figures 2, 6 and 8), the Jibalah Group overlies the Shammar Group rhyolites. It is divided into the undated Rubtayn Formation (conglomerates, sandstones and fine siliciclastics), undated Badayi Formation (andesite-basalt flows) and undated carbonates of the Muraykhah Formation, and is overlain by the Siq Sandstone Formation along the Sub-Siq Unconformity (525 ± 5 Ma; Table 1; see Al-Husseini, 2010, 2014).

In the Dhaiqa area in the northwestern part of Al Wajh Quadrangle (Figures 2 and 3), the Jibalah Group consists of the Mataar and Dhaiqa formations (Figure 6). The Mataar Formation consists of approximately 150 m of conglomerates and siliciclastics that overlie granitoids dated 609 Ma, and passes conformably upwards to the carbonates of the Dhaiqa Formation (Davies, 1985; Miller et al., 2008; Table 1 and Figure 6, see summary in Al-Husseini, 2014). The Dhaiqa Formation has been dated 560 ± 4 Ma (Vickers-Rich et al., 2010), and is unconformably overlain by the Siq Sandstone Formation (≤525 ± 5 Ma; Table 1). The Mataar Formation is ≤609 and ≥560 Ma and therefore time-correlative to the lower part of the Jibalah and Thalbah groups, and probably to the Polymictic Member of the Rubtayn Formation and Ridam Formation (Figure 6). The absence of marine-influenced clastics, evaporites or carbonates in the Thalbah Basin, found in other areas of the Arabian Peninsula (e.g. Huqf Supergroup of Oman, Forbes et al., 2010; Jibalah Group, Al-Husseini, 2014), may be due to their erosion prior to the deposition of the Siq Sandstone Formation (525 ± 5 Ma; Table 1), or to them not having been deposited.
In the central Arabian Shield, the Jibalah Group unconformably overlies the Shammar Group or older rocks, and is divided into the Umm al Aisah and Jifn formations (Delfour, 1970, 1977; Figures 2 and 6; see summary in Al-Husseini, 2014). The Shammar Group consists of rhyolite flows, ignimbrite, ash flow tuff, felsic breccias, basalt, and red-brown polymict conglomerate, sandstone and siltstone (Brown and Jackson, 1960; Defour, 1970, 1977). Johnson (2006) estimated the age of the Shammar Group to be approximately 630 Ma based on a Rb/Sr whole-rock age of 632 ± 18 Ma (Calvez and Kemp, 1989), and considered it to be a possible extrusive equivalent of adjacent granites dated ca. 625 Ma (see “Shammar Group” below).

In several other localities in the northwestern Arabian Shield some authors have explicitly or tentatively identified the Jibalah and Shammar groups, but preferred naming them after local places because they occur in isolated outcrops. In the following discussion rock units that may be equivalent to the Jibalah and Shammar groups, and related units, are briefly reviewed starting in the northwest in the Shaghab Quadrangle (Figures 6 and 9). The objective of this review is to not only to identify synonyms and correlative units, but also to help guide future fieldwork towards rock units that may carry significant Ediacaran stratigraphy.

Figure 9: Simplified geological map of the Shaghab Quadrangle (reproduced from the 1:1,000,000-scale Structural Sketch Map relating to the 1:250,000-scale map of the Shaghab Quadrangle, Grainger and Hanif, 1989). The Naghr (“n”) and Farra’ah (“f”) formations are equivalent to the Jibalah and Shammar groups, respectively.

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Farra’ah and Naghr Formations, Shaghab Quadrangle

The Farra’ah Formation consists of silicic volcanic rocks and intercalated coarse-grained sedimentary rocks. It crops out in an approximately 20 km-long and 3 km-wide, W- to NW-trending ridge on the northern side of Wadi al Farra’ah in the Shaghab Quadrangle (Johnson and Trent, 1966; Grainger and Hanif, 1989; Figure 9). Grainger and Hanif (1989) consider the undated Farra’ah Formation, as well as the Meddan and Qaraqir formations of Hanif (1985), to be equivalent to the Shammar Group (Figure 6). Based on aerial photographs, the Farra’ah Formation is unconformably overlain by the Naghr Formation (Grainger and Hanif, 1989).

The undated Naghr Formation, named after Wadi Naghr, consists of well-bedded unmetamorphosed sedimentary rocks, which F.B. Davies and R.A. Agar (in Grainger and Hanif, 1989) consider to be possibly equivalent to the Jibalah Group of Delfour (1970, 1977; Figure 6). F.B. Davies (in Grainger and Hanif, 1989) and Vickers-Rich et al. (2010) describe the Naghr Formation as sandstone with horizons of conglomerate and lesser amounts of siltstone, claystone and limestone, containing stromatolitic buildups. Vickers-Rich et al. (2010) add that ripples in the sandstone beds point to shallow-water conditions. Some of the conglomerates with big boulders of rhyolitic and granitic composition, according to Vickers-Rich et al. (2010), resemble glacial diamictites with outsized clasts. Moreover, they support that locally observed diamictites represent dropstones and were deposited in a glacial environment. A few horizons of vesicular, basic to intermediate, lava flows are locally present in the upper part of the formation.

The Sub-Siq Unconformity (Figure 6) was inferred by Johnson and Trent (1966) between the Naghr and Siq Sandstone formations. It is evident on aerial photographs as seen by D. Grainger, and was confirmed in the field by D. Vaslet (Davies and Grainger, 1985).

Saluwah and Sulaysil Formations of the “Thalbah group”, Shaghab and Al Muwaylih Quadrangles

In the Al Muwaylih Quadrangle (Figures 1, 6 and 7), Davies and Grainger (1985) divided the so-called “Thalbah group” into the Saluwah and overlying Sulaysil formations. As explained above, the interpretation of ages in the present paper indicate this group to be older and to differ from the Thalbah Group in the Thalbah Basin. It is therefore distinguished with quotation marks and considered, based on lithology and age, a part-equivalent of the Shammar Group.

The conglomeratic Saluwah Formation is named after Wadi Salwah, and the main conglomerate crops out in the Wadi Salma area. Davies and Grainger (1985, on p. 13 in section “Shar complex”) also mention the “Salma formation of the Thalbah Group”, which is apparently an earlier informal name of the Saluwah Formation. The Saluwah Formation lies unconformably on the Zaam Group (763 ± 25 to 660 ± 4 Ma, Table 1), and is intruded by the Shar Complex, an ovoid body of alkali granite dated 625 ± 5 Ma (U-Pb TIMS) and 630 ± 10 Ma (Rb/Sr) by Hedge (1984; Table 1, Figures 6 and 7).

The Saluwah Formation is conformably overlain by the Sulaysil Formation, which consists of litharenite and silicic volcaniclastic rocks. In the Wadi Salma area, the Sulaysil Formation is intruded by rhyolite sheets up to 50 m thick; locally laminated and welded rhyolite tuff and welded agglomerate make up the base of the formation.

Grainger and Hanif (1989) extended the maps of the Saluwah and Sulaysil formations of the “Thalbah group” from the Al Muwaylih Quadrangle into the Shaghab Quadrangle (Figure 9). The Saluwah Formation is not described in detail in the latter quadrangle. It is equivalent to the “volcanic rocks” of the “Upper Volcanics” of Smith (1979), which he described as fine-grained andesite, basalt, fine-grained silicic volcanic rocks, and subsidiary pyroclastic rocks of mainly tuffaceous origin.

The Massah Complex is an approximately circular monzogranite intrusion, about 20 km in diameter, which straddles the Al Muwaylih and Shaghab quadrangles (Figures 7 and 9). It intrudes...
the Zaam, Bayda and “Thalbah” groups (Grainger and Hanif, 1989), and is dated 629 ± 12 Ma (Kemp et al., 1980). The Massah and Shar igneous complexes both intrude the Saluwah Formation implying it is older than 625 ± 5 and 629 ± 12 Ma (Table 1). These constraints imply the “Thalbah group” in the Shaghab and Al-Muwaylih quadrangles has an age centered at approximately 630–625 Ma, and is older than the Thalbah Group in the Thalbah Basin (≤ 605 ± 5 Ma). The Sulaysil Formation rhyolites may be equivalent to the Shammar Group rhyolites.

**Misyal and Salih Formations, Al Wajh Quadrangle**

The Misyal and overlying Salih formations are exposed in three isolated places near the igneous Warid Complex in the northwestern part of the Al Wajh Quadrangle (Figure 3) and were assigned to the “Diqan group” by Davies et al. (1981). Davies (1985) subsequently abandoned the “Diqan group” nomenclature, but retained the two formations. The Misyal Formation, named after Wadi Misyal (misspelled as “Miysal” in figure 7 of Grainger and Hanif, 1989), consists of a lower polymictic conglomerate (few 10s to several 100s of meters thick), and an upper unit of litharenite, siltstone and conglomerate. The Salih Formation, named after Jabal Salih (misspelled “Salah” in figure 7 of Grainger and Hanif, 1989), lies unconformably on the Misyal Formation, and its basal unit consists of flow-banded quartz and feldspar porphyritic rhyolite, about 150–200 m thick. The rhyolite is conformably overlain by a well-bedded, pebbly siltstone intercalated with thicker beds of polymictic conglomerate, which may represent the lower part of the Jibalah Group.

The Misyal Formation was intruded by diorite and monzogranite of the Habd Complex of the Marabit Suite (Figure 3), and the Salih Formation was deposited after the intrusion (Davies, 1985). The Habd Complex is dated 608.9 ± 2.8 Ma (Sample FK 27/3, Kennedy et al., 2011a; Table 1). Other dated Marabit Suite plutons by Kennedy et al. (2011a) are the igneous Ash Shab Complex (609 ± 3.6 Ma) and Abu Suar Complex (625.8 ± 4 Ma; Table 1). The rhyolites of the Salih Formation (≤ 608.9 ± 2.8 Ma; Table 1) may represent the younger limit of the Shammar Group rhyolites (see “Shammar Group” below).

**Shammar Group: 630 to 609 Ma?**

The Farra’ah, Sulaysil (and its synonymous Meddan and Qaraqir), and Salih formations are dominated by massive rhyolite flows, suggesting they may be equivalent to the Shammar Group rhyolites (Figure 6). The undated Farra’ah Formation, by its stratigraphic position immediately below the Jibalah-equivalent Naghr Formation, has been recognized as equivalent to the Shammar Group (Grainger and Hanif, 1989). The Sulaysil Formation of the “Thalbah group” is intruded-by and therefore younger–than the alkali granites of the Shar Complex (625 ± 5 Ma) and Massah Complex (629 ± 12 Ma, Table 1). The Salih Formation is intruded by the Habd Complex (608.9 ± 2.8 Ma, Table 1), implying it is older than approximately 609 Ma. It is conformably overlain by the pebbly siltstone intercalated with polymictic conglomerate, which may represent the lowermost Jibalah Group deposits (≤ 605 ± 5 Ma, Table 1). These rhyolite-dominated rock units range between approximately 630 and 609 Ma, and occupy the time interval just prior the Sub-Jibalah Unconformity (605 ± 5 Ma, Table 1). They are therefore considered to represent the Shammar Group with an estimated age of 630 to 609 Ma.

**Saluwah Formation (660–630 Ma) and Marinoan Glaciation: 650–635 Ma**

The conglomeratic Saluwah Formation unconformably overlies the Zaam Group (763–660 Ma, Table 1), and is intruded by the Shar and Massah complexes, which are dated 625 ± 5 and 629 ± 12 Ma, respectively (Table 1). It is conformably overlain by the Sulaysil Formation, which is interpreted to represent the Shammar Group (ca. 630–609 Ma, Table 1). The depositional age of the Saluwah Formation between approximately 660 and 630 Ma indicates it may coeval to the Marinoan Glaciation (650–635 Ma; see review in Al-Husseini, 2014).

No evidence for a Marinoan-equivalent glaciogenic or glacio-fluvial settings has been reported from the Saluwah Formation. Its age and conglomeratic lithology suggest this possibility, which is worthy of further field investigation. Davies and Grainger (1985) report that the Saluwah
Formation crops out in narrow NW-trending synclinal folds in the central part of the Al Muwaylih Quadrangle. They describe the main conglomerate in Wadi Salma to consist of an unsorted basal sequence of boulders up to one meter in diameter in a red litharenite matrix, which grades to pebble conglomerate within 10 m from the base of the unit. The clasts are coarse-grained granodiorite, and granite, diorite, rhyolite, feldspar-porphyritic andesite, sandstone and siltstone. The conglomerate grades upward into litharenite containing feldspar clasts and some angular siltstone fragments. The total thickness of the formation is not reported.

**Shar, Kara Dakha and Liban Complexes, Marabit Suite**

The ages of the Shar, Liban and Kara Dakha igneous complexes (Figures 3 and 7) are used by some authors to date the Thalbah Group as $\geq 634/621$ Ma (Hedge, 1984), or $\geq 635$ Ma (Johnson and Kattan, 2012), or $\leq 635$ Ma (R.N. Bezenjani, written communication, 2014; Table 1). As explained above, the Shar Complex ($625 \pm 5$ Ma, Table 1) intrudes the “Thalbah group” in the Al Muwaylih Quadrangle, which is interpreted by the present author to be much older than the Thalbah Group in the Thalbah Basin, and probably partly equivalent to the Shammar Group. The Kara Dakha Complex ($632 \pm 4$ Ma; Kozdroj et al., 2010, in Johnson et al., 2013; Table 1) crops out to the west of the Thalbah Basin, but is not in contact with the Thalbah Group (Figure 3).

Davies (1985), unlike reports by other authors, does not state nor imply that the Thalbah Group was intruded by the microgranites of the Liban Complex ($621 \pm 7$ Ma, Hedge, 1984; Table 1, Figure 3). In his map he shows that the Ridam Formation is in contact with the Liban Complex, and this contact only occurs along a 3 km-long, NS-trending fault in one area named Abu an Naam (near 26°35’N, 36°30’E, Figure 4).

The outcrop belt of the Ridam Formation in the western part of the basin is mapped in a 30 km-long, NS-trending syncline to the east of the Liban Complex, and then continues to the northwest of the complex where it crops out parallel to several NW-trending faults (Figure 4). As noted by Davies (1985), the distribution of the Ridam Formation in the western part of the Thalbah Basin suggests that the Liban Complex formed a pre-existing topographic high at the time of deposition of the Thalbah Group. He reported that clasts of gray granodiorite and red granite in the Ridam Formation are predominant, and probably derived from the Liban and Kara Dakha complexes. If the Liban Complex was a pre-existing topographic high during the deposition of the Thalbah Group, then its age only sets a maximum age for the deposition of the Thalbah Group, i.e. $\geq 634–621$ Ma. This interpretation is consistent with the Thalbah Group in the Thalbah Basin being younger than about 618 Ma, the dating of the Wadi Thalbah Andesite Dike (Table 1), and as proposed here younger than 605 ± 5 Ma.

Based on satellite images, R.N. Bezanjani (written communication, 2014) notes that there are some apparent intrusive rocks in the Thalbah Group that may be fingers of the igneous Liban and Kara Dakha complexes (e.g. unassigned and undated monzogranite pluton “gm” in Figures 3 to 5). He adds that the detrital zircons from the Thalbah Group sediments analyzed by Bezanjani et al. (2014) do not show a peak at approximately 635 Ma, as would be expected if the two complexes were older than the Thalbah Group. He therefore concludes that the depositional age of the Thalbah Group may be between about 635 Ma and younger than 596 Ma.

**Age of Muwaylih Dike Swarm: 575 ± 5 Ma**

Besides the swarm of dikes that intrude the Thalbah Group in the Thalbah Basin (see “Depositional and Structural Setting” above; Figure 4), a second E-trending dike swarm intrudes the Zaam Group (labelled “zg” in Figure 7b) further north in Al Muwaylih Quadrangle (Davies and Grainger, 1985), here informally named the “Muwaylih Dike Swarm” (Figure 7, Table 1). The dikes have similar compositions to those in the Thalbah Basin: about 75 percent consist of andesite porphyry, which are cut by the rest consisting of porphyry microgranites. The dikes are subvertical, spaced 50–100 m apart, and occupy 25 percent of the rock exposure; individual dikes are up to 10 km long. Margin irregularities and dike offsets indicate dextral displacements across the margins of many of the dikes. The age of this swarm is directly constrained by the dating of the dikes themselves, as well as older and younger groups and complexes (Hedge, 1984).
The Muwaylih Dike Swarm cuts the Zaam Group (763–660 Ma, Table 1) to the east and west of the Dabbagh Complex, but is not mapped as cutting the complex (Figure 7b). The swarm is about 7 km (EW) and 12 km (EW) long on the eastern and western sides of the Dabbagh Complex, respectively. The rim of the Dabbagh Complex consists of alkali granite dated 577 ± 4 (U-Pb TIMS) and 570 ± 7 (Rb/Sr) (Hedge, 1984; Table 1). Hedge (1984) dated four samples from the dikes, whose composition he described as “felsic dikes of approximate quartz syenite”, and obtained an age of 575 ± 5 Ma (Rb/Sr), thus implying they are older-than or contemporaneous to the alkali-granite rim of the Dabbagh Complex (Table 1, Figures 6 and 7). Further west, the swarm extends westwards and cuts the igneous Sadr Complex dated 599 ± 5 Ma (U-Pb TIMS) and 598 ± 30 Ma (Rb/Sr) by Hedge (1984; Table 1). These radiometric dates constrain the age of the dikes to between ≤ 599–598 Ma and ≥ 577 Ma, as consistent with their own estimated age of 575 ± 5 Ma (Hedge, 1984).

The dike swarm in the Thalbah Basin cuts the Zhufar and Ridam formations (Figure 4), and if it has the same age as the Muwaylih Dike Swarm in the northern part of Al Muwaylih Quadrangle, then these two formations would be older than 575 ± 5 Ma. Dating the dike swarm that cuts the Thalbah Group should be considered for future research.

**Age of Ajjaj Shear Zone**

The Ajjaj Shear Zone *sensu* the Saudi Geological Survey (Kennedy et al., 2011a, b; Johnson and Kattan, 2012) trends EW and crosses the Al Wajh Quadrangle to the south of the Baladiyah and Imdan complexes, and the southern limit of the Thalbah Group outcrops (Figure 3). Kennedy et al. (2011a) collected two samples (AJ-1 and AJ-2, Figure 3 and Table 1) from this zone, which indirectly adds some support for the younger age limit of the Thalbah Group sediments at about 575 (Figure 6) to possibly 560 Ma (P.R. Johnson, written communication, 2014).

Kennedy et al. (2011a) report that Sample AJ-1 (26°01.060’N, 37°13.557’E) was collected from an undeformed, NNE-trending lamprophyric dike emplaced almost perpendicular to the strike of the Ajjaj Shear Zone. The dike is at least a few kilometers long and cuts the shear zone. It may be the youngest intrusive rock in the region, and is post-kinematic in relation to the movements along the Ajjaj Shear Zone (Kennedy et al., 2011a). According to the cathodoluminescence microscopy (CL) images, the zircons include fragmented, weakly zoned, slightly rounded zircons and highly rounded zircons that have a detrital appearance (Kennedy et al., 2011a). The 27 data points spread along the concordia with 206Pb/238U ages that range from 352 to 592 Ma. Twenty-three zircons form a group between 558 and 594 Ma, with a weighted mean age of 573.1 ± 5.2 Ma. The relative probability diagram shows that within this group there is a peak of zircon growth at ca. 560 Ma.

Sample AJ-2 (26°00.931’N, 37°15.575’E) consists of weakly foliated and lineated fine-grained granite intercalated with the paragneissess of the Zaam Group (Kennedy et al., 2011a). The CL images show this sample contains apparent oval zircons, ranging in form from fragmented, weakly zoned, slightly rounded zircons to strongly rounded zircons, both of which are overgrown by high-U rims. The 23 data points are spread along the concordia between 206Pb/238U ages of 433 to 713 Ma. Nineteen, low- to moderate-U zircons form a weakly defined group between 547 and 613 Ma, with a weighted mean age of 575.1 ± 9.6 Ma.

Kennedy et al. (2011a) consider the geological interpretation of AJ-1 and AJ-2 zircon data problematic, especially the presence of rounded zircons. They believe it is unlikely that the rounded zircons are detrital and originate from a sedimentary system because it would imply the majority would have been shed from a source or sources with a very narrow age range of ca. 580 Ma. Instead they suggest that the rounded zircons may be interpreted as metamorphic, inherited grains derived from partially melted high-grade rocks – possibly granulites – still present in the roots of the Ajjaj Shear Zone. If so, a peak of zircon growth at about 580 Ma may indicate an age of granulite metamorphism (in the roots of Ajjaj Shear Zone) concurrent with frictional heating, melting of granulites, and intrusion of AJ-2 granites into shallow crustal levels.
If the AJ-1 and AJ-2 zircons are not detrital then they set the maximum age of movement for the Ajaj Shear Zone at about 575 Ma. If they are detrital then the age intervals of 594–558 Ma (AJ-1) and 613–547 Ma (AJ-2) suggest erosion from rock units that are in part coeval to the Jibalah and Thalbah groups (Figure 6, Table 1).

**Age of Greater Qazaz Complex**

Several reviewers of the present paper suggested that the Thalbah Basin and gneiss complexes like the Greater Qazaz Complex evolved at the same time (e.g. P.R. Johnson, R.J. Stern, S.E. Meyer, written communication, 2014). Davies (1981a, 1983, 1985) assigned the Qazaz Complex to the Usaylah Suite, which he considered to be the oldest rock unit in the Al Wajh Quadrangle. Hedge (1984) obtained a Rb/Sr age of 672 ± 30 Ma for the complex. More recently Kennedy et al. (2010) dated four samples from the Qazaz Dome. One sample (MT-41c) gave no valid results and was discarded by Kennedy et al. (2010). The results of the other three samples are paraphrased here from their report.

Samples MT-39 (26°39'45.2"N, 36°42'56.2"E) and MT-40 (26°40'27.7"N, 36°42'29.0"E) were collected from the central part of the Qazaz Dome, and Sample MT-43 (26°44'20.1"N, 36°41'25.7"E) from the shear zone north of the dome (Figure 3). The former two samples are characterized as an orthogneiss and granite-gneiss, respectively. Foliation planes in the gneiss and schist are parallel, suggesting that both rocks were affected by the same deformation and metamorphic event. Quartz, usually showing undulose extinction, is often recrystallized indicating thermal rejuvenation following the metamorphic peak.

Sample MT-39 orthogneiss is a well-foliated rock produced by ductile shearing and metamorphism of a granitic protolith. The analyses of 25 zircon grains gave a spread of 206Pb/238U ages that range from 708 to 634 Ma. The 17 least-disturbed analyses of zircons gave a mean age 691.9 ± 4.4 Ma at 95% confidence. Kennedy et al. (2010) believe ca. 692 Ma is the best estimate for the initial crystallization age of the MT-39 granite protolith, and that partial Pb loss has occurred in some zircons with rims with ages of approximately 640–635 Ma.

A total of 24 zircons were analyzed from Sample MT-40; the oldest eight ages are from large, moderate-U zircons that have broad oscillatory zoning but no well-developed rims; they give a concordia age of 710 ± 5 Ma. Kennedy et al. (2010) suggest that this age may possibly represent the crystallization age for red granite and that the other 16 zircons underwent variable amounts of Pb loss.

Sample MT-43 represents basic orthogneiss derived from a primary dioritic protolith. It belongs to a co-magmatic intrusive affected by strong deformation and metamorphism along a regional shear zone that passes northwest of the Qazaz Dome (Figure 3). Most of the rocks are transformed to gneiss and their fabric shows different levels of deformation ranging from weakly deformed diorite, through proto-mylonite and mylonite with common gneissosity, to ultramylonite with strongly developed metamorphic "lamination". The analyses of 28 zircons gave 206Pb/238U ages ranging from 686 to 744 Ma, of these 24 yielded an age of 720 ± 3.2 Ma, which Kennedy et al. (2010) interpreted as the age for the time of intrusion and cooling of the diorite protolith.

**TECTONO-STRATIGRAPHIC INTERPRETATION OF THALBAH BASIN**

**Thalbah Pull-Apart Basin**

The tectonic setting of the Thalbah Basin has been briefly interpreted in a few studies (Davies, 1985; Genna et al., 2002; Johnson et al., 2013; Meyer et al., 2014). In this paper it is interpreted as a pull-apart basin that was subjected to sinistral shear faulting and folding. The proposed mechanism involves a major left-lateral dislocation along the NE flank of the basin (RQFZ Fault in Figure 3, passing through Wadi Rabbigh in Figure 4) turning across a left-stepping NE-trending jog situated west of the Baladiyah Complex. This geometry is consistent with NW-SE extension as manifested by the NE-trending dike swarm in the northern part of the basin (Figure 4).
The interpretation of the Thalbah Basin as a pull-apart basin situated side-by-side to the metamorphic Qazaz Dome raises the question of whether the two features developed at the same time (Figure 3). The dating of the Qazaz Dome indicates that it was intruded into the Midyan Terrane to the northwest of the Yanbu Suture between about 720 and 690 Ma (Figure 2). This time interval approximately coincides with the collision between the Midyan and Hijaz terranes along the Yanbu Suture at ca. 730–710 Ma (Ali et al., 2010). The Midyan-Hijaz collision was followed by younger collisions along the NS-trending Nabitah Suture (ca. 680–640 Ma, extending into the Ruwah, Ad Dafinah and Hulayfah faults) and the youngest-known Amar Suture (ca. 640–635 Ma), both situated farther to the east (Figure 2). These collisions span 730 to 635 Ma and are likely candidates to have caused metamorphism in the Midyan Terrane as evident in the metasediments and metavolcanic of the Zaam and Bayda groups (≥ 660 Ma) and younger metamorphic complexes.

The analysis of nearly 80 zircon grains from the three samples recovered from the Qazaz Dome by Kennedy et al. (2010) does not suggest any resetting of their apparent ages due to thermal or metamorphic events. The only exception is the partial Pb loss that occurred in some zircons with rims at approximately 640–635 Ma (Sample MT-40). It is not clear whether this result is significant in regards to the age of metamorphism of the dome, or the thermobarometric analysis by Meyer et al. (2014). Nonetheless, it is noteworthy that zircon geochronology of the Qazaz Dome does not appear to identify any event that is younger than about 635 Ma, which represents the final age of the collisions along the Nabitah and Amar sutures; this age is also interpreted by some authors as the oldest possible age of the Thalbah Group (e.g. R.N. Bezanjani, written communication, 2014).

Depositional Setting

The stratigraphic column of the Thalbah Group has not been described in a detailed measured section as implied in figure 19 of Johnson et al. (2013). The basal clasts of the Hashim and Zhufar conglomerates may represent coeval deposition during the earliest stage of basin development; they are described as subrounded pebbles and cobbles with diameters of 5–10 cm. The basal conglomerates of the younger Ridam Formation are notably out-of-sequence, and together with the Sub-Ridam Unconformity, represent a different continental setting. In the northern part of the Thalbah Basin they are 200 m thick and include sporadic out-sized boulders with diameters of up to 2 m. The much greater size of the Ridam clasts suggests that the Sub-Ridam Unconformity and Ridam conglomerates represent a dramatic change in depositional setting, which may be unrelated to tectonic movements.

The age of the Ridam Formation, although weakly constrained between ≤ 596 ± 10 and possibly ≥ 575 ± 5 Ma, suggests it may have been deposited at the same time as the Ediacaran Gaskiers Glaciation (584–582 Ma; see review in Al-Husseini, 2014). The formation may have been deposited in a high-energy, glacio-fluvial setting associated with melting mountain glaciers, with rivers flowing into the Thalbah Basin. Other likely coeval units that have been highlighted as possibly of glaciogenic origin are the Mataar Formation (609–560 Ma) in the Dhaiqa area in the northwestern part of the Wajh Quadrangle by Miller et al., 2008 (Figure 6), and the Naghr Formation in the Shaghab Quadrangle by Vickers-Rich et al. (2010; Figure 9). The absence of marine carbonates in the Thalbah Basin, such as those found the Dhaiqa Formation (560 ± 4 Ma, Table 1) and likely correlative Muraykhah Formation that crop out further northeast, may be due to erosion prior to the deposition of the Siq Sandstone Formation (≤ 525 ± 5 Ma, Table 1), or to them not having been deposited.

Connecting the Rika and Qazaz Fault Zones

The proposed potential correlation of the Thalbah and Jibalah groups in the time interval after about 605 Ma has implications for dating and reconstructing the regional-scale movement along the Rika and Qazaz fault zones of the Najd Fault System. As shown in Figure 2, the left-lateral dislocation of the NE-trending ophiolite belt of the Yanbu Suture (≥ 700 Ma, see age reviews in Johnson and Kattan, 2012; Johnson et al., 2013) by the Qazaz Fault Zone is about 100 km, which is the same dimension as the NW-SE length as the Thalbah Basin.
The southeastern trace of the Qazaz Fault Zones terminates at approximately 39°E where the flood basalts of the Cenozoic Harrat Khaybar cover the Arabian Shield (Figure 2). The southwestern limit of the basalt flows between about 39°E and 40°30'E has the same NW strike as the Qazaz Fault Zone. This pattern suggests to the present author that the limit of the basalt flows represents the trace of the Qazaz Fault Zone, which could have been re-activated as a structural or topographic feature during the Cenozoic.

Southeast of approximately 41°E, starting near the southeastern corner of the Harrat Khaybar flood basalts and continuing to the eastern edge of the Arabian Shield (Figure 2), the ca. 600 km-long NW-trending Rika Fault Zone has the same strike as the Qazaz Fault Zone. The Rika Fault Zone passes through the North and South Sukhaybarah, Bir Sija and Kibdi pull-apart basins. These basins contain the Jibalah Group and are therefore believed to have started forming at the same time as the Thalbah Basin. The dislocation of the ophiolite belts along the Dafinah and Hulayfah fault zones (sometimes interpreted as parts the Nabitah Suture Zone, 680–640 Ma; see discussion in Johnson and Kattan, 2012) by the Rika Fault Zone occurs across the North Sukhaybarah Basin. The left-lateral dislocation is about 100 km (NW-SE) and has a similar NW-SE dimension as the North Sukhaybarah Basin.

The following spatio-temporal and structural considerations argue that the Rika and Qazaz fault zones form one-and-the-same continuous 30 km-wide, 1,200 km-long, N63°W-striking fault zone, the “Rika-Qazaz Fault Zone” (RQFZ, Figure 2) of the Najd Fault System:

1. correlation of the Sub-Thalbah and Sub-Jibalah unconformities at approximately 605 ± 5 Ma implies that both the Thalbah and Jibalah basins started forming as pull-apart basins at the same time along the RQFZ;
2. locations of five pull-apart basins along the RQFZ;
3. locations of the dislocations of the Yanbu and Ad Dafinah-Hulayfah ophiolites along the RQFZ;
4. similar magnitude of the 100-km left-lateral dislocations of the ophiolite belts implies the same amount of lateral movement occurred across the RQFZ;
5. location and strike of the southwestern limit of the Cenozoic Harrat Khaybar flood basalts along the gap between the traces of the Rika and Qazaz fault zones;
6. strike, linearity and extent of the Rika (600 km) and Qazaz (300 km) fault zones.

On the basis of these considerations, the Rika-Qazaz Fault Zone is interpreted to have dislocated the Arabian Shield by about 100 km after 605 ± 5 Ma. The fault zone consists of several long fault segments (100s km) separated by left-stepping, pull-apart basins (Figure 2). The linear aspect of the fault zone is seen in the magnetic anomaly map of the Arabian Shield (Figure 10; Zahran et al., 2003). The cessation of movements along the Rika-Qazaz and other Najd fault zones is constrained by the early Cambrian Siq Sandstone Formation, which is unaffected by faulting associated with the Najd Fault System. The Sub-Siq Unconformity is a peneplain surface with an estimated age of 525 ± 5 Ma.

The implication of this interpretation is that the main left-lateral, strike-slip fault of the Rika-Qazaz Fault Zone, which passes between the main Thalbah Group outcrop and Qazaz Dome (RQFZ in Figure 3), displaced the dome by many 10s kilometers, but not by more than about 100 km. In this scenario the Qazaz Dome may have been metamorphosed and exhumed sometime between about 720 and 635 Ma, and much before the left-lateral dislocation started at about 605 ± 5 Ma. The dome may then have been kinematically displaced and folded, together with Thalbah sediments in the vicinity of the fault, but after 605 Ma. The younger event may have caused greenschist metamorphism of the older amphibolite-facies rock in the dome (P1). The NNW-trending folding of the outcrop outlier of the Zhufar Formation, where Meyer et al. (2014) collected samples P2 to P4 (Figure 3), appears to suggest this interpretation. The outlier may have been transported away from its original depocenter, folded and metamorphosed to greenschist facies as a result of local compression during its translation. This interpretation may explain the abrupt change in metamorphic facies and depth of burial between the Thalbah sediments and Qazaz Dome rocks (Table 2). It is nevertheless clear that the possible co-evolution of the Thalbah Basin and Qazaz Shear Zone must be further evaluated.
Figure 10: Reduced-to-the-pole magnetic anomaly map of the Arabian Shield and surrounding regions (Zahran et al., 2003; see also Johnson and Kattan, 2012). The limits of the Rika and Qazaz fault zones near the Red Sea and the southeastern edge of Arabian Shield (white outline) are indicated by arrows. The Rika-Qazaz Fault Zone is expressed as a magnetic lineament with high values ($\geq 144$ nT).
CONCLUSIONS

This paper reproduces the maps that show key Ediacaran–Cambrian rock units in the northwestern Arabian Shield as published by the original authors from the Saudi Arabian and French geological surveys (Figures 3 to 5, and 7 to 9). It also compiles all known geochronological data from this region and time interval (Table 1). This spatial and temporal dataset, as presented here in one document, offers the reader a state-of-the-art report on what is known about the Thalbah Basin, and highlights significant chronostratigraphic contradictions that prevail in the literature. The paper seeks to synthesize the dataset where possible, and recommends further focused work to better understand it. The here-proposed new Ediacaran–mid Cambrian chronostratigraphic model honors all known geochronological constraints for northwest Saudi Arabia (Table 1, Figure 6). It adds another contribution to the work-in-progress Ediacaran–Cambrian Middle East Geologic Time Scale.

The new model suggests that the age of the Thalbah Group is between 605 ± 5 Ma to possibly 575 Ma, and therefore several 10s of million years younger than previously reported in the literature. It proposes for the first time that the Thalbah Group is coeval to the lower part of the Jibalah Group that crops out in pull-apart basins along the Najd Fault System. The proposed correlation, together with numerous spatio-structural features, provide the justification for connecting the 300 km-long Qazaz Fault Zone to the 600 km-long Rika Fault Zone, across the Cenozoic flood basalts in the central Arabian Shield (Figures 2 and 10). The paper proposes naming this linear and continuous tectonic feature the “Rika-Qazaz Fault Zone” (RQFZ) of the Najd Fault System. The RQFZ is a 1,200 km-long zone that dislocated the Arabian Shield left-laterally by about 100 km after 605 ± 5 Ma and sometime before 525 ± 5 Ma, the age of the Sub-Siq Unconformity. It is unlikely that it does not extend beyond the shield, which raises the question as to where its northwest and southeast continuations and terminations are, and its relationship to coeval tectonic events.

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