EDIACARAN–CAMBRIAN MIDDLE EAST GEOLOGIC TIME SCALE 2014

Proposed correlation of Oman’s Abu Mahara Supergroup and Saudi Arabia’s Jibalah Group

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ABSTRACT

The Ediacaran–Cambrian Middle East Geologic Time Scale is extensively revised in the 2014 version (Enclosure). It suggests the top of the Abu Mahara Group glacial diamictites in Oman represent the termination of the late Cryogenian Marinoan Glaciation at 635 Ma. The overlying Ediacaran Nafun Group of Oman is shown between 635 and 547 Ma based on geochronologic data, and divided into: (1) the Lower Nafun Supersequence (635–582 Ma) consisting of the Hadash Formation (cap carbonate), the Masirah Bay Formation (clastics) and the Khufai Formation (carbonates); and (2) the Upper Nafun Supersequence (582–547 Ma) consisting of the Shuram Formation (clastics and carbonates) and the Buah Formation (carbonates). The Nafun Group lies below the Ediacaran–lower Cambrian Ara Group (evaporites and carbonates), which contains the Ediacaran/Cambrian Boundary currently dated at 541 Ma.

The Sub-Shuram Unconformity, which corresponds to the global Shuram δ13C Negative Excursion, separates the Nafun supersequences. Its age was estimated by assuming the thicknesses of the Nafun formations are proportional to time in the Masirah-1 Well, where the Nafun Group attains its greatest-known thickness of 2,308 m in Oman. This assumption coincidently estimated the unconformity at 582 Ma, the same age as the Ediacaran Gaskiers (Varanger or Varingian) Glaciation. The new calibration was used to correlate the Nafun formations to the rock-time units of the Jibalah Group in several isolated basins along the Najd Fault System in the Arabian Shield, using recently published geochronologic data and δ13C measurements, as follows.

The younger part of the Lower Nafun Supersequence (635–582 Ma) is here correlated to the Lower Jibalah Supersequence (605 ± 5 to 582 Ma), represented by the Umm al-Aisah Formation in the Jifn Basin, located along the Halaban-Zarghat Fault Zone of the Najd Fault System. The Umm al-Aisah Formation consists of volcanics and clastics that give way to the Umm al-Aisah Limestone. The Upper Nafun Supersequence (582–547 Ma) is here correlated to the Upper Jibalah Supersequence, which unconformably overlies the Umm al-Aisah Limestone, with its basal unit being the Gaskiers-coeval Jifn Polymictic Conglomerate (≥ 200 m thick). In the Bir Sija Basin, located along the Rika Fault Zone of the Najd Fault System, the likely Gaskiers-coeval polymictic conglomerate (150 m thick) is overlain by a 20 m-thick limestone unit, the Bir Sija Limestone, possibly a cap carbonate. The Upper Jibalah Supersequence continues with clastics overlain by the Muraykhah Formation (carbonates) or mixed clastics-carbonates of its equivalent formations. In several outcrops the Upper Jibalah Supersequence is overlain by the lower Cambrian Siq Sandstone Formation (≤ 525 ± 5 Ma) implying the Sub-Siq Unconformity represents a hiatus between 547 and 525 ± 5 Ma. The Jifn Formation in the Jifn Basin, however, may represent continuous deposition between 582 Ma and 525 ± 5 Ma.
INTRODUCTION

The Jibalah Group in Saudi Arabia (Delfour, 1970; Hadley, 1974) and Huqf Supergroup in Oman (see review in Forbes et al., 2010) attain thicknesses of up to several kilometers, and represent some of the oldest-known Neoproterozoic–Cambrian sedimentary rocks in the Middle East (see Enclosure: Ediacaran–Cambrian Middle East Geologic Time Scale 2014, reviews and references in Al-Husseini, 2010a, 2011). These rock units are variably dated and occur in far-apart localities (Figures 1 and 2) rendering their age calibration and time-correlation highly speculative. Nevertheless, placing these rock units in a regional time scale, which is regularly updated, is important because it compiles previous and new data and interpretations in a single chronostratigraphic framework (Enclosure). This time scale can potentially highlight what further data is required to refine age constraints and reduce speculative correlations. Ultimately, it can contribute to a better understanding of the tectono-stratigraphic evolution of the Neoproterozoic–Cambrian phase of Middle Eastern sedimentary basins and their petroleum habitat (Al-Husseini, 2000; Sharland et al., 2001; Al Siyabi, 2005).
Figure 2: Map of the Arabian Shield showing outcrops of the Jibalah Group and Najd Fault System (after Delfour, 1977; Hadley, 1974; Brown et al., 1989; corrected from Al-Husseini, 2011).
This paper starts by estimating the age of a regionally correlative “early” Cambrian unconformity, the Angudan Unconformity in the Middle East Geologic Time Scale (Enclosure). It then presents a new age calibration for the formations of the Ediacaran Nafun Group of the Huqf Supergroup. The calibration suggests that a major unconformity in the group, the Sub-Shuram Unconformity corresponding to the global Shuram δ¹³C Negative Excursion, has the same age as the relatively short-lived Gaskiers (Varanger or Varingian) Glaciation, dated between 584 and 582 Ma (Bowring et al., 2007; Altermann et al., 2012; Enclosure). This calibration is compared to previous ones, which have been the subject of debate (Bowring et al., 2007, 2009; Le Guerroué, 2006; Le Guerroué et al., 2006a, 2006b, 2009; Al-Husseini, 2010b).

Next the paper identifies key rock-time units of the Jibalah Group in several isolated outcrops in the Arabian Shield in the context of recently published chronostratigraphic data (Figures 1 and 2; Miller et al., 2008; Nettle, 2009; Kennedy et al., 2010, 2011; Vickers-Rich et al., 2010, 2013; Halverson et al., 2013; Nettle et al., 2013). The Jibalah rock-time units are tentatively jump-correlated from outcrop to outcrop across about 800 km in the northern Arabian Shield, and then another 1,500 km to the formations of the Huqf Supergroup (Enclosure, Figures 1 and 2). The Enclosure also incorporates the Ediacaran-middle Cambrian succession in Jordan based on an ongoing review of radiometric results.

Note: Throughout the paper informal names for rock units are shown in quotation marks where first introduced. All radiometric ages are determined by U-Pb (Uranium-Lead) dating of zircons (e.g. SHRIMP: Sensitive High Resolution Ion MicroProbe; LAICPMS: Laser Ablation Inductively Coupled Plasma Mass Spectrometry; ID TIMS: Isotope Dilution Thermal Ionization Mass-Spectrometry), and summarized in tables together with their authors. Where dates are interpreted by their authors as maximum ages of deposition younger-than symbols (≤) are shown. Where ages are poorly estimated the range is shown with error estimates (±), or prefixed by ca. (about).

**ANGUDAN UNCONFORMITY: THE AFRO-ARABIAN PENEPLAIN**

In Oman, the Angudan Unconformity represents the upper boundary of the Huqf Supergroup (Forbes et al., 2010; Enclosure), which from youngest to oldest consists of: (1) early Cambrian Nimr Group (clastics); (2) late Ediacaran–early Cambrian Ara Group (evaporites and carbonates); (3) Ediacaran Nafun Group (clastics and carbonates); and (4) Cryogenian volcanic and glaciogenic Abu Mahara Group. The unconformity correlates to the Sub-Siq Unconformity of Saudi Arabia, Ram (Sub-Salib) Unconformity in Jordan and Sub-Lalun Unconformity in Iran (Enclosure; Al-Husseini, 2010a; Powell et al., 2014), and is referred to as the Angudan Unconformity in the Middle East Geologic Time Scale. The unconformity is recognized throughout the Middle East and North Africa, and has been referred to as the “lower Cambrian peneplain” or “Afro-Arabian Peneplain” (e.g. Stern et al., 2006; Miller et al., 2008).

The age of the Angudan Unconformity is not precisely constrained by biostratigraphic or radiometric data, but can be estimated based on stratigraphic considerations and regional correlations. In Oman, the Ediacaran/Cambrian Boundary is identified by biostratigraphy in the middle of the Ara Group and radiometrically dated 541 Ma (Enclosure; Amthor et al., 2003; Bowring et al., 2007). Taking into account the depositional duration of the Cambrian part of the Ara Group and Nimr Group sediments, Forbes et al. (2010) gave the unconformity a tentative age of 520 Ma. In Jordan, the Angudan-correlative Ram Unconformity underlies the Salib Formation, which is overlain by the “middle” Cambrian carbonates and shales of the Burj Formation (Enclosure). The Burj Formation is dated by biostratigraphy near the boundary between Series 3/Series 2 of the Cambrian Period (Powell et al., 2014), with an age of 509 Ma in the Geologic Time Scale 2012 (Gradstein et al., 2012). In the Levant, the basal Cambrian sandstones that are coeval to the Salib Formation gave U-Pb SHRIMP detrital zircon ages of 550–530 Ma (Avigad et al., 2003; Kolodner et al., 2006).

The constraints noted above imply the unconformity is “early” Cambrian (541–509 Ma). More specifically it is younger than the detrital zircons dated 530 Ma in the Levant, and older than the 520 Ma estimate in Oman. In the Middle East Geologic Time Scale it is taken halfway between 530 and
NAFUN GROUP, HUQF SUPERGROUP, OMAN

Forbes et al. (2010) selected the Miqrat-1 Well to represent the subsurface type section of the Nafun Group (Figures 1 and 3), and interpreted it as two second-order sequences, here referred to as “supersequences” (Enclosure). The “Lower Nafun Supersequence” consists of the Hadash Formation (cap carbonate) above the Abu Mahara Group, and Masirah Bay Formation clastics that are conformably overlain by the Khufai Formation carbonates. The “Upper Nafun Supersequence” consists of the Shuram Formation clastics and carbonates, which are conformably overlain by the Buah Formation carbonates. According to Forbes et al. (2010) the boundary between the Khufai and Shuram formations is usually picked as an unconformable contact in the subsurface, and is here referred to as the “Sub-Shuram Unconformity”. The Nafun Group is overlain by the Ara Group along the Ara Sequence Boundary or correlative Sub-Ara Unconformity.

Age Models for the Nafun Group

Only the ages for the top and base of the Nafun Group are reliably dated at 547 and 635 Ma (Enclosure and Table 1). The boundaries separating the Nafun formations are not directly dated and the two published age models differ by many 10s of million years (Bowring et al., 2007, 2009; Le Guerroué, 2006; Le Guerroué et al., 2006a, 2006b, 2009; see Forbes et al., 2010; Table 1). The top of the Nafun Group is constrained at 547 Ma by geochronologic data from both outcrops (Fara Formation, Al Jabal al-Akhdar, Figure 1; Brasier et al., 2000; Bowring et al., 2007), and subsurface (Ara Group, South Oman Salt Basin, Figure 1; Amthor et al., 2003; Bowring et al., 2007), as explained by Forbes et al. (2010).

The age for base Nafun Group is estimated by correlation to the end of the Marinoan Glaciation at 635 Ma as summarized here from Forbes et al. (2010). In the cored Lahan-1 Well (Figure 1), the glaciogenic Abu Mahara Group is capped by the carbonates of the Hadash Formation, the basal formation of the Nafun Group. An ash layer, 9 m below the cap carbonate, was dated at 645 Ma and taken as its maximum age (Bowring et al., 2007). The negative δ¹³C excursion to -2 to -4.5‰ in the Hadash Formation in Lahan-1 (Bowring et al., 2007), when compared to the global composite δ¹³C curve of Halverson et al. (2005), convinced Forbes et al. (2010) to correlate the base Nafun Group to the end of the Marinoan Glaciation. The end of the glaciation is constrained by U-Pb zircon dating: (1) ash beds interbedded with upper Ghaub diamicite in central Namibia dated 635.5 ± 0.8 Ma (Hoffmann et al., 2004); (2) ash beds 2.3 m above the Nantuo Tillite in South China dated 635.2 ± 0.8 Ma (Condon et al., 2005); and (3) 636.41 ± 0.45 Ma from a possible volcanilithic dolomitic sandstone in the top meter of the Cottons Breccia on King Island (Tasmania) Australia (Calver et al., 2013).

The calibration of the formation boundaries of the Nafun Group, proposed by Bowring et al. (2007, 2009), uses high-precision geochronology in the lower Ara Group, and a correlation of the δ¹³C curve between Oman and China (Figure 4, modified after Bowring et al., 2007). They used this data to calculate a range for the sediment accumulation rate for the Buah Formation and extrapolated it to the Shuram Formation. The δ¹³C curve in Oman is characterized by the most extreme negative seawater δ¹³C anomaly in Earth’s history, known as the “Shuram δ¹³C Negative Excursion” (Figure 3). The δ¹³C curve swings from about -12‰ in the lowermost Shuram Formation to about +4‰ down-section in the uppermost Khufai Formation (Fike et al., 2006; Le Guerroué, 2006; Figures 3 and 4).

Besides Oman, the excursion is recorded in: (1) Australia’s Wonoka Formation, where it was also first documented (Pell et al., 1993), and hence is also referred to as the “Shuram-Wonoka Excursion” (Calver, 2000); (2) USA’s Johnnie Formation (Corsetti and Kaufman, 2003); (3) China’s Doushantuo Formation (Condon et al., 2005); and (4) Siberia (Melezhik et al., 2009). The excursion provides a global correlative marker, but is limited as a chronostratigraphic tool due to the large uncertainty in its age and duration, and associated unconformities; it is constrained over a range between
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ca. 554 Ma (Bowring et al., 2007; Forbes et al., 2010) and ca. 600 Ma (Le Guerroué, 2006; Le Guerroué et al., 2006a, 2006b, 2009; Macdonald et al., 2013).

In South China the stratigraphic position at which the Shuram δ¹³C curve achieves an up-section value of 0.0‰, the “End Shuram Anomaly”, is dated at 550.5 ± 0.8 Ma (Condon et al., 2005). By correlating this stratigraphic position to Oman, an age of 550.5 Ma is inferred in the Buah Formation (Figures 3 and 4). Bowring et al. (2007, 2009) used the ages of this position, and two more in the lower Ara Group, to calculate sediment accumulation rates that vary between 30 and 100 m/Myr. They chose rates within this range, which when applied in Miqrat-1 imply the age for base Buah Formation is between 552.5 and 551.5 Ma, and base Shuram Formation between 562 and 554 Ma (Table 1). Forbes et al. (2010) took the midpoints of these intervals to give approximate ages of 552 and 558 Ma for the two boundaries (Table 1).

In order to tie the age of 635 Ma for base Nafun Group and maintain a sediment accumulation rate similar to that of the Upper Nafun Supersequence, Bowring et al. (2007, 2009) introduced a hiatus of several 10s of million years between the Upper and Lower Nafun supersequences. Forbes et al. (2010) cautiously adopted this assumption by taking the hiatus to be ca. 32 Myr long between 590 and 558 Ma (Table 1).

Le Guerroué (2006) and Le Guerroué et al. (2006a, 2006b, 2009) argued that there is no evidence for a hiatus in the Nafun Group. Instead they calibrated the Nafun formations using a thermal subsidence model that accounts for compaction. Based on the age of detrital zircons from the upper Khufai Formation they estimated the age for base Shuram Formation at ca. 600 Ma (Table 1). Like Bowring et al. (2007) they concluded that the Shuram δ¹³C Negative Excursion is unrelated to the Gaskiers Glaciation.

### Masirah-1 Age Calibration of the Nafun Formations

The Nafun Group attains its maximum-known thickness in Oman of 2,308 m in the offshore Masirah-1 Well (Figure 1; see figure 6 and table 1 in Allen and Leather, 2006). Table 1 gives the thicknesses of the Nafun formations in Masirah-1, and for comparison in the subsurface type well

### Table 1

**Age Models of the Formations of the Nafun Group (Age in Million Year, Ma; Thickness in meter)**

| Surface and Formation | Al Huqf Type Section Thickness | Al Jabal al-Akhdar Thickness | Miqrat-1 Thickness (Figure 3) | Masirah-1 Thickness (3) | Bowring et al. (2007); Forbes et al. (2010) Age | Le Guerroué et al. (2006a,b) Age | This Study Calculated and (approx.) Age |
|-----------------------|---------------------------------|------------------------------|-------------------------------|------------------------|----------------------------------|-------------------------------|-----------------------------------|
| Top Nafun Group       |                                 |                              |                               |                        | 547                              | 547                           | 547.0 (547)                      |
| Buah Fm               | 0–310 (1)                        | 150 (2)                      | 250                           | 360                    |                                   |                               | + 13.7                           |
| Base Buah Fm          |                                 |                              |                               |                        | 551.5–552.5                      | 575                           | 560.7 (561)                      |
| Shuram Fm             | 230–330 (1)                      | 530 (2)                      | 350                           | 560                    |                                   |                               | + 21.4                           |
| Base Shuram Fm        |                                 |                              |                               |                        | 554–562                          | 600                           | 582.1 (582)                      |
| Sub-Shuram Unconformity|                                |                              |                               |                        | 562–590                          |                               | 0.0                              |
| Top Khufai            |                                 |                              |                               |                        | 590                              | 600                           | 582.1 (582)                      |
| Khufai Fm             | 240–340 (1)                      | 100 (2)                      | 325                           | 250                    |                                   |                               | + 9.5                            |
| Base Khufai Fm        |                                 |                              |                               |                        | 615                              | 610                           | 591.6 (592)                      |
| Masirah Bay Fm        | > 250 (3)                        | 170–200 (3)                  | 111                           | 1,138                  |                                   |                               | + 43.5                           |
| Top Hadash            |                                 |                              |                               |                        | 634.5                            | 634.5                         | N/A                              |
| Hadash Fm             | 15                              | 15                           | 8                             | 0                      |                                   |                               | N/A                              |
| Base Nafun Group      |                                 |                              |                               |                        | 635                             | 635                           | 635.0 (635)                      |

(1) Gorin et al. (1982); (2) Glennie et al. (1974); (3) Allen and Leather (2006)
Miqrat-1, and at outcrop in the Al Huqf type section and Al Jabal al-Akhdar (Figure 1; Glennie et al., 1974; Gorin et al., 1982; Hughes Clarke, 1988; Allen and Leather, 2006). In Masirah-1, the Buah Formation is overlain by Mesozoic carbonates (Beauchamp et al., 1995), and underlain by more than 230 m of the Abu Mahara Group (Allen and Leather, 2006). The Hadash Formation is absent in this well but because its maximum thickness in Oman is only 20 m its depositional duration is likely short (<< 1 Myr; Forbes et al., 2010).

In this paper it is assumed that the ages of the Nafun formations are proportional to their thicknesses in Masirah-1 between 635 and 547 Ma, implying an average sedimentation rate of 26.2 m/Myr (2,308 m/88 Myr; Table 1). This assumption does not account for variations in subsidence, sediment accumulation rates or compaction, which probably varied over time, by lithology and across Oman’s basins (Allen and Leather, 2006; Allen, 2007). Assumptions regarding the quantitative contributions of these variables to the Nafun age model have been made by previous authors with highly conflicting results that differ by 10s of million years (Bowring et al., 2007, 2009; Le Guerroué, 2006; Le Guerroué et al., 2006a, 2006b, 2009; Table 1).

The present author believes that in the absence of age constraints in the Nafun Group adopting the average rate of 26.2 m/Myr is the simplest approach for constructing an approximate Nafun time model. Importantly, this approach coincidently calibrates the Sub-Shuram Unconformity (Shuram δ13C Negative Excursion) at 582.1 Ma in Masirah-1, implying it has the same age as the Gaskiers Glaciation, dated by U-Pb zircon chronometry of tuffs in bounding strata between 584–582 Ma (Bowring et al., 2007; Altermann et al., 2012). This result seems highly likely because it correlates two of the most prominent Ediacaran global events, the Shuram δ13C Negative Excursion and the Gaskiers Glaciation.

In order to further investigate this age correlation, the Nafun model of Bowring et al. (2007) is here reviewed in greater detail. Bowring et al. (2007) obtained a minimum sediment accumulation rate for the lower Ara Group and upper Buah Formation of 30 m/Myr in Miqrat-1 (Figures 1 and 3). Their 30 m/Myr estimate is comparable to the 26.2 m/Myr rate in Masirah-1 obtained in the present study. However, to calculate the oldest possible age of the Sub-Shuram Unconformity, they used a greater rate of 40 m/Myr to convert the thickness of the Buah-Shuram interval (600 m in Miqrat-1) to time (15 Myr). They added the resulting 15 Myr to the age of the top Buah Formation at 547 Ma to arrive at 562 Ma (Table 1). If instead the 30 m/Myr rate is applied in Masirah-1, where the Buah-Shuram interval is 920 m thick, then the Sub-Shuram Unconformity would have an estimated age of 578 Ma, which is much more comparable to the age of the Gaskiers Glaciation (584–582 Ma).

Another important aspect to consider is how Bowring et al. (2007) arrived at the age of the End Shuram Anomaly in Miqrat-1 (Figures 3 and 4). The ages for base Buah and Sub-Shuram Unconformity partly hinge on correlating the position of the End Shuram Anomaly between Oman and China (δ13C = 0.0 at 550.5 Ma). The Masirah-1 calibration of the present study estimates the age of the base Buah at 561 Ma (Table 1), nearly 9 Myr older than its calibration between 552.5 and 551.5 Ma by Bowring et al. (2007). In South China this position occurs just above an unconformity and therefore the curve is incomplete and the correlation uncertain (Figure 4).

More specifically in Miqrat-1, Bowring et al. (2007) picked the End Shuram Anomaly at 3,370 m (“End A” in Figure 3), where the δ13C curve first attains an up-section value of 0.0‰ in the Buah Formation. In contrast, assuming the Buah Formation was deposited uniformly between 547 and 561 Ma in Miqrat-1, implies that 550.5 Ma corresponds to 3,265 m (“End B” in Figure 3). This shallower position results in the alternative and approximate correlation of the trend from 0.0‰ to +6.0‰ in Miqrat-1 to the trend from 0.0‰ to +4.0‰ in China (Figure 4).

The present paper adopts the shallower position for the End Shuram Anomaly in Miqrat-1 as consistent with the Masirah-1 calibration (Table 1), implying the Sub-Shuram Unconformity is coeval to the Gaskiers Glaciation at 584–582 Ma. In the next section this calibration is used to determine if and how the rock units of the Jibalah Group in the Arabian Shield might correlate to the formations of the Huqf Supergroup.
In the Miqrat-1 Well, Oman (from Forbes et al., 2010) the Shuram δ13C Anomaly starts at the excursion from +2.0‰ to -10‰ across the Khufai-Shuram transition, and ends where δ13C returns to 0.0‰ in the Buah Formation. Bowring et al. (2007) picked the End Shuram δ13C Anomaly at 3,370 m (A), whereas this paper suggests it occurs at 3,265 m (B). See Figure 4 for discussion, and Figure 1 for location.
The Jibalah Group crops out in more than 10 isolated basins that formed along the Najd Fault System in the northern Arabian Shield in Saudi Arabia (Figure 2, Delfour, 1970, 1977, 1979, 1980, 1981, 1983; Hadley, 1974, 1986; Brown et al., 1989; Kusky and Matsah, 2003; see reviews in Johnson et al., 2011, 2013, and Al-Husseini, 2011). The chronostratigraphy of the group is documented in just three basins in several recent publications (Figures 1 and 2): (1) Dhaiqa (Miller et al., 2008; Vickers-Rich et al., 2010, 2013); (2) Antaq (Nettle, 2009; Nettle et al., 2013); and (3) Jifn (Halverson et al., 2013). In the following discussion Jibalah Group stratigraphy in these three basins, as well as the Mashhad outcrop and Bir Sija Basin, is briefly reviewed in order to identify key lithostratigraphic units that may serve as rock-time building blocks. For each outcrop the rock-time units are placed in a regional correlation that is based on making several key assumptions as follows.

**Lithostratigraphic Correlations:** Whereas the Nafun and Ara groups were deposited in a mainly marine setting in Oman, the Jibalah carbonates may have been deposited in intermontane lakes (P. Johnson and R. Stern, written communication, 2013), or in generally restricted basins with some communication with the open ocean (G. Halverson and N. Miller, written communication, 2013). In this paper it is assumed that besides glacio-eustasy, global climatic fluctuations also affected the depositional settings across the Middle East region. This assumption implies that carbonates, regardless of whether lacustrine or marine, reflect warmer arid climates and can also be used to guide time correlations between widely separated basins. Thus, in the following discussion, thick successions (100s of meters), which consist of conglomerates, or fine clastics, or sections with carbonates (whether marine or lacustrine), are considered regionally time-correlative units (Enclosure).

**Diachronous Development of Jibalah Basin:** P. Johnson and N. Miller (written communication, 2013) highlighted the possibility that movements along the different Najd fault zones and the development of the Jibalah basins may not have been simultaneous or continuous. This possibility...
is particularly relevant for the Ruwah Fault Zone (Figure 2), along which the Jibalah Group is absent. This zone may have formed and moved before the deposition of Jibalah Group. In this paper the age of movements along the Najd fault zones are not directly addressed. Instead the proposed regional correlations are focused on the few Jibalah basins where lithostratigraphic and chronostratigraphic constraints are available.

Crustal Continuity of Arabian Peninsula: Another concern raised by P. Johnson (written communication, 2013) is that the crust of Oman may not have been adjacent to the Arabian Shield during the Ediacaran–early Cambrian. Instead Oman may have been situated on the flank of a separate continent that included the Indian Plate. The correlations in the present paper are based on the assumption that Oman and the rest of the Arabian Plate were situated in the Rayn Microplate (Al-Husseini, 2000). The Rayn Microplate and the Arabian Shield collided along the NS-trending Amar Suture (ca. 45˚E, Figure 2) between 640 and 620 Ma, and as documented in the following discussion the Jibalah Group is dated by geochronology as younger than the 618 Ma, and more likely ≤ 605 ± 5 Ma. The correlations in this paper are therefore mainly focused in the interval that is younger than 605 ± 5 Ma, the likely age for the Sub-Jibalah Unconformity.

Jibalah Group in Dhaiqa Outcrop

In the Dhaiqa region, the Jibalah Group overlies granitoids (“Dhaiqa Basement”) with a 609 Ma SHRIMP zircon age (Kennedy et al., 2010; Table 2), and consists of the Mataar Formation clastics and overlying Dhaiqa Formation carbonates (Davies, 1985). The undated Mataar Formation (150 m) starts with the “Mataar Polymictic Conglomerate” and grades upward into arkose and lithic arenite (Miller et al., 2008, Figure 5). The Mataar clasts are poorly sorted, subangular to subrounded, and vary in size ranging up to m-scale, matrix-supported outsized boulders. The thickness of the Dhaiqa Formation is between 300 m (Miller et al., 2008) and 400 m (Vickers-Rich et al., 2010). It begins conformably above litharenite of the Mataar Formation as intermittent limestone beds, followed by more-or-less continuous limestone deposition throughout the remainder of the formation (Miller et al., 2008). The Dhaiqa Formation is overlain by the Siq Sandstone Formation along the Sub-Siq Unconformity, which as explained above, correlates to the Angudan Unconformity estimated at 525 ± 5 Ma (Figure 5 and Enclosure).

At level ca. 180 m in the Dhaiqa Formation, a 2–3 m-thick “Intra-Dhaiqa Diamictite” (Figure 5) consists of glauconitic arenite followed by poorly sorted polymict conglomerate, with clasts ranging up to 0.5 m (Miller et al., 2008). Detrital zircons extracted from a fine-grained sandstone in this interval were dated by SHRIMP U-Pb analysis, and the youngest ages in the dataset are from the core (599 ± 4.8 Ma) and rim (570 ± 4.6 Ma) of a single zircon grain. Miller et al. (2008) concluded that because both of these ages occur in the same grain and due to the limited set of observations from which to judge rim/core age relationships, the significance of the rim versus core age is unclear.

In a subsequent study, Vickers-Rich et al. (2010) reported on the results of LA-ICP-MS U-Pb zircon dating of 37 zircon grains recovered from a volcanic ash bed, which is above the Intra-Dhaiqa Diamictite (P. Vickers-Rich, written communication, 2013). Based on the spread of ages between 837 ± 25 and 555 ± 15 Ma, Vickers-Rich et al. (2010)
Figure 5: Proposed correlation of Jibalah Group between the Dhaiqa (Miller et al., 2008) and Mashhad sections (Hadley, 1974) (see Figures 1 and 2 for location). In the Dhaiqa outcrop, the youngest zircon population (17 grains) extracted from an ash bed above the Intra-Dhaiqa Diamictite gave a concordia age of 560 ± 4 Ma by the U-Pb LA-ICP-MS technique (Linnemann and Hofmann, in Vickers-Rich et al., 2010, 2013). The Jibalah Group at these localities is interpreted as the Upper Jibalah Supersequence (582–547 Ma). The Sub-Siq Unconformity separates the Muraykhah and lower Cambrian Siq Sandstone Formation and may span 547–525 ± 5 Ma. The Sub-Mataar Unconformity is interpreted to merge with the Sub-Jibalah Unconformity, and to span 609–582 Ma.
concluded the sample is from a re-deposited volcanic ash, a tuffite. The youngest 17 zircon dates cluster between 563–555 Ma, and gave a concordia age of 560 ± 4 Ma. They interpreted this age as a maximum constraint for sedimentation in the middle part of the Dhaiqa Formation, possibly recording a contemporary volcanic event. Vickers-Rich et al. (2013) obtained an additional LA-ICP-MS U-Pb date of 569 ± 3 Ma based on the youngest zircon samples from the middle Dhaiqa Formation.

**Proposed Regional Correlation**

The youngest-known date for the Dhaiqa Formation is ca. 560 ± 4 Ma (Vickers-Rich et al., 2010; Figure 5 and Table 2), and it could therefore correlate to the Buah Formation if it was deposited between 561 and 547 Ma as inferred from the Masirah-1 calibration (Table 1 and Enclosure). Such a correlation is consistent with one of the options considered by Miller et al. (2008). They measured δ13C values from 10 stratigraphic intervals in the Dhaiqa Formation and concluded that it could correlate to either the Buah Formation or Ara Group.

Assuming the Dhaiqa and Buah are time-correlative then the age of the Mataar Formation would fall between 609 and 561 Ma. The gradational nature of the Mataar-Dhaiqa transition suggests the Mataar Formation correlates to the Shuram Formation (582–561 Ma). Such a correlation implies the basal Mataar Polymictic Conglomerate may be coeval to the Gaskiers Glaciation, and possibly a glacial diamicite (Miller et al., 2008; N. Miller, written communication, 2013). These interpretations suggest the Mataar-Dhaiqa succession forms a second-order sequence, the “Upper Jibalah Supersequence”, a direct correlative to the Upper Nafun Supersequence (582–547 Ma).

The above correlations imply the “Sub-Mataar Unconformity”, which separates the Jibalah Group from the Dhaiqa Basement, represents a hiatus that spans 609–582 Ma (Figure 5). The Sub-Siq (Angudan) Unconformity, which separates the Upper Jibalah Supersequence from the Siq Sandstone at Dhaiqa may span 547 to 525 ± 5 Ma, and correlate to the Ara and Nimr groups in Oman (Enclosure).

**Jibalah Group in Mashhad Outcrop**

The Jibalah Group (905 m) crops out in Mashhad area in the northern Arabian Shield, about 100 km east-southeast of Dhaiqa (Figures 1 and 2). In this outcrop, Hadley (1974) defined the Rubtayn, Badayi and Muraykhah formations in the Jabal Rubtayn type section and correlated them to Jabal Nadah located about 10 km further south (Figure 5). In the type section, the Rubtayn Formation overlies the poorly dated Shammar Rhyolite Group, and the Muraykhah Formation is overlain by the lower Cambrian Siq Sandstone.

Hadley (1974) described the Rubtayn Formation (375 m) at Jabal Rubtayn in terms of ascending “facies”, here considered members: (1) Boulder Conglomerate (75 m thick); (2) Sandstone (200 m); (3) Red Beds (40 m); and (4) Pebble Conglomerate (60 m). In 1986, he divided the Rubtayn Formation in the southeastern Sahil Al Matran Quadrangle (Figures 1 and 2) into three informal members, in ascending order: (1) Volcanic Conglomerate (700 m); (2) Polymictic Conglomerate (1,500 m); and (3) Sandstone (1,000 m) (Enclosure). He also introduced the undivided Rubtayn Formation and undivided Jibalah Group. The type localities and lithological sections for these units are not documented in the Explanatory Notes of the Sahil Al Matran Quadrangle map by Hadley (1986).

In Jabal Rubtayn, the Badayi Formation (120–150 m) conformably overlies the Rubtayn Formation, and consists of well-bedded, 1–3 m-thick, amygdaloidal basalt flows (Hadley, 1974). The conformably overlying Muraykhah Formation starts with the “Basal Muraykhah Conglomerate” (10 m), which has the same appearance as the uppermost Rubtayn Pebble Conglomerate (Hadley, 1974). The overlying Muraykhah Formation (330–370 m) consists in ascending order of two carbonate “facies”, here considered members: (1) lower cherty, non-dolomitic member (135 m); (2) a ca. 20 m-thick interval consisting of red siltstone and mudstone; and (3) upper dolomitic, chert-poor member (135–175 m) (Figure 5).
Proposed Regional Correlation
State-of-the-art U-Pb zircon chronology in the Mashhad area are unavailable. Based on the relative proximity of the Dhaïqa and Mashhad regions (ca. 100 km, Figures 1 and 2) and similar lithology and thicknesses of the Muraykhah and Dhaïqa formations (Figure 5), it is suggested that the latter two formations are coeval. This correlation suggests the Rubtayn Boulder Conglomerate in Jabal Rubtayn may be coeval to the Mataar Formation and the Gaskiers Glaciation. These correlations imply the Jibalah Group in Jabal Rubtayn represents the Upper Jibalah Supersequence (Enclosure).

Jibalah Group in Antaq Basin
The Jibalah Group crops out in the Antaq Basin along the Halaban-Zarghat Fault Zone in the eastern Arabian Shield (Figure 2), and consists of ca. 2,500 m of relatively undeformed and unmetamorphosed conformable sediments (Delfour, 1979; Figure 6, after Nettle et al., 2013). The “Antaq Basement” is dated as older than 618 Ma and possibly older than 597 Ma (Table 3), implying the base Jibalah Group is younger than 618–597 Ma. Nettle (2009) divided the group into the lower and upper Antaq successions, and subsequently Nettle et al. (2013) divided it into the Rubtayn, Badayi and Muraykhah formations, following the definitions in Jabal Rubtayn (Figure 5, Hadley, 1974).

The Rubtayn Formation consists of a basal polymictic conglomerate overlain by mostly arkosic sandstone and siltstone (ca. 1,790 m; Figure 6). At about 1,380 m from the base of the formation a ca. 200 m-thick conglomerate, the “Antaq Polymictic Conglomerate”, has a maximum age of ≤ 573 ± 12 Ma (Nettle, 2009) revised to ≤ 596 ± 17 Ma (Nettle et al., 2013) (Table 3). The Rubtayn Formation is overlain by the volcanogenic Badayi Formation (ca. 100 m thick) consisting of a series of discrete, subaerially extruded, alkali andesite–basalt flows, in places separated by pyroclastic units.

The Muraykhah Formation (650 m) overlies the Badayi Formation. The lower part (ca. 150 m) consists mainly of sandstone. Three sections (S01, S02 and S03), located ca. 5 km apart, each ca. 250 m thick, were measured and logged by Nettle et al. (2013), who used several conspicuous volcanic tuffs to trace between them (Figure 6). The composite section is ca. 500 m thick and consists of mixed fine clastics and carbonates characterized by 21 “fourth-order” transgressive-regressive sequences and 76 parasequences (Nettle, 2009).

Nettle et al. (2013) collected 61 carbonate samples from the three logged sections of the Muraykhah Formation and measured their δ¹³C and δ¹⁸O isotope composition. The δ¹³C values mostly cluster between -4.0‰ and 0.0‰, and show significant scatter both stratigraphically and between sections, with no consistent correlation with facies.

Proposed Regional Correlation
The dates obtained in the Muraykhah Formation are nearly 20 Myr older at the higher stratigraphic position (325 m) than at the lower one (255 m) implying these age constraints only set maximum limits for the Muraykhah Formation (Figure 6). A different criterion for constraining the age of the Muraykhah Formation is the up-section trend of the δ¹³C curve from -4.0‰ to 0.0‰. It resembles that of the Buah Formation rather than the Khufai Formation as characterized by the curve of
Figure 6: Jibalah Group in the Antaq Basin (see Figures 1 and 2 for location, from Nettle, 2009; and Nettle et al., 2013, reproduced by permission of John Wiley & Sons Ltd.). (a) The succession from Basement to the base of the Antaq Polymictic Conglomerate is interpreted as the Lower Jibalah Supersequence (605 ± 5 to 582 Ma), and the succession from base Antaq Polymictic Conglomerate to top Muraykhah Formation is interpreted as the Upper Jibalah Supersequence. (b) Nettle et al. (2013) conclude that the δ13C trend in the upper 500 m of the Muraykhah Formation is similar to the profile through the Buah Formation in Oman (Fike et al., 2006). Note the calibration of the upper 500 m section between 561–547 Ma implies the End Shuram Anomaly (550.5 ± 0.8 Ma) occurs at about 372 m.
If the Muraykhah Formation is correlated to the Buah Formation, then the Antaq Polymictic Conglomerate, by its stratigraphic position, may correlate to the Rubtayn Boulder and Mataar Polymictic conglomerates (Enclosure). Nettle (2009) described the Antaq Polymictic Conglomerate as dominated by sub-rounded clasts of white quartz in a predominantly quartz-feldspathic matrix. The conglomerate is blocky and contains almost no sedimentary structures, with only occasional cross-beds. In support of these correlations is the comparable thickness of the Jibalah Group in Mashhad (905 m), and the 1,050 m-thick succession from base Antaq Polymictic Conglomerate to top Muraykhah Formation in Antaq. The age estimates for the interval just above the Antaq Polymictic Conglomerate, ≤ 573 ± 12 Ma (Nettle, 2009) revised to ≤ 596 ± 17 Ma (Nettle et al., 2013), do not exclude 582 Ma for its age within the error bounds.

These considerations suggest that the succession from base Antaq Polymictic Conglomerate to top Muraykhah Formation represents the Upper Jibalah and correlative Upper Nafun supersequences. The section from Antaq Basement to base Antaq Polymictic Conglomerate is tentatively assigned to the “Lower Jibalah Supersequence” (≤ 618–597 to 582 Ma), a partial correlative to the Lower Nafun Supersequence (635–582 Ma).

### Jibalah Group in Bir Sija Basin

Along the NW-trending Rika Fault Zone, the Jibalah Group crops out in four main basins, (Figure 2): (1) Kibdi; (2) Bir Sija; (3) Sukhaybarah; and (4) Hawaqah. The group in these basins is only briefly described in the explanatory notes of several 1:250,000 quadrangle maps (Delfour, 1970, 1981; Leca and Al-Shanti, 1972; Letalenet, 1979). Only the explanatory notes of the Afif Quadrangle by Letalenet (1979) provide a lithological summary with thicknesses for the units of the Jibalah Group in the Bir Sija Basin (Figure 2). This NW-trending pull-apart basin is ca. 6 x 30 km in areal extent and formed where the sinistral (left-lateral) strike-slip Rika Fault has a left-step offset (Figure 2). In the Bir Sija Basin, the Jibalah Group overlies the poorly dated Shammar Rhyolite Group and consists of eight units, with a total thickness of ca. 2,520 m; in ascending order (Letalenet, 1979; Enclosure and Table 4): (1) Conglomerate with Shammar pebbles (500 m); (2) Andesite-Basalt (150 m); (3) Sandstone (200 m); (4) Polymictic Conglomerate (150 m); (5) Limestone (20 m), the “Bir Sija Limestone”; (6) Sandstone and Mudstone (700 m); (7) Sandstone and Limestone (300 m); and (8) Sandstone and Siltstone (500 m).

### Proposed Regional Correlation

The Jibalah Group in Bir Sija is undated; nevertheless, the lithostratigraphic evolution suggests that units 1–3 (850 m) represent the Lower Jibalah Supersequence (Enclosure). The Upper Jibalah Supersequence (1,170 m) would start with units 4 and 5 (Polymictic Conglomerate and Bir Sija Limestone), possibly a Gaskiers-coeval conglomerate and cap carbonate. Units 4 and 5 may correlate to the lowermost part of the Shuram Formation or a hiatus corresponding to the Sub-Shuram Unconformity. The Upper Jibalah Supersequence would continue with units 6 and 7, possibly equivalent to the Shuram-Mataar clastics and Buah-Muraykhah carbonates, respectively. Unit 8 (500 m) would then correlate to the Ara and Nimr groups of Oman (Enclosure).

The interpretations noted above imply units 4 to 8 (1,170 m) were deposited between 582 and 547 Ma, corresponding to an average accumulation rate of 33.4 m/Myr (1,170 m/35 Myr). Using this conversion gives ages for the top and base Jibalah Group of 532 and 607 Ma, which closely match those of the Sub-Siq (Angudan) and Sub-Jibalah unconformities, at 525 ± 5 and 605 ± 5 Ma, respectively (Table 4). Base Unit 6 (presumed base Murakhah Formation) is about 5 Myr younger than base Buah Formation as estimated in Masirah-1, which may be due to attributing nearly 5 Myr (582–576.9 Ma) to the Gaskiers-coeval units 4 and 5, compared to its estimated duration of about 2 Myr (Le Guerroué, 2006; Altermann et al., 2012).
Table 4
Possible Correlation of Jibalah Group to Huqf Supergroup
(Time and Age in Million Year, Ma; Thickness in meter)

| Surface/Unit       | Thickness | Time (2) | Age      | Age (3) | Surface/Unit       |
|--------------------|-----------|----------|----------|---------|--------------------|
| Bir Sija Basin, Saudi Arabia | Oman      |          |          |         |                    |
| Top Jibalah        |           |          | 532 (2)  | 525 ± 5 | Angudan            |
| Unit 8             | 500       | 14.9     |          |         |                    |
| Top Unit 7         |           |          | 547 (1)  | 547     | Top Buah           |
| Unit 7             | 300       | 9.0      |          |         |                    |
| Top Unit 6         |           |          | 555.9 (2)| 561     | Base Buah          |
| Unit 6             | 700       | 21.0     |          |         |                    |
| Top Unit 5         |           |          | 576.9 (2)|         |                    |
| Units 4+5          | 170       | 5.1      |          |         |                    |
| Top Unit 3         |           |          | 582 (1)  | 582     | Sub-Shuram         |
| Unit 3             | 200       | 6.0      |          |         |                    |
| Top Unit 2         |           |          | 588 (2)  | 592     | Base Khufai        |
| Unit 2             | 150       | 4.2      |          |         |                    |
| Top Unit 1         |           |          | 592.2 (2)|         |                    |
| Unit 1             | 500       | 14.9     |          |         |                    |
| Base Jibalah       |           |          |          | 607.1 (2)|                    |
| Sub-Jibalah        |           |          |          | 605 ± 5 |                    |
| Unconformity       |           |          |          |         |                    |

(1) Assumed age, (2) calculated at 33.4 m/Myr, (3) Masirah-1 Calibration

Gaskiers Cap Carbonate: According to Smith (2009) Glaskiers cap carbonates are typically 5–27 m thick, and are known from occurrences in Newfoundland, North China and Tasmania. In the Middle East, the earliest Ediacaran Hadash Formation of Oman is the only-known cap carbonate and it marks the end of the Marinoan Glacieration at ca. 635 Ma (Figure 3 and Enclosure). No Gaskiers-correlative glacial diamictites or cap carbonates are known in the lowermost Shuram Formation in Oman. Therefore correlating the undated 150 m-thick polymictic conglomerate (unit 4) and overlying 20 m-thick Bir Sija Limestone (unit 5) in the Bir Sija Basin to the Gaskiers Glacieration is speculative, and requires further investigation with chemostratigraphic and geochronologic data.

Badayi Andesite-Basalt Formation: Andesite–basalt flows that are typically 100–150 m thick are named the Badayi Formation of the Jibalah Group in Jabal Rubtayn, Jabal Nadah and the Antaq Basin (Figures 5 and 6). The flows are undated, and in the Enclosure they are not assumed to be time-correlative except in the Mashaad area. In the framework of this paper they may range between ca. 561 and 582 Ma, i.e. older than the Muraykhah Formation and younger than the Sub-Shuram Unconformity. In the Bir Sija Basin, unit 2 also consists of a 150 m-thick andesite-basalt flow, but it is interpreted to be older than 582 Ma because it occurs below units 4 and 5, which may be coeval to the Gaskiers Glacieration.

Jibalah Group in Jifn Basin

The Jibalah Group in the Jifn Basin (ca. 2,710 m thick) is divided into the Umm al-Aisah Formation (ca. 840 m) and overlying Jifn Formation (ca. 1,870 m) (Figures 2 and 7, after Delfour, 1970; Kusky and Matsah, 2003; Halverson et al., 2013; Table 5 and Enclosure). The Umm al-Aisah Formation was also recognized by Delfour (1970) in the Jibalah Basin (Figure 2), where he defined the Jibalah Group. In the Jifn Basin the Umm al-Aisah Formation consists of a lower volcaniclastic unit (ca. 500 m; “Lower Conglomerate” of Delfour, 1970), and the upper “Umm al-Aisah Limestone” (ca. 340 m).
Halverson et al. (2013) reported that carbon-isotope values in the Umm al-Aisah Limestone mostly lie between 5.0‰ and 8.0‰.

The overlying Jifn Formation (ca. 1,870 m) starts with the “Jifn Polymictic Conglomerate” (≥200 m, “Upper Conglomerate” of Delfour, 1970) and grades upwards to alternating decimeter-thick beds of sandstones, siltstone, shale, minor conglomerates and carbonates (ca. 1,670 m). The thickness of the Jifn Formation is estimated from the cross-section depicted by Delfour (1970); however, G. Halverson (written communication, 2013) cautioned that the cited thickness may not be very precise.

Proposed Regional Correlation: An Exceptional Basin?
The constraints (1) Jifn Formation is older than 576.6 ± 5.3 Ma (Kusky and Matsah, 2003); (2) basal part of the Umm al-Aisah Limestone is younger than 589.5 ± 0.5 Ma (Halverson et al., 2013); (3) ca. 580 Ma estimate for the Umm al-Aisah Limestone (Halverson et al., 2013); and (4) 5.0–8.0‰ δ13C values (Halverson et al., 2013), provide several criteria for correlating the Umm al-Aisah Limestone to the Khufai Formation (592–582 Ma). This correlation implies the Umm al-Aisah Formation represents the Lower Jibalah Supersequence, and the Jifn Formation the Upper Jibalah Supersequence. The “Sub-Jifn Unconformity” separates the supersequences.

The proposed assignment of these rock units to the two supersequences raises several issues. The first one is that the top Jifn Formation is shown at ca. 525 Ma in the Enclosure, or about 50 Myr younger than allowed by the radiometric dating of 576.6 ± 5.3 Ma obtained by Kusky and Matsah (2003). A second issue is that the Umm al-Aisah Limestone in the Jifn Basin is not recognized in the other reviewed Jibalah outcrops. Conversely, the Muraykhah-Buah marine flooding interval, interpreted in other outcrops, is not identified in the Jifn Basin. Some of these issues are addressed below.

Dating of the Jifn Formation?
A sample taken from a felsite dike that cuts the Jifn Formation in the Jifn Basin gave a TIMS U-Pb zircon age of 576.6 ± 5.3 Ma (Kusky and Matsah, 2003; Enclosure), and this date is widely quoted in the literature as the younger depositional limit of the Jibalah Group. The underlying Umm al-Aisah Limestone is dated as ≤589.5 Ma about 30 m above its base, implying it has an age of ca. 580 Ma (Halverson et al., 2013). These two dates would therefore constrain the deposition of the Jifn Formation between ca. 580 and 576.6 ± 5.3 Ma. The present author believes this interpretation is wrong based on the implied sediment accumulation rate for the Jifn Formation, when compared to that of the underlying Umm al-Aisah Formation (Table 6).

Assuming the Jifn Formation was deposited between 580–576.6 Ma, or even 582–571.3 Ma (the maximum interval implied by correlation to the Gaskiers Glaciation and the error bound of -5.3 Ma), implies rates of between 175 and 550 m/Myr, nearly 3 to 25 times greater than for the underlying Umm al-Aisah Formation (20–47 m/Myr; Table 6). In contrast, converting at an average rate of 34 m/Myr, as obtained for the underlying Umm al-Aisah Limestone (Table 6), gives an age of 582–526 Ma. The latter calibration suggests the Jifn Formation correlates to the Upper Jibalah Supersequence (582–547 Ma), as well as the Ara and Nimr groups of Oman (547–525 ± 5 Ma).

Table 5
Age of Jibalah Group, Jifn Basin

| Rock Unit          | Age (Ma)     | Rate (m/Myr) |
|--------------------|--------------|--------------|
| Jifn Formation     | ≥576.6 ± 5.3 | 20–30        |
| Umm al-Aisah       | ≤589.5 ± 0.5 | 30–47        |
| Limestone at 30 m  | ≤589.5 ± 0.5 | 30–47        |
| above its base     | CA. 580 Ma   | 30–47        |
| Umm al-Aisah       | 589.5–580    | 30–47        |
| Limestone          | 592–582      | 30–47        |
| Jifn Basement      | ≥624.9 ± 4.2 | 550          |

Table 6
Average Sediment Accumulation Rates in Jifn Basin

| Rock Unit          | Thickness (m) | Age (Ma)     | Rate (m/Myr) |
|--------------------|---------------|--------------|--------------|
| Umm al-Aisah       | 840           | 624.9–582    | 20–30        |
| Formation          |               | 610–582      | 30–47        |
|                    |               | 607–582      | 34–47        |
|                    |               | 600–582      | 34–47        |
| Umm al-Aisah       | 320           | 589.5–580    | 30–47        |
| Limestone          |               | 592–582      | 30–47        |
| Jifn Formation     | 1,870         | 580–576.6    | 550          |
|                    |               | 582–571.3    | 175          |

(meter per million year: m/Myr)
**Muraykhah-Buah Marine Flooding Interval in Jifn Basin?**

The “Muraykhah-Buah marine flooding interval” is interpreted in the Mashhad, Dhaiqa, Antaq and Bir Sija outcrops, but is not recognized in the Jifn Basin (Enclosure). Delfour (1970) reported that the Jifn Formation includes finely stratified beds of siltstone (millimeter to centimeter, sometimes 10 cm thick) that are occasionally intercalated with thin lenses of carbonates. The siltstone beds terminate with ripple marks before passing to argillaceous, varicolored (brown, green and yellow), sometimes carbonaceous and organic-rich shale. The stratigraphic position of the carbonates occurs in the middle part of the Jifn Formation in the depiction of Delfour (1970) in Figure 7. This interval may represent the Muraykhah-Buah marine flooding interval.

The Jifn Basin may have been restricted like the Antaq Basin. Nettle (2009) and Nettle et al. (2013) conclude that although much of the Jibalah Group in the Antaq Basin was likely deposited in a non-marine environment, sedimentary structures in the middle–upper Muraykhah Formation imply deposition in a shallow, marginal-marine environment. This interval consists of a succession of mixed shale, siltstone and carbonate characterized by 5–20 m-thick, transgressive-regressive (T-R) “fourth-order” sequences (Figure 6). In section SO2, the typical sequence has a sharp base and comprises convoluted shale or rippled siltstone, fining upward to a subtle marine flooding surface, then grading upward into fine to medium feldspathic sandstone with swaley cross-stratification, symmetric and asymmetric ripples, and tabular cross-bedding. Carbonates are common in the cycles and variably occur near the marine flooding surface or at the tops of cycles as carbonate-cemented fine sands or nodular cements.

**Khufai Marine Flooding Interval?**

The Umm al-Aisah Limestone is found in the Jifn and Jibalah and possibly other basins, but not as a marine-influenced unit in the Antaq Basin. If it represents the “Khufai marine flooding interval” then the open sea would have been in the east towards Oman. The Jifn and Antaq basins are located on the Halaban-Zarghat Fault Zone (Figure 2) and the latter is closer to Oman but does not apparently record this marine incursion below the Antaq Polymictic Conglomerate (Figure 6). It is conceivable that it is hidden in the fine clastics or the non-exposed sections of the Rubtayn Formation, a matter that requires further field investigation.

In the Bir Sija Basin, the Lower Jibalah Supersequence (850 m) has the same thickness as in the Jifn Basin (840 m), but the Khufai marine flooding is not recognized. Perhaps the 200 m-thick sandstone unit 3 contains subtle evidence for the Khufai marine flooding; once again a matter that requires further field investigation. Nor do Jibalah sediments record the Khufai marine flooding interval in the northwest in the Dhaiqa and Mashhad outcrops, where the Lower Jibalah Supersequence is interpreted to be missing (Enclosure). The absence of the lower supersequence in these basins suggests they may have formed at a later time.

**Lacustrine Umm al-Aisah Limestone?**

Another possibility for explaining the absence of the Khufai marine flooding in all the Jibalah basins is that it was deposited in intermontane lakes. Favoring this lacustrine interpretation is the study by Halverson et al. (2013). They noted that the \(^{87}\text{Sr}/^{86}\text{Sr}\) data from the Umm al-Aisah Limestone are much lower than the accepted seawater values for the middle Neoproterozoic (ca. 0.7085), implying that the basin was largely restricted from the open sea. The variable restriction is also reflected by the highly variable \(^{18}\text{O}\) values, some of which are > 0‰. Low-resolution sulfur-isotope data on carbonate associated sulfate show extraordinary variability, but they postulated that this variability may be linked to the volcanic tuff horizons and associated organic-rich and methanogenic (?) intervals. The lacustrine interpretation, however, does not explain why the 200–320 m-thick Umm al-Aisah Limestone was not simultaneously deposited in similar lakes in other Jibalah basins. It was presumably deposited during a period of arid conditions, and most likely over a period of ca. 10 Myr at the same time as the Khufai Formation (592–582 Ma).

**Narrow Sea in the North?**

The Khufai marine flooding arriving from the north is another possible explanation for its limited distribution. Kusky and Matsah (2003) based on BRGM reports (Brosset, 1970; Delfour, 1983; not seen by the present author) note that the Sumaymiyah and Zarghat basins, located further north...
Figure 7: Type section of the Umm al-Alia and Jifn formations of the Jibalah Group, Jifn Basin (see Figures 1 and 2 for location; after Delfour, 1970).

(a) Geologic map in the Jabal Umm al-Alia (also spelled Umm Leissah) area based on air photography at 1:20,000 scale and geological map at 1:100,000 scale. (b) The Umm Al-Aisah Formation consists of the Lower Conglomerate and Cherty Limestone units, here assigned to the Lower Jibalah Supersequence. The Jifn Formation consists of the Polymictic Conglomerate overlain by finer clastics. The limestones interbedded with sandstone in middle of the Jifn Formation are interpreted as the Muraykhah marine-flooding interval.
(Figure 2) contain deposits that resemble those in the Jīfn Basin. Hutin (1983) suggested this scenario in a BRGM report as part of an extensive BRGM feasibility study to mine phosphates from the Jībahah carbonates. The study covered the Mashhad area and extended from the Bir Sija Basin in the southeast to the Zarghat Basin in the northwest (Figure 2). He tentatively concluded that the open sea was located north of the Arabian Shield, whereas an evaporitic setting prevailed to the east. In his report, however, he did not consider the possibility that the Umm al-Aisah Limestone and Muraykhah Formation may not be correlative. This assumption was also made in Al-Husseini (2011) and now seems incorrect.

Erosion by Gaskiers Glaciers?
The Umm al-Aisah Limestone, regardless of whether marine or lacustrine, may have been preferentially eroded if Gaskiers-coeval ice sheets covered the Arabian Shield. The limestones would have been situated immediately below the ice sheets and therefore the first candidates to be eroded. Indeed Kusky and Matsah (2003) note that fanglomerates in the Jīfn Basin “contain angular to sub-angular cherty limestone clasts of Jībahah Group … and that these fanglomerates were deposited after deposition of some of the Jībahah limestones.” It is therefore possible that the Umm al-Aisah may have been more widespread and eroded by glacial processes.

Stern et al. (2006) pointed out that whether ice sheets extended over the Arabian Shield has not been widely explored in the literature, largely because unequivocal evidence for glaciation of the appropriate age has not been found. The required evidence may include, for example, scratches and striations on boulders, dropstones, etc. They suggested: “clast lithology and age may be better ways of determining whether or not Arabian-Nubian Shield diamictries are glaciogenic. Those that may be glacial in origin should contain a large diversity of lithologies, shapes, and sizes (polymict conglomerate or heterolithologic breccias, depending on clast shape).” These criteria seem to be satisfied in the Jīfn Basin (Figure 7) by the ≥ 200 m-thick Jīfn Polymictic Conglomerate overlying the 320 m-thick Umm al-Aisah Limestone dated at ca. 580 Ma (Halverson, written communication, 2013).

Indeed as noted by Stern et al. (2006) and Miller et al. (2008), Kusky and Matsah (2003) show in their figure 7d a photograph of a possible glacial dropstone in the Jīfn Formation (unknown stratigraphic position in the Jīfn Formation). G. Halverson (written communication, 2013), however, noted that this photo is not diagnostic of a dropstone, and that he saw no evidence for glacial rocks in the Jīfn Basin. Possible evidence for glaciation was also reported in the Shaghab Quadrangle in NW Arabia by Vickers-Rich et al. (2010). It consists of possible glacial diamicrites and dropstones in the Naghr Formation, which is presumed to correlate to the Jībahah Group.

ORBITAL-TUNING OF THE EDIACARAN TO MID-CAMBRIAN

The global Marinoan ice age came to a relatively abrupt end at ca. 635 Ma as characterized by the boundary between the Abu Mahara glaciogenic rocks and overlying Hadash cap carbonate (Forbes et al., 2010; Figure 3). The sharp boundary separating the Umm al-Aisah Limestone and the overlying Jīfn Polymictic Conglomerate, implies an abrupt switch from an extended period of arid climate to pluvial-humid conditions, possibly the Gaskiers Ice Age (Figure 7). In Oman, this switch is similarly characterized by the Khufai–Shuram transition as a change from pluvial-humid to arid conditions (Le Guerroué, 2006). The Ara Group represents one more climate switch that began at 547 Ma with a drop in relative sea level and an extremely arid environment in Oman (Enclosure). The Burj Sequence Boundary, which separates the continental Siq Sandstone Formation from the overlying marine Burj carbonates and shales (Al-Husseini, 2010a), represents another sharp eustatic event, dated by biostratigraphy near the Series 3/Series 2 boundary of the Cambrian at ca. 509 Ma (Enclosure). The Angudan Unconformity may be partly tectonic and partly related to a climate switch (Enclosure).

These changes in climate and sea level correspond to regional sequence boundaries across the Middle East. The 635 and 582 Ma switches are clearly global glacio-eustatic events, but their triggering mechanism is not understood. A phenomenon that may have caused them is orbital-forcing glacio-eustasy. Matthews and Al-Husseini (2010) constructed a time scale that predicts
Table 7

Empirical and Orbital Ages (Million Years, Ma)

| Surface                        | Authors            | Empirical Age          | Orbital Scale |
|--------------------------------|--------------------|-------------------------|---------------|
| Burj Sequence Boundary         | Powell et al. (2014) | Cambrian Series 3/2 Boundary ca. 509 | 511.8         |
| Angudan Unconformity           |                    | ca. 525 ± 5             | 526.4         |
| Basalmost Ara Group            | Bowring et al. (2007) | 546.7                   | 545.9         |
| Top Nafun                      | Forbes et al. (2010) | 547                     |               |
| Gaskiers Glaciation            | Bowring et al. (2007) | 582                     | 579.9         |
|                                | Altermann et al. (2012) | 584–582                 |               |
| End Marinoan Glaciation        | Hoffmann et al. (2004) | 635.5 ± 1.2             | 633.4         |
|                                | Condon et al. (2005)  | ≤ 635.2 ± 0.6            |               |
|                                | Calver et al. (2013)  | 636.41 ± 0.45           |               |
| Start Marinoan Glaciation      | Stern et al. (2006)  | 660–650                 | 648.0         |

glacio-eustatic drops (regional sequence boundaries and their correlative unconformities) occur when the Earth's orbit approaches a circle. This phenomenon is caused by the gravitational attraction between the planets, which causes the Earth's orbit to oscillate between high eccentricity (ca. 5%) and zero eccentricity (circle).

The building blocks of the scale are 0.405 Myr long-eccentricity orbital cycles that tune transgressive-regressive sequences named “stratons”. These orbital cycles are manifested in the late Permian as shown in a study by Wu et al. (2013). The orbital scale predicts that 12 stratons form one “dozon” that lasts 4.86 Myr and is bounded by regional sequence boundaries starting at 1.586 Ma (Enclosure). The application and accuracy of this scale for the mid-Permian to Early Triassic was tested with encouraging results (Al-Husseini and Koehrer, 2013), but its application to the Ediacaran Period remains to be shown.

In the Antaq Basin, Nettle (2009) interpreted approximately 21 transgressive-regressive, “fourth-order” sequences formed by about 72 “parasequences” in the upper 500 m of the Muraykhah Formation. The occurrence of these sequences suggests that orbital-forcing may have played a driving role for Ediacaran–Cambrian glacio-eustasy.

By adding multiples of 4.86 Myr starting at 1.586 Ma, the orbital scale predicts the regional sequence boundaries shown in Table 7 and the Enclosure. It predicts that the Lower Nafun Supersequence lasted 53.5 Myr between 633.4–579.9 Ma compared to the empirical estimate of 635–582 Ma, and to consist of 11 dozons (53.5 = 11 x 4.86 Myr). The Upper Nafun Supersequence is predicted to have lasted 34.0 Myr between 579.9–545.9 Ma compared to the empirical estimates of 582–547 Ma, and to consist of 7 dozons (34 = 7 x 4.86 Myr).

CONCLUSIONS

Lithostratigraphic, radiometric and chemostratigraphic data from the Nafun Group in Oman and the Jibalah Group in the Arabian Shield are used to revise the Ediacaran–Cambrian Middle East Geologic Time Scale (Figures 1 and 2, Tables 2, 3 and 5, Enclosure). Several key age calibrations and correlations in the time scale are summarized as follows.
Sub-Shuram Unconformity: This unconformity represents the globally recognized Shuram δ\(^{13}\)C Negative Excursion (Figures 3 and 4, Enclosure), but its age is poorly constrained between 554 and 600 Ma. In this paper, by assuming an average sediment accumulation rate for the Ediacaran Nafun Group in the Masirah-1 Well, where it attains its greatest-known thickness in Oman, an age model for the Nafun formations was calculated and compared to other models (Table 1). The Nafun age model of the present paper does not conflict with any known constraints, and coincidently estimates the age of the Sub-Shuram Unconformity at 582 Ma, implying it time-correlates to the mid-Ediacaran Gaskiers Glaciation (584–582 Ma; Bowring et al., 2007; Altermann et al., 2012; Figure 3 and Enclosure).

Correlation of Khufai Formation and Umm al-Aisah Limestone: The Khufai Formation (250 m thick in Masirah-1) of the Nafun Group immediately underlies the Sub-Shuram Unconformity (Figures 1 and 3, Enclosure). The Nafun model of the present paper estimates its age between ca. 592 and 582 Ma (Table 1). In the Jifn Basin in the Arabian Shield (Figures 2 and 7), the Umm al-Aisah Limestone is 320 m thick, dated ≤ 589.5 ± 0.5 Ma about 30 m above its base, and has δ\(^{13}\)C values that are consistent with a correlation to the Khufai Formation (Halverson et al., 2013). These considerations support a correlation between the Umm al-Aisah Limestone and the carbonates of the Khufai Formation, as calibrated by the Nafun model in the interval ca. 592–582 Ma.

Correlation of Sub-Shuram and Sub-Jifn Unconformities: In the Jifn Basin the Sub-Jifn Unconformity separates the Umm al-Aisah Limestone from the overlying Jifn Polymictic Conglomerate (≥ 200 m thick, Figures 2 and 7, Enclosure). If the Khufai Formation and Umm al-Aisah Limestone are correlative as proposed above, then so too are their capping Sub-Jifn and Sub-Shuram unconformities (Enclosure).

Gaskiers Glaciation: The correlation of the Sub-Shuram and Sub-Jifn unconformities implies the Jifn Polymictic Conglomerate is coeval to the Gaskiers Glaciation, and correlates to either the lower part of the Shuram Formation or a hiatus corresponding to the Sub-Shuram Unconformity (Enclosure). However, no evidence for the Gaskiers Glaciation is conclusively recognized in the Jifn Formation, or in the lower part of the Shuram Formation. These units should be investigated for glaciogenic features. Also worthy of investigation is a 20 m-thick limestone overlying a 150 m-thick polymictic conglomerate in the Bir Sija Basin, which may be a possible Gaskiers-coeval cap carbonate (Figure 2 and Table 4).

Correlation of Buah and Dhaiqa Formations: The Nafun model estimates the depositional age of the Buah Formation (360 m thick in Masirah-1) of the Nafun Group between 561 and 547 Ma (Table 1). In the northwestern Arabian Shield, the Dhaiqa Formation of the Jibalah Group is 400–500 m thick (Figures 2 and 5). The youngest zircon population in its middle part is dated 560 ± 4 Ma (Vickers-Rich et al., 2010), and δ\(^{13}\)C values measured from its carbonates are consistent with those of the Buah Formation or Ara Group (Miller et al., 2008). In the time scale the Dhaiqa Formation is correlated to the Buah Formation, as calibrated by the Nafun age model in the interval ca. 561–547 Ma.

Buah and Khufai Marine Flooding: The carbonates of the Buah and Dhaiqa formations, and likely-correlative Muraykhah Formation in the Mashhad and Antaq basins, may represent a widespread marine flooding over parts of the Middle East. The distribution and depositional setting (restricted marine or lacustrine) of the Umm al-Aisah Limestone is unclear and requires further investigation; nevertheless it is here interpreted to be coeval to the Khufai Formation.

Angudan Unconformity: The Sub-Siq (Saudi Arabia), Sub-Salib or Ram (Jordan), Sub-Lalun (Iran) and Angudan (Oman) unconformities were previously correlated at 525 ± 5 Ma and given the unifying name “Angudan Unconformity” in Al-Husseini (2010a; Enclosure). The present paper adds that this unconformity is recognized throughout the Middle East and North Africa, where it has been named “lower Cambrian peneplain” or “Afro-Arabian Peneplain” (e.g. Stern et al., 2006; Miller et al., 2008).
**Sub-Siq (Angudan) Unconformity:** In the northwestern Arabian Shield, this unconformity may span the interval 547–525 ± 5 Ma (Figure 5). In the Jifn and Bir Sija basins, clastic units in the uppermost Jibalah Group may represent deposition during this time interval and correlate to the Ara and Nimr groups of Oman (Figure 7, Table 4 and Enclosure). This correlation, however, implies the radiometric date obtained by Kusky and Matsah (2003) for the upper limit of the Jifn Formation is incorrect – a matter that requires further evaluation.

**Sub-Jibalah Unconformity:** (Figure 2, Tables 2, 3 and 5, and Enclosure): Radiometric dating of basement rocks below the Jibalah Group are: ≥ 625 Ma in Jifn (Kusky and Matsah, 2003); ≥ 597 Ma (Kennedy et al., 2010) or ≥ 618 Ma in Antaq (Nettle et al., 2013); and ≥ 609 Ma in Dhaiqa (Kennedy et al., 2010). The model presented in the time scale assumes the oldest Jibalah basins started forming at about the same time and estimates the age of the Sub-Jibalah Unconformity at 605 ± 5 Ma.

**Ediacaran Supersequences:** In the time scale the Ediacaran Period (635–541 Ma, Enclosure) is represented by (1) the Lower Nafun Supersequence (635–582 Ma) and its part-correlative Lower Jibalah Supersequence (605 ± 5 – 582 Ma); (2) correlative Upper Nafun and Upper Jibalah supersequences (582–547 Ma); and (3) the lower part of the Ara Group (547–541 Ma). The Lower Nafun Supersequence is bounded by the Marinoan and Gaskiers glacialions, and the Upper Nafun Supersequence by the Gaskiers Glaciation and the Ara Group. These supersequences are interpreted to carry the signature of glacio-eustasy and global climatic fluctuations, possibly related to orbital-forcing.

The above correlations between the northern Arabian Shield and Oman cover a distance of about 2,000 km. They are weakly constrained in just a few localities where lithostratigraphic, geochronologic and chemostratigraphic data are available. Therefore acquiring similar data, particularly from the Jibalah Group at outcrop, is critical in order to refine and/or revise the time scale. Publication of seismic data that image the Neoproterozoic and data from boreholes that penetrate the Neoproterozoic can substantially improve our understanding of the evolution of the Ediacaran and Cambrian periods in the Middle East and beyond.

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