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Ediacaran Araba Complex of Jordan

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ABSTRACT

The Ediacaran Araba Complex in Jordan is defined and described for the first time in lexicon style, with an emphasis on the sedimentary, volcanic and volcaniclastic units outcropping adjacent to Wadi Araba, and from seismic and deep exploration well data. The Araba Complex ranges in age from ca. 605 to 550 Ma and comprises a major cycle of sedimentary, volcanic and volcaniclastic, and igneous rocks emplaced in an overall extensional tectonic regime that followed intrusion and amalgamation of the granitoid and metamorphic Aqaba Complex, a part of the Gondwanan Arabian-Nubian Shield (ANS; ca. 900 to 610 Ma).

The Araba Complex is bounded by two major erosional unconformities, the newly defined Ediacaran Araba Unconformity (ca. 605 Ma) at its base, underlain by the Aqaba Complex, and the post-extensional, regional lower Cambrian Ram Unconformity (ca. 530 Ma) that is marked by the widespread deposition of thick alluvial and marginal-marine siliciclastics (Ram Group).

Two sub-cycles can be recognised in the Araba Complex mega-cycle. The earliest (Safi Group) followed suturing and extensional rifting of the Aqaba Complex that resulted in rapid basinal subsidence and the deposition of coarse-grained, polymict conglomerates (Saramuj Formation) in predominantly proximal, but evolving to more distal, alluvial fan settings. The early extensional basin appears to have been orientated approximately north-south (depocentre to the west) and can be traced from north Sinai to Lebanon, approximately parallel to the present-day Dead Sea Transform. Rounded clasts, up to boulder-size, include a variety of local to regionally-derived basement lithologies, including granites, diorites, metamorphic rocks; doleritic and rhyolitic dyke rocks. Rapid isostatic uplift and weathering of the granitoid basement resulted in high sediment flux that kept pace with rapid basin subsidence; this, in turn, led to erosion and partial peneplanation of the hinterland ANS. Regional detrital zircon ages from the conglomerate clasts and matrix indicate age ranges from ca. 650 to 600 Ma with a minor cluster between 750 to 700 Ma, indicating mostly a local or, at least, near-field provenance. Subsequent to this early, rapid basin-fill, continued crustal extension resulted in tapping of rhyolitic and basaltic effusive volcanics and volcaniclastics (Haiyala Volcaniclastics and Museimir Effusives, ca. 598–595 Ma), including flow-banded rhyolitic lavas and air-fall tuffs, the latter deposited in a lacustrine or shallow-water environments.

The second Araba sub-cycle (595–586 Ma) is characterised by renewed basinal subsidence, very low burial metamorphism to about 6 km depth, and associated stock-like intrusion of the Qunaia Monzogabbro (595 ± 2 Ma) that resulted in thermal contact metamorphism of the Saramuj conglomerate, as well as granite plutons (e.g. Feinan-Humrat intrusions) and dolerite dykes. The second cycle is characterised by renewed extension, rifting and the deposition of volcanic rocks, agglomerates (Aheimir Volcanics) and monomict conglomerates (Umm Ghaddah Formation) that were sourced, locally, from volcanic rocks on the rift margins.

To the east, in the sub-surface of south-central Jordan, the early Safi sub-cycle is absent. Deep exploration wells and seismic data in the Jafr area demonstrate that the Araba Complex comprises terrestrial lavas (Ma'an Formation) with weathered soil horizons, unconformably overlying weathered Aqaba Complex granitic basement (Araba Unconformity). Seismic data in the Jafr region records the eruption of lavas in north-south trending graben and half-graben settings, and possible northwest-trending bounding faults similar to the Najd basins in Saudi Arabia. Again, in contrast to the outcrop areas to the west, the upper part of the Araba Complex, hereabouts, consists of fine-grained, in part carbonate-cemented sandstone and claystone, together with anhydrite (Jafr Formation) suggesting a shallow-marine or coastal sabkha setting, and a possible link to similar shallow-marine extensional basin-fills that developed widely within NW-trending Najd basins across the ANS in Saudi Arabia (e.g. Jibalah and Antaq basins). To date, no Ediacaran biotas have been described from the Araba Complex, but the Jafr Formation, which post-dates the appearance of soft-bodied faunas around 579 Ma, and which was probably deposited in marginal-marine environments, is a potential candidate for these enigmatic fossils.

Subsequent to the final Araba extensional rifting phase, renewed regional uplift, far to the south, of the ANS hinterland during the early Cambrian, led to widespread deposition of alluvial and shallow-marine siliciclastics as a progradational 'sand-sea' (Ram Group) that blanketed the now peneplained Aqaba Complex in south Jordan and surrounding countries (Ram Unconformity). However, the younger Ediacaran Araba Complex outcrops adjacent to Wadi Araba remained, in places, as a relatively immature palaeotopography. It was not until early mid-Cambrian times (ca. 509 Ma), during the Burj marine transgression that this late Ediacaran palaeotopography was finally buried.

The Araba Complex in Jordan with its multi-cycle development provides an insight to the regional development of Ediacaran extensional basins in the Arabian-Nubian Shield, an important phase in the evolution and transition from Neoproterozoic to Phanerozoic crustal tectonics and associated basin-fill.

INTRODUCTION

The Ediacaran Period (635–541 Ma) represents an important interval in the history of the Earth, involving the transition from the Proterozoic to the Phanerozoic eons, and an important phase in the evolution of life (Knoll et al., 2006; Narbonne et al., 2012 and references therein). In Jordan, the latest Cryogenian to Ediacaran-age rocks include some of the youngest strata and intrusives that comprise the last phase of amalgamation of the Arabian-Nubian Shield (ANS) and the passage from Proterozoic to Phanerozoic tectonic processes, and geological and biotic evolution, including the amalgamation and assembly of the Gondwana Supercontinent during the late Neoproterozoic (Stern, 1994, 2002; Johnson et al., 2011, 2013). The focus of this paper is the predominantly volcano-sedimentary Araba Complex (Powell, 1988; McCourt and Ibrahim, 1990; Jarrar et al., 2013) and its associated granitoid intrusions that formed over the time period ca. 605–550 Ma, following intrusion and amalgamation of the metamorphic and post-tectonic granitoid Aqaba Complex (McCourt and Ibrahim, 1990; Jarrar et al., 2013).

The Ediacaran Period is characterised by a unique biota that evolved after the Cryogenian Marinoan ('Snowball Earth') Glaciation, the cap carbonate of which marks the base at 635 Ma (Knoll et al., 2006; Hoffman, 2011). Soft–bodied Ediacaran biota such as *Fractofusus* and *Charniodiscus* (Boynton and Ford, 1995) that characterise much of the period, appear later than the spiny achritarchs and simple animal embryos found above the cap carbonate (Knoll et al., 2006). These soft-bodied faunas first appeared after the subsequent mid-Ediacaran Gaskiers Glaciation (584–582 Ma) at around 579 Ma (Narbonne et al., 2012), and are followed by bilateral burrows (ca. 555 Ma) and calcified animals such as *Cloudinia* at 550 Ma. Ediacaran biotas became extinct before the Ediacaran/Cambrian boundary at 541 Ma, which is marked by large complex shelly faunas and complex infaunal burrows (Brasier et al., 1996). In the Middle East, the Cryogenian/Ediacaran and Ediacaran/Cambrian boundaries are currently calibrated only in Oman (see Amthor et al., 2003; Forbes et al., 2010; Al-Husseini, 2014). The latter boundary has historically been named the Precambrian/Cambrian Boundary (PCB).

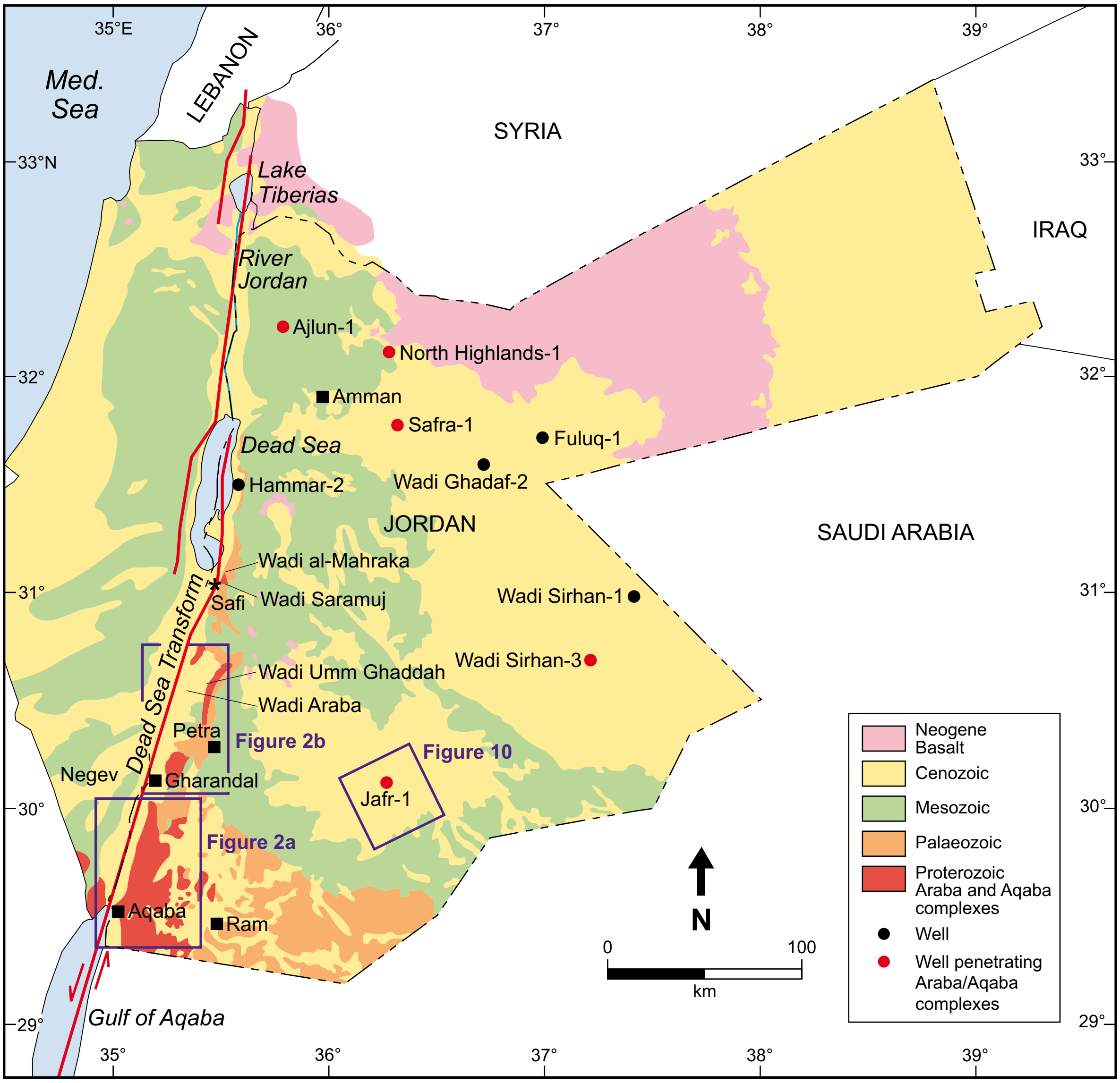


Figure 1: Generalised geological map of Jordan showing location of outcropping Proterozoic rocks (after Natural Resources Authority, Jordan), and the position of deep exploration wells that penetrated Palaeozoic strata and the Araba and Aqaba complexes (after Andrews, 1991). Inset maps refer to Figures 2a and 2b and Figure 10.

In Jordan, Ediacaran sedimentary, igneous and volcanic rocks, defined as the Araba Complex crop out in narrow, elongate NS- to NE-trending, fault-bounded blocks adjacent to Wadi Araba from Safi, at the southern end of the Dead Sea, southwards to the Gharandal area; it is also present in the form of small plutons of alkali feldspar granite to the east and northeast of Aqaba (Bender, 1974; Powell, 1988; McCourt and Ibrahim, 1990; Jarrar et al., 1991; Amireh et al., 2008; Figures 1 and 2). Ediacaran sedimentary, volcanic and volcaniclastic rocks have also been proved in deep exploration wells in east, southeast and north Jordan (Andrews, 1991) and seismically below the Golan Heights (Meiler et al., 2011). Ediacaran rocks in Jordan, and similar rocks in the Eilat area (Weissbrod and Sneh, 2002), which is offset from the Jordan outcrops by ca. 110 km left-lateral shear on the Dead Sea Transform (DST) (Freund et al., 1970), consist mostly of alluvial conglomerates and associated braided-river siliciclastics, volcanic effusives and extrusives and dyke rocks, and volcaniclastic deposits, along with granitoid stocks and minor monzogabbros and diorites, in a broadly rifted or half-graben tectonic setting. Consequently, the Ediacaran rocks of Jordan and surrounding countries represent an important part of the late Neoproterozoic 'jigsaw' that comprises the Arabian Plate.

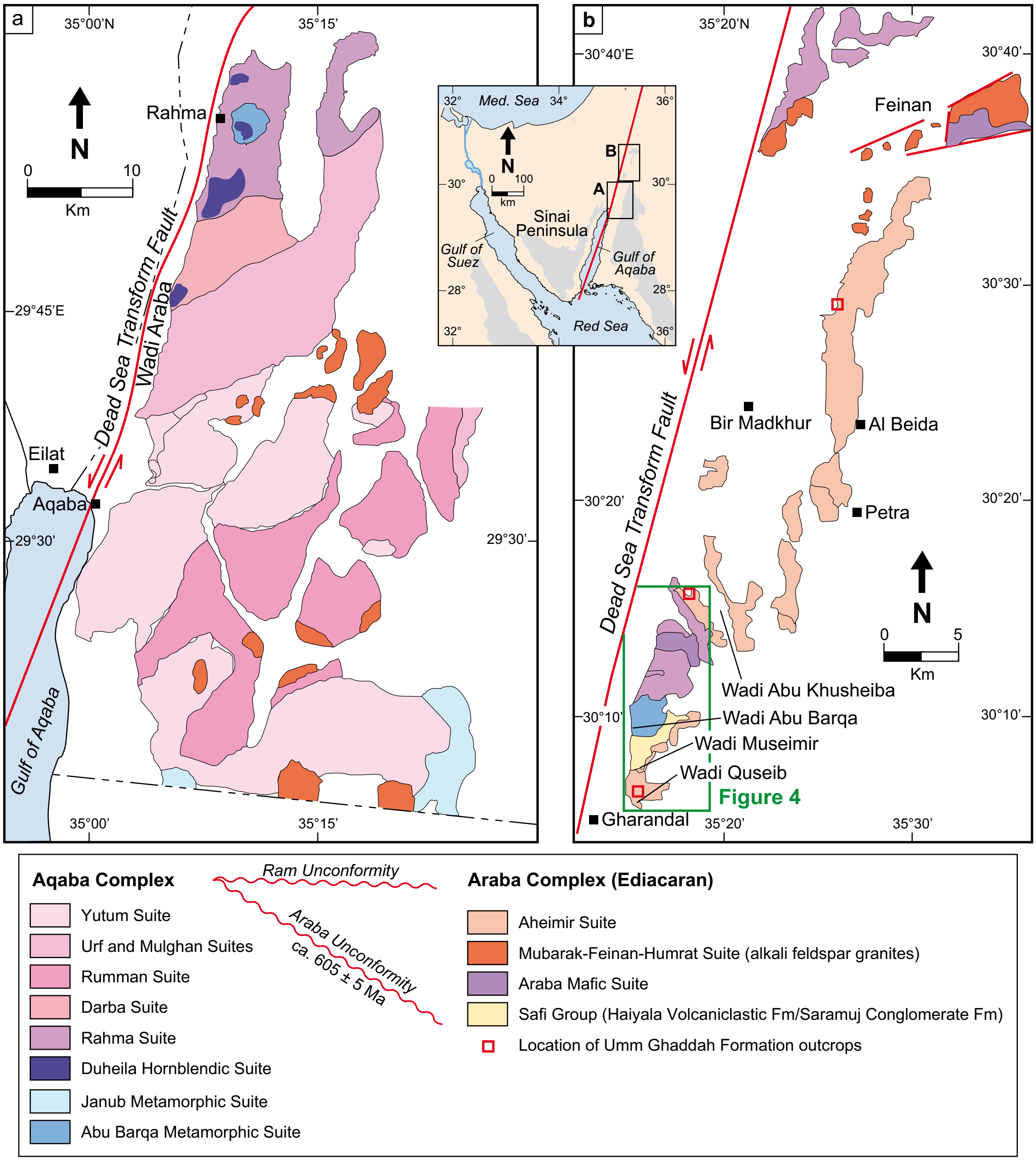


Figure 2: Generalized geological map of the Aqaba and Araba complexes in southwest Jordan (after McCourt and Ibrahim, 1990; Jarrar, 2011).

Although definitive Ediacaran biotas have not been reported, to date, from the succession in Jordan, the presence of fine-grained, water-lain tuffs and other volcaniclastic deposits, similar to lithofacies that have yielded Ediacaran fossils (e.g. *Charnia*) worldwide (Narbonne, 2010) raises the possibility of their discovery and potential biostratigraphical correlation in the region. In contrast, a geochronology based on Rb-Sr ages (McCourt and Ibrahim, 1990; Ibrahim and McCourt, 1995) enabled the relative chronostratigraphical relationships to be established. However, these Rb-Sr ages are generally believed to be about 10–20 Myr younger than the corresponding radiometric ages based on more reliable U/Pb zircon ages, either conventional or SIMS (Secondary Ion Mass Spectrometry), derived from cross-cutting dykes, volcanics and granitoids (Jarrar, 1985; Jarrar et al., 1983, 2003, 2008, 2013). U/Pb zircon ages thus provide a more robust geochronology for the Araba Complex (ca. 605 to 550 Ma) and the underlying Aqaba Complex (ca. 900 to 610 Ma) that enables tentative correlation with

Table 1
Geochronology of the Araba and Aqaba Complexes

Complex	Features	Units (lithologies)	Suite	Field Characteristics	Petrography	Age
Ram Unconformity (ca. 530 Ma)						
Dyke pulse: dolerite dykes (561 ± 31 Ma)						
Araba Complex (605 – 550? Ma)	Alluvial fan and footwall conglomerates; braided river and shallow marine or lacustrine sequences in extensional regime	Umm Ghaddah Formation (El Zubda Monomictic Conglomerate), Mufaraqad Conglomerates and agglomerates; Jafr Formation.		Umm Ghaddah Formation unconformable on Saramuj Formation and on the Aheimir Volcanic Suite in isolated fault-bounded slithers adjacent to Wadi Araba. Jafr Formation proved only in deep boreholes overlying Ma'an Formation volcanic rocks in Jafr area.	Monomict, footwall conglomerates and arenites largely composed of locally sourced volcanic rocks mainly of the Aheimir Volcanic Suite.	late Ediacaran (no geo-chronological age)
	Bimodal igneous activity; Alkaline and Peralkaline Magmatism	Ma'an Formation Al Beida Porphyrites Abu Sakakin comendites, Harun Microgranite Museimir Effusives (598.2 ± 3.8 Ma) (U-Pb) Composite dykes of Wadi Rahma (601 ± 12 Ma)(U-Pb)	Aheimir Volcanic	Extrusive, effusive (fragmental) and intrusive rocks extending from Gharandal to Feinan in narrow belt ca. 65 km by 3 km, parallel to Wadi Araba. Immature palaeotopography below Cambrian Ram Unconformity. Ma'an Formation volcanic rocks are only proven in Jafr area.	Fragmental effusives dominated by air-fall lithic tuffs, ignimbrites and welded tuffs; local agglomerates and volcanic breccias; massive sills or flows of porphyritic felsite rhyolite; local microgranites. Local rhyolitic and doleritic dykes.	Ranging from 598.2 ± 3.8 Ma to 601 ± 12 Ma
		Es Sail Aplogranite	Feinan–Humrat–Mubarak Granitic	Late stage intrusives. Red Feinan Granite distinctive in the field. Cut by late stage dykes (ca. 561 Ma).	Alkaline rhyolitc and alkaline peraluminous granites and syenogranites.	Ranging from 603.6 ± 2.6 Ma to 586.2 Ma ±5 Ma
		Fidan Syenogranite (603.6 ± 2.6 Ma) (U-Pb)				
		Humrat Syenogranite, Al-Rashdia aplite (586.2 ± 5 Ma) (U-Pb)				
		Mubarak Monzogranite (601.8 ± 3.1 Ma) (U-Pb)				
		Sammaniya Microgranodiorite	Araba Mafic (585–595 Ma)	Isolated grey to dark coloured plug-like plutons, closely jointed, forming low hills and ridges.	Basalts to basaltic andesites and microgabbro with abundant alteration to chlorite and epidote; diorites and quartz diorites with abundant biotite and hornblende.	Mureihil Diorite: 598 ± 5 Ma and 585 ± 13 Ma
		Ghuweir Volcanics (572 ± 48 Ma) (Rb-Sr)				
		Mureihil (Umm Rachel) Diorite (ca. 598 ± 5 and 585 ± 13 Ma)* (U-Pb)				
		Qunaia Monzogabbro (595 ± 2 Ma) (U-Pb)		Small stock-like intrusion in Wadi Qunaia; intrudes and locally dykes Saramuj Formation with thermal contact zone, but cut by dykes probably associated with Aheimir Suite.	Monzogabbro with K-feldspar and minor quartz; labradorite plagioclase, pyroxene, biotite, olivine, Fe-oxides.	595 ± 2 Ma
	Sedimentary and Volcaniclastic Rocks	Haiyala Volcaniclastic Formation***	Safi Group	Steeply dipping volcaniclastics, ranging from coarse-grained ash and lapilli tuff and finely laminated siltstones and claystones, rhythmically bedded, interbedded with rhyolitic lavas. Flow folds common. Upward-fining with wave ripples and desiccation cracks (Haiyala) – overlying…. Poorly sorted, well-rounded pebble - to boulder-grade polymict conglomerate with sand grade cross-laminated matrix, in part, passing up to cross-bedded lithic arenite with rounded pebbles (Saramuj).	Lithic and lithic-crystal tuffs with graded silt to granule grade pyroclastic fragments including regional basement rocks and quartz, sanidine, microcline and zircon (Haiyala). Lithic arenite matrix and granule to boulders lithologies derived from regional Aqaba Complex granitoids and metamorphic rocks. Locally derived angular intraclasts also present (Saramuj).	595–600 Ma (Haiyala) 605 ± 5 to 595 ± 2 Ma (Saramuj)
		Saramuj Conglomerate Formation				

Continued on pages 104 and 105.

Table 1 *(continued)*

Araba Unconformity (ca. 605 Ma)						
Aqaba Complex (ca. 900–610 Ma)	Calc-alkaline Granitoids (ca. 630–610 Ma)	Abu Jedda Monzogranite (608 +38/-21 Ma) (U-Pb)	Yutum Granitic	Relatively homogenous, medium- to coarse-grained plutons, topographically rugged; dykes common, but of variable density, often NE trend; few xenoliths. Pink-white; biotite conspicuous; hornblende characteristic of Imran unit, with higher colour-index. Contacts of Abu Jedda Monzogranite often marked by vein zones of pegmatite.	Monzogranite-Syenogranite. Simple subsolvus granite mineralogy, dominated by perthitic orthoclase, some myrmekite; quartz and sodic plagioclase commonly altered to sericite. Albite twins. Microcline more common in the Abu Jedda unit. Coarse 'pools' of quartz, K-feldspar, encloses plagioclase and biotite, the latter the characteristic mafic mineral, but with essential hornblende in the Imran unit. Sphene (titanite), zircon and apatite accessories.	ca. 608 + 38/-21 Ma based on Abu Jedda Monzogranite
		Imran Monzogranite				
		Qara Granite				
		Ishaar Granodiorite	Rumman Grano-diorite (615 Ma)	Dominated by granodiorite unit with distinctive green-grey weathered outcrop of low relief; heavily dyked with characteristic hornblende and small rounded xenoliths of mafic granofels prominent at outcrop. The Qara granitic phase is distinguished by its lower colour index and increased K-feldspar modal percentage; however, the characteristic hornblende and mafic xenoliths are still carried through, albeit much less abundant.	Granodiorite-Monzogranite. Medium-grained with essential modal hornblende, together with biotite, sodic plagioclase, quartz and perthitic orthoclase. Sphene (titanite), apatite and ilmenite commonly present along with fine-grained biotite and opaques as characteristic mafic clots. Secondary chlorite, fibrous amphibole and sericite.	ca. 615.8 ± 1.9 Ma based on Sabil Granodiorite
		Sabil Granodiorite (615.8 ± 1.9 Ma) (U-Pb)				
		Hubayra Diorite				
		Mulghan Granodiorite				
		Huneik Monzogranite	Urf Por-phyritic Suite (620 Ma) (Rb-Sr)	Porphyritic granitoids with low relief white-grey weathering outcrops and craggy topography; heavily dyked. Phenocrysts of pink alkali-feldspar except Abyad Granodiorite that has tabular white feldspar. Mafic minerals subhedral and weakly aligned, generally biotite, but hornblende in Marsad Monzogranite. Quartz typically fractured, and in Rubeiq Granodiorite has distinctive 'greasy' lustre. Xenoliths not common.	Monzogranite-Granodiorite. Medium- to fine-grained groundmass consists of perthitic orthoclase, oligoclase, quartz and biotite-chlorite aggregates. Phenocrysts of perthitic orthoclase, rare microcline and zoned plagioclase. Myrmekite common; consertal quartz characteristic. Sphene (titanite)and apatite accessories.	ca. 620 Ma based on Rb-Sr
		Abyad Granodiorite				
		Filk Monzogranite				
		Rubeiq Granodiorite				
		Muheirid Granodiorite				
		Marsad Monzogranite				
		Barraq Granodiorite				
		Waara Granodiorite	Darba Tonalitic	Main lithology 'black-white' quartz diorite with conspicuous idiomorphic white tabular plagioclase and high colour-index reflecting modal biotite and hornblende percentage. Microdiorite xenoliths common; heavily dyked and generally deeply weathered outcrops. Second unit 'pink-grey 'granitic internal pulse with much lower colour-index, but still carries isolated crystals of idiomorphic plagioclase although xenoliths rare to absent.	Quartz Diorite-Granodiorite. Medium-grained with ubiquitous biotite and prismatic hornblende; zoned idiomorphic plagioclase perthitic, interstitial K-feldspar and quartz. Abundant opaques commonly in clusters, chlorite and sericite alteration, the latter often in cores of plagioclase. Second unit fine- to medium-grained; only minor hornblende; remnants of zoned plagioclase enclosed by orthoclase.	ca. 612 ± 2 Ma based on Huwwar Granite
		Muhtadi Granodiorite				
		Huwwar Two Mica Granite (612 ± 2 Ma) (U-Pb)				
		Taba Monzogranite Synplutonic dikes	Rahma Foliated	Grey weathering typically massive outcrop, variably but characteristically foliated; Turban Monzogranite coarsely porphyritic. Field association with metamorphic rafts and xenoliths.	Monzogranite–granodiorite. Medium-grained with abundant quartz and sodic plagioclase, subordinate K-feldspar dominantly perthitic orthoclase, rare microcline. Biotite is the only mafic mineral and defines foliation/ schistosity, in places paralleled by ribbon quartz. Accessory sphene (titanite), zircon and opaques.	ca. 615 ± 3 Ma based on Umm Saiyala Granite
		Es Sadra Granodiorite				
		Umm Saiyala Granite (615 ± 3 Ma) (U-Pb)				
		Turban Granite/Granodiorite (610 ± 1 Ma) (U-Pb)				
		Abu Radmar Granodiorite				
		Naba Monzogranite				

Continued on page 105.

Table 1 *(continued)*

Aqaba Complex (ca. 900–610 Ma)	Calc-alkaline Gabbros	Qattar Hornblende Gabbro Thawr Gabbro (ca. 610–605 Ma) (U-Pb) Hornblendite (ca. 640 Ma)** (U-Pb)	Duheila Horn-blendic	Three varieties of this suite are seen in the field: (a) pegmatitic diorite; (b) biotite-hornblende gabbrodiorite characterized by foliation; and (c) massive variety of diopside-hornblende gabbro-diorite. Cumulates occur as roof pendants to, and xenoliths within, granites of the Rahma Suite.	Gabbro-diorite. Pegmatitic diorite with conspicuous amphibole crystals up to 10 cm long. Foliated biotite-hornblende gabbro-diorite. Diopside-hornblende gabbro-diorite, characterised by predominance of equi-dimensional blocky amphibole rhombs and the presence of diopside, the latter containing anhedral interstitial pink orthoclase.	ca. 610–605 Ma based on Thawr Gabbro Or ca. 632 Ma if inferred from similar rocks north of Eilat‡
	Metamorphic Rocks (ca. 900–620 Ma)	Hornblende biotite schist and Amphibolites	Abu Saqa Schist*	Schistose remnants and mega-xenoliths within Aqaba Complex granitoid rocks near Quweira.	Biotite and amphibole schists with hornblendite/amphibolite, meta-hornblende gabbro and pelitic gneiss; green schist grade.	See notes
		Granitic gneiss Schistose dykes	Buseinat Gneiss*	Grey-white schistose remnants and mega-xenoliths within Aqaba Complex granitoid rocks. Biotite foliation.	Intermediate plagioclase, quartz, biotite with subordinate hornblende and pink-white K-feldspars.	ca. 630 Ma if inferred from similar rocks north of Eilat ‡
		Mylonites, metaconglomerates, metaarkoses, hornfelses	Janub Meta-morphic (633.2 ± 4.5 to 617.5 ± 4.7 Ma) (U-Pb)	Schistose remnants and mega-xenoliths within Aqaba Complex granitoid rocks in extreme southern part of Aqaba Complex outcrop; roof pendants and large xenoliths in Yutum Suite. Slaty or phyllitic cleavage in part.	Low-grade (greenschist facies) metasedimentary rocks with protoliths of quartzite, claystone, siltstone, and probable volcanic rocks. Mineralogy of albite to oligoclase, chlorite, epidote, quartz and sericite, plus biotite and even sillimanite and cordierite in contact zones with later Araba granitoids.	Ranging from ca. 633.2 ± 4.5 to 617.5 ± 4.7 Ma
		Tonalitic gneiss (787 ± 3.8 Ma) (U-Pb) , Paragneiss, sillimanite garnet schist (ca. 860~680 Ma detrital zircons) (U-Pb) Barraq granitic gneiss (626 ± 3 Ma) (U-Pb)	Abu Barqa Meta-morphic	Schistose remnants and mega-xenoliths within Aqaba Complex granitoid rocks.	High-grade sillimanite-garnet schists, biotite–garnet schists including metasediments and meta-igneous protoliths. Fine-to medium-grained grey schists and dark biotite-rich pelites with small garnets. Schists consist of quartz, oligoclase-andesine plagioclase, K-feldspar, sillimanite, biotite and sparse cordierite. The same metapelites in Wadi Huwwar consist of: biotite, muscovite, quartz, oligoclase, garnet, andalusite and staurolite with retrograde chlorite.	Ranging from ca. 860–626 ± 3 Ma

Modified chronostratigraphical lithostratigraphical (field established and supported by absolute ages) hierarchy of the Aqaba and Araba complexes in Jordan (original data from McCourt and Ibrahim, 1990, Ibrahim and McCourt, 1995; Jarrar et al., 2003, 2008; and recent unpublished SIMS age data).

* No absolute ages for these two suites but field relationships suggest the same age as the Abu Barqa Metamorphic Suite

** Age is inferred from similar rocks on the western side of the Dead Sea Transform Fault north of Eilat (Kröner et al., 1990)

*** Haiyala Volcaniclastic Formation is paraconformably overlain by the Aheimir Volcanic Suite.

‡ Inferred age from coeval Roded unit located west of the Dead Sea Transform Fault (Katz et al., 2004).

Ediacaran fossil-bearing rocks in Oman (Amthor et al., 2003) and Saudi Arabia (Vickers-Rich et al., 2010, 2013; Nettle et al., 2014). Two major erosional unconformities bound the Araba Complex; the base is marked by the **Araba Unconformity** (ca. 605 Ma; see below) and the top is bounded by the **Ram Unconformity** (ca. 530 Ma) above which lower Cambrian sandstones (Ram Group) are present (Powell, 1989; Powell et al., 2014) (Plates 1 to 4; Table 1).

The purpose of this paper is to define the lithostratigraphical, lithodemic and geochronological framework of the Ediacaran Araba Complex, and to outline the tectono-stratigraphical evolution of this sequence that post-dates and unconformably overlies metasedimentary, meta-igneous and intrusive rocks of the Cryogenian–Ediacaran 'basement' Aqaba Complex (McCourt and Ibrahim, 1990), part of the ANS (Stern, 1985; 1994), which is summarised to provide the context for the younger Araba Complex. We also discuss correlation of the Araba Complex, at outcrop, with the successions proved in distant exploration wells in Jordan, and more widely with Ediacaran rocks on the Arabian Plate.

This lexicon-style synthesis draws on the earlier work of Bender (1974), Jarrar (1985), Powell (1988), McCourt and Ibrahim (1990), Ibrahim and McCourt (1995), Jarrar et al. (1991, 2003, 2008, 2013), Amireh and Abed (2000) and Amireh et al. (2008). The paper is a contribution to the evolving *Middle East Geologic Time Scale* that was launched in 2008 in order to provide the rock-time language by which geoscientists can communicate across the boundaries of countries, from outcrop to subsurface, and with stratigraphers worldwide (Al-Husseini, 2008, 2010, 2014). The accuracy of the chart hinges on accurate descriptions of the rock-time units in each country, how well they are dated and which unconformities are regionally correlative.

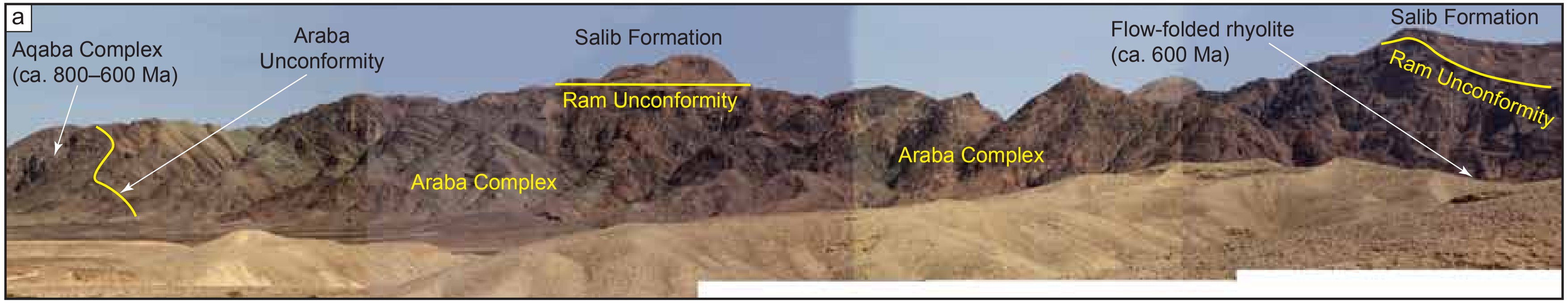
Table 1 provides the lithostratigraphical hierarchy and petrographic characteristics of the igneous and metamorphic rocks of the Aqaba and Araba complexes. At outcrop, the Araba Complex comprises the Safi Group (Saramuj Conglomerate and Haiyala Volcaniclastic formations), Araba Mafic Suite, Feinan-Humrat-Mubarak Granitic Suite, Aheimir Volcanic Suite, Umm Ghaddah Formation and dolerite dykes (Table 1). The paper focuses mainly on four of these units because they appear to be of regional extent and to constitute correlative rock-time building blocks: (1) Saramuj Conglomerate Formation, (2) Haiyala Volcaniclastic Formation, (3) Aheimir Volcanic Suite, and (4) Umm Ghaddah Formation. We also speculate on correlation between the type outcrop and newly defined Ediacaran formations proven in a number of exploration wells in the region (Andrews, 1991; Rabi, 1992; Abu Saad and Andrews, 1993).

The predominantly granitoid Aqaba Complex basement terrain spans the Cryogenian and early Ediacaran periods and is described briefly to inform the overall tectonic setting and evolution of the Arabian-Nubian Shield in the region (Al-Husseini, 1988); the ANS was the source of pebble-cobble clasts that comprise the Saramuj Formation conglomerate (basal Araba Complex), and the more mature sandstones that characterise the Cambrian–Ordovician Ram Group (Powell et al., 2014). The regional peneplain (Ram Unconformity) that marks the boundary between the ANS and the lower Cambrian sandstones (Salib Formation) was initiated during the earlier Saramuj erosional phase.

NEOPROTEROZOIC TECTONIC SETTING: OVERVIEW OF THE AQABA COMPLEX 'BASEMENT'

The Aqaba Complex is briefly summarised in order to provide the context for the subsequent evolution of the Araba Complex for which it was the source of thick granitoid conglomerates in the lower part. The Aqaba Complex crops out to the east and northeast of Aqaba along the eastern shoulder of Wadi Araba for a distance of about 85 km, and continues intermittently as far as Humrat Fidan about 140 km north of Aqaba city (Figure 1). The complex is also exposed on the western side of Wadi Araba (Weissbrod and Sneh, 2002). Heimbach (1976, and references therein) attributed the authorship of the Aqaba Complex to L. Damesin (1948, unpublished report) and Quennell (1951). He also provided a detailed list of synonyms and authors starting with 'Massif cristallins' (Lartet, 1869) and ending with 'Crystalline Complex of South Jordan' (van den Boom and Rösch, 1969).

ARABA AND RAM UNCONFORMITIES



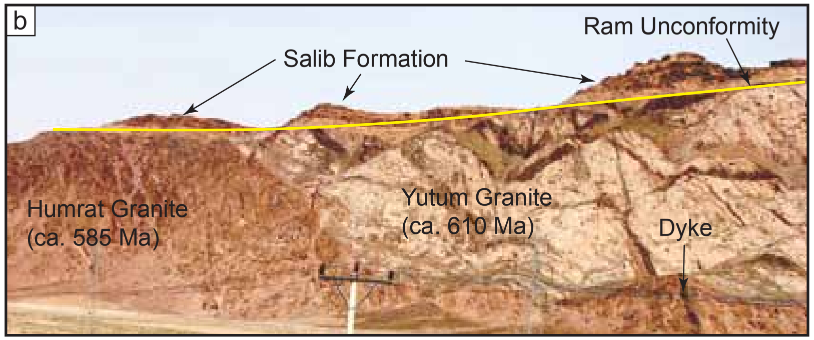
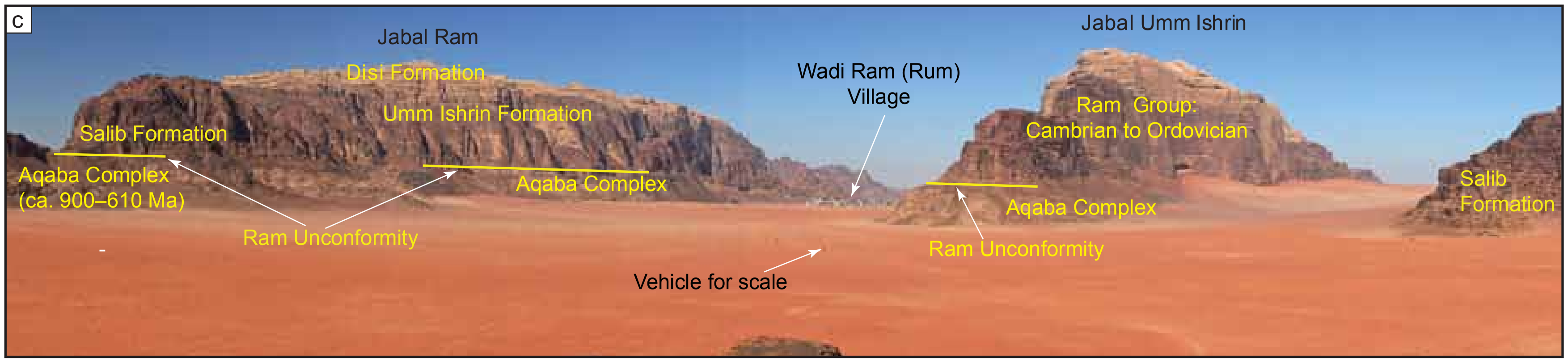


Plate 1: (a) North-south panoramic photo-mosaic along the eastern side of Wadi Araba, between Wadi Abu Barqa (N) and Wadi Museimir (S), about 70–75 km north of Aqaba city (see Figures 1 and 2 for location, width of image about 5 km). At the left (N) the Araba Unconformity separates the Aqaba and Araba complexes. In the centre and the right, the Ram Unconformity separates the lower Cambrian Salib Formation and Araba Complex. (b) Roof pendant of Yutum Granite (Aqaba Complex) on Humrat Granite (Araba Complex). The complexes are intruded by several generations of dykes (ca. 560 Ma). A dolerite dyke that cuts both complexes is indicated by arrow in lower right corner. Both complexes are truncated by the Ram Unconformity, and overlain by the Salib Formation. Photos by Gh.H. Jarrar.



(c) Panoramic view of Wadi Ram (see Figure 1 for location), looking north, showing the lower Cambrian Ram Group sandstones overlying unconformably Aqaba Complex granitoids and dykes. Note the extensive peneplained surface (Ram Unconformity). Overall view is several kilometres wide. Photo by J.H. Powell.

RAM UNCONFORMITY

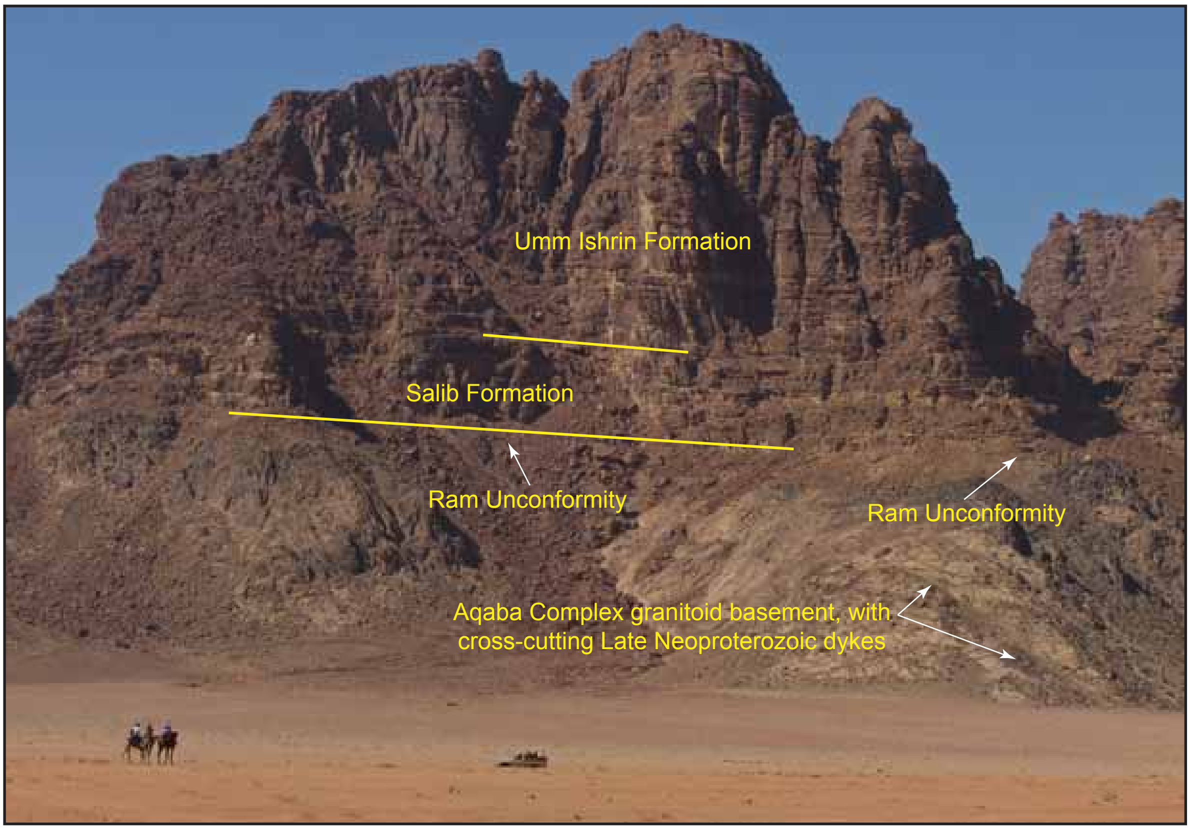


Plate 2: Ram Unconformity in Wadi Ram, west; lower Cambrian sandstone (Ram Group) overlying the peneplained Aqaba Complex granitoids. See Figure 1 for location. View is several hundreds of metres wide. Photo by J.H. Powell.

RAM UNCONFORMITY

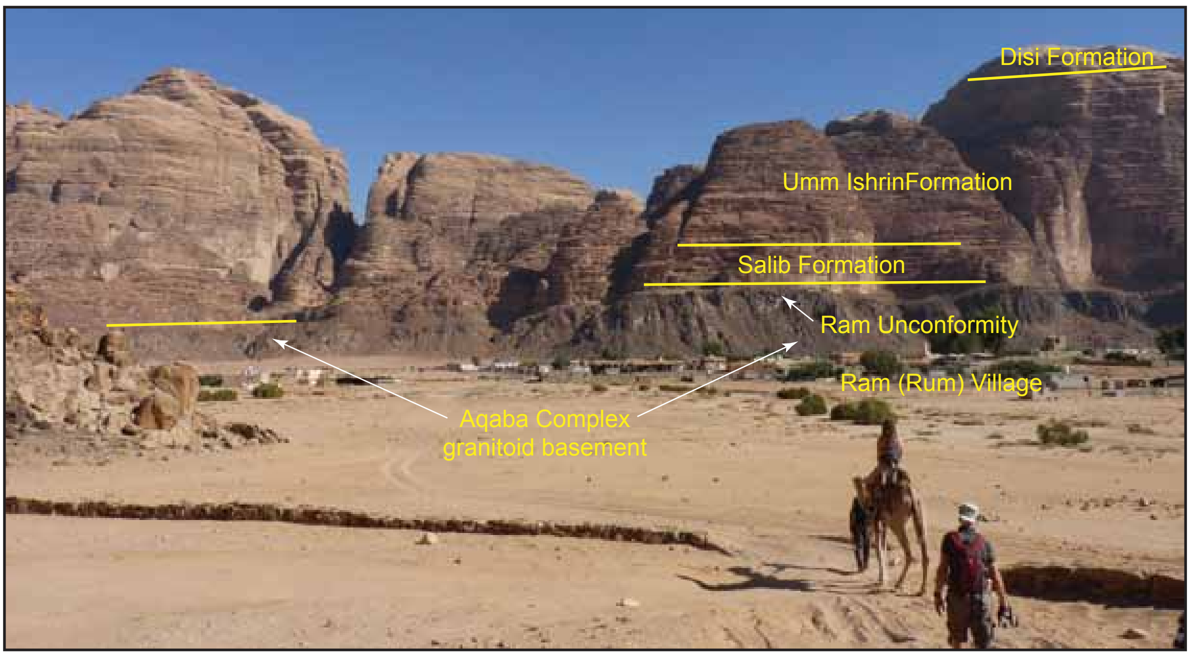


Plate 3: Ram Unconformity at Wadi Ram village, Ram Group sandstone overlying the peneplained Aqaba Complex granitoids. See Figure 1 for location. View is several hundreds of metres wide. Photo by J.H. Powell.

RAM UNCONFORMITY

Plate 4: Lower Cambrian sandstone (Ram Group) unconformably overlying the immature palaeotopography of the Aheimir Suite volcanic rocks (Araba Complex) west of Petra. View is several hundreds of metres wide. See Figure 2 for location. Photo by J.H. Powell.

The Aqaba Complex was formally defined by McCourt and Ibrahim (1990), and consists of six plutonic suites and four metamorphic suites as defined by Ibrahim and McCourt (1995) and Jarrar et al. (2003; Table 1). The six plutonic suites are: (1) Duheila Hornblendic Suite (ca. 610–605 Ma), (2) Yutum Granitic Suite (ca. 608 Ma), (3) Urf Porphyritic Suite (ca. 620 Ma), (4) Rumman Granodioritic Suite (ca. 615 Ma), (5) Darba Tonalitic Suite (ca. 612 Ma), and (6) Rahma Foliated Suite (ca. 615 Ma). The metamorphic suites are (1) Abu Barqa Metamorphic Suite (ca. 860–626 Ma), (2) Janub Metamorphic Suite (ca. 633–617 Ma), (3) undated Abu Saqa Schist Suite, and (4) Buseinat Gneiss Suite (ca. 630 Ma). Only three deep wells have penetrated basement rocks (Figure 1): Safra-1 (Bender, 1974), Jafr-1 (Andrews, 1991, based on unpublished reports by Jordan Hunt Oil Company, 1989; Paleoservices, 1989), and Ajlun-1 (H. Rabi, 1992, unpublished NRA report).

The Aqaba Complex formed part of Neoproterozoic ANS terrane that was split by the Cenozoic Dead Sea Transform and Red Sea Rift system into the Midyan Terrane in the Arabian Shield, the Sinai Peninsula, and the Eastern Desert Terrane in the Nubian Shield (Africa) (Figure 3). The Midyan Terrane is separated from the Hijaz Terrane, located farther south in the Arabian Shield, by the Yanbu Suture Zone. The Allaqi-Heiani-Sol Hamed Suture Zone forms the continuation of the Yanbu Suture Zone in Africa and it separates the Eastern Desert and Gabgaba-Gebeit terranes (see review in Fritz et al., 2013). Ali et al. (2010) concluded that the ophiolites in this 600 km-long Arabian-Nubian suture zone formed in two stages (810–780 Ma and 750–730 Ma). They proposed an arc–arc collision occurred along this suture between 730 and 709 Ma.

The metamorphic rocks of the Aqaba Complex occur as remnants within the surrounding Neoproterozoic intrusive rocks. The Abu Barqa Metamorphic Suite contains the oldest rocks known from Jordan (Figures 2 and 4, Table 1). The suite consists of paragneiss, tonalitic gneiss, metasediments, and granitic gneiss that are sporadically exposed along the eastern margin of Wadi Araba for about 40 km. The major exposures form EW-trending belts in wadis Huwwar, Barraq, Umm Saiyala, Abu

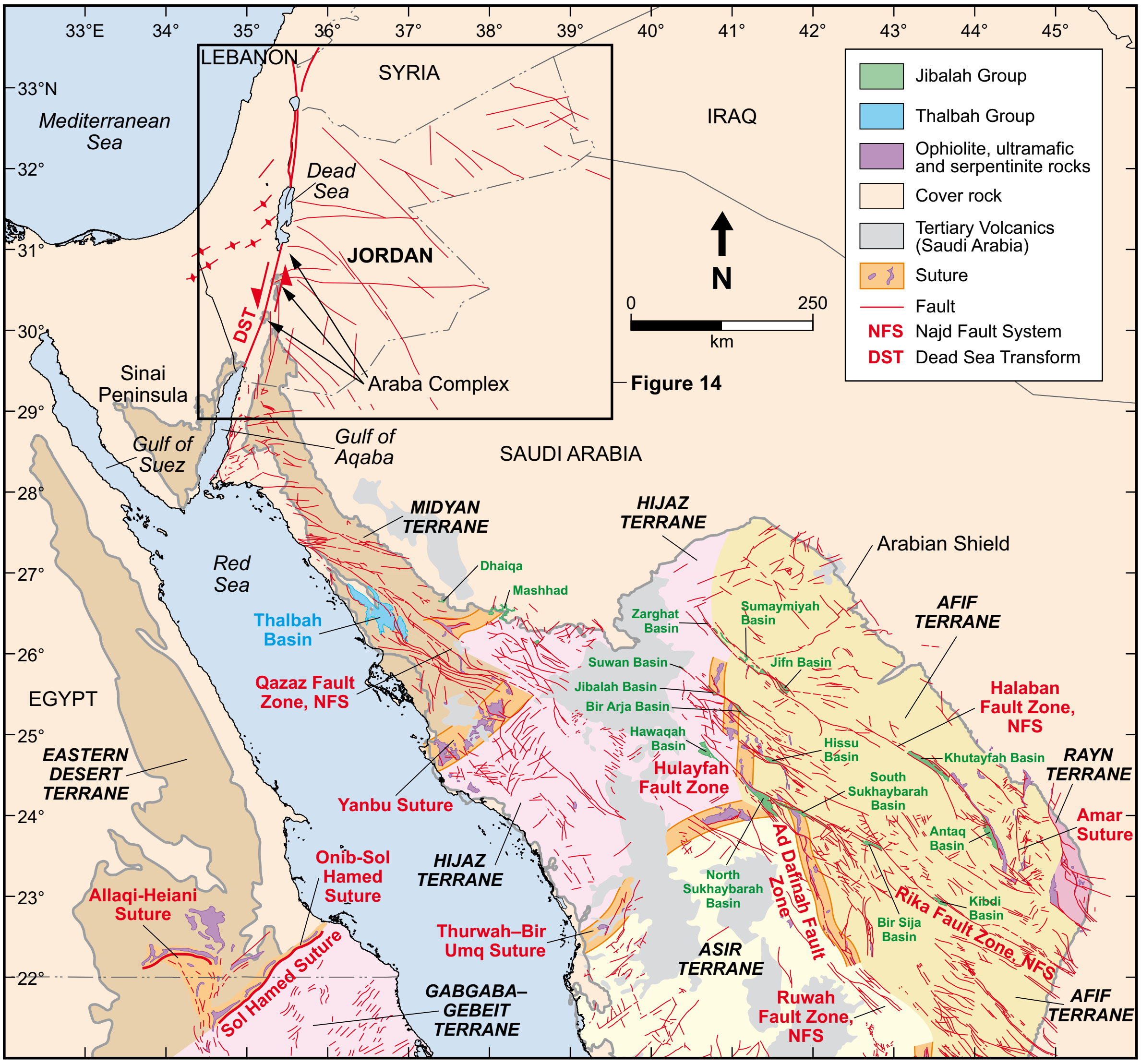


Figure 3: Proterozoic terranes and sutures of the northern Arabian-Nubian Shield (ANS) compiled from the literature by M.I. Al-Husseini. The Aqaba Complex in southwestern Jordan forms part of the Midyan Terrane in the Arabian Shield. During the Cenozoic the Midyan Terrane was split by the Dead Sea Transform (DST) and Red Sea Rift system into the Sinai Peninsula, and the Eastern Desert Terrane in the Nubian Shield. The Yanbu and Allaqi-Heiani-Sol Hamed suture zones are characterised by ophiolites, and represent the collision between the Midyan and Gabgaba–Gebeit terranes in the northwest, and the Midyan and Eastern Desert terranes in the southeast between about 730 and 709 Ma (Ali et al., 2010).

Barqa, and Rahma (Figures 1, 2 and 4). Single zircon SIMS dating of the tonalitic gneiss constrain the age of the Abu Barqa Suite to about 787 Ma, whereas zircons in the metasediments show a wide age span, from 1,030 Ma to about 700 Ma, most probably reflecting the age of the source rocks (Jarrar et al., 2013). Geochemically, the great majority of the investigated metapelites plot in the shale field and the gneisses plot in the fields of greywackes. Thus, the protolith of the suite is of pelitic and psammitic character and their depositional setting is interpreted as an active continental margin/island arc (Jarrar et al., 2013).

The undated Buseinat Gneiss Suite consists of light-grey orthogneisses composed of andesine plagioclase, quartz, and biotite with subordinate amphibole and potassium feldspar (McCourt and Ibrahim, 1990). Absolute age dating of these gneisses is lacking but field relationships suggest

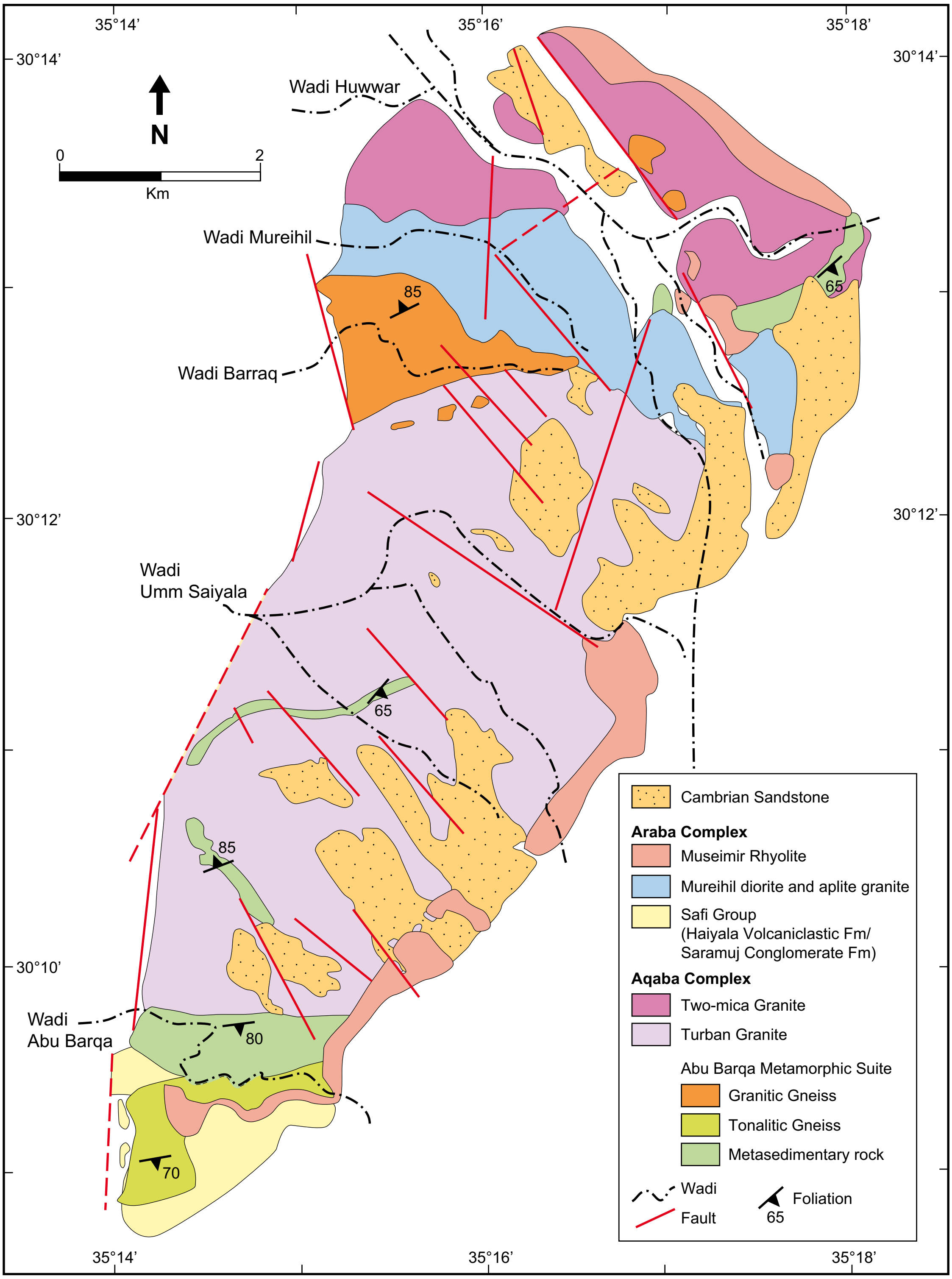


Figure 4: Geologic map of central Wadi Araba showing the distribution of the Abu Barqa Metamorphic Suite (after Jarrar, 1985; Jarrar et al., 2013). See Figure 2b for location.

similarity to the Abu Barqa Metamorphic Suite and in particular to the constituent tonalitic gneiss (Jarrar et al., 2013). The Abu Barqa (787–700 Ma) and probably the undated Buseinat suites reflect a tectonic event that may be related to the closure of the Yanbu Suture Zone (730–709 Ma).

Several dated metamorphic and granitic suites (Plates 5 and 6) have ages that fall in a window between ca. 630–610 Ma, that is, spanning the early Ediacaran Period (635–541 Ma; Table 1). These include:

GRANITOIDS AND DYKES

Plate 5: Proterozoic grainitoids (Aqaba Complex) cut by Late Neoproterozoic dolerite dykes near Qa Disi. Photo by J.H. Powell.

Plate 6: Lower Cambrian Salib sandstone (Ram Group) unconformably overlying Late Neoproterozoic Aqaba Complex granitoids with cross-cutting dykes. Height of exposure about 80 m. Wadi Yutum, Southern Desert. Photo by J.H. Powell.

(1) Calc-alkaline granitoids (Plate 5) dated by U-Pb zircons at 625−608 Ma intrude the Abu Barqa Metamorphic Suite (Jarrar, 1985; Jarrar et al., 2003).
(2) Janub Metamorphic Suite consisting of metaconglomerates, meta-arkoses, cataclasites, mylonites, and hornfelses (Hassuneh, 1994; Habboush, 2004, Habboush and Jarrar, 2009) are constrained by preliminary SIMS single zircon determinations between 640 to 595 Ma (Jarrar et al., in prep.). The suite is intruded by granites as old 620 Ma.
(3) Duheila Hornblendic Suite consisting of diorites and minor gabbros, and hornblendites. The major element composition and normative mineralogy suggest calc-alkaline and tholeiitic affinities. Dating by K-Ar yielded 611 ± 5 Ma (Lenz et al., 1972), and by SIMS zircon 610–605 Ma (Yaseen et al., in prep.).
(4) Examples of the high-potassium, calc-alkaline and alkaline granitoids of the Aqaba Complex are the Yutum Suite (608 Ma), Rahma Suite (615 Ma) and Sabil Granitoid of the Rumman Suite (615 Ma).

According to Jarrar et al. (2013), the intrusive rocks of the Aqaba Complex formed during the terminal collision at about 630–605 Ma between East and West Gondwanaland by the addition of magmas derived from mantle-derived melts.

ARABA UNCONFORMITY

The boundary between the Aqaba Complex basement and overlying Araba Complex is here defined as the 'Araba Unconformity' (Plates 1a, b). The unconformity represents a marked change from the older calc-alkaline, convergent-margin unimodal granitoid suite of the Aqaba Complex to the younger bimodal, rift-related suite of the Araba Complex. The change was accompanied by a phase of crustal extension expressed as fault-bounded basins and half-grabens in which the oldest sedimentary formation, the Saramuj Formation, comprising mostly granitoid Aqaba Complex clasts, was deposited on the Araba Unconformity (Figure 5). Although this boundary is not seen at outcrop in the Saramuj type locality, it has been reported farther south on the southern shoulder of Wadi Abu Barqa, where about 40 m of Saramuj conglomerate directly overlie the Aqaba Complex. The Araba Unconformity is also proven in the subsurface in the Safra-1 (SA-1) and Ajlun-1 (AJ-1) wells in north Jordan (Bender, 1968; Rabi, 1992) (Figure 1), and is interpreted on seismic profiles in south central Jordan (unpublished report by Jordan Hunt Oil Company, 1989; Andrews, 1991) and the Golan Heights (Meiler et al., 2011). Based on the radiometric dating the age of the Araba Unconformity is estimated at ca. 605 Ma.

ARABA COMPLEX

The Araba Complex was defined by McCourt and Ibrahim (1990) as all the rock units above the regional unconformity marked by the Saramuj Formation that unconformably overlies the predominantly granitoid Aqaba Complex (amalgamated Arabian-Nubian Shield) and below the lower Cambrian Ram Unconformity (Powell et al., 2014) (Plates 1 to 4). It comprises the Safi Group, Feinan Plutonic Suite, Araba Mafic Suite, Aheimir Volcanic Suite, Umm Ghaddah Formation, Ma'an Formation and Jafr Formation (see details below, Table 1 and Figure 5). Outcrops of the Araba Complex are mostly confined to the eastern side of Wadi Araba, along the DST margin, between Gharandal in the south to the southern Shores of the Dead Sea near Safi (Figure 1). Late-stage intrusions, such as the Humrat, Fidan and Mubarak granites, also cross-cut Aqaba Complex granitoids in the Southern Desert (Plate 5).

In the subsurface the various units of the Araba Complex have been proven in a number of deep exploration wells such as North Highlands-1, Ajlun-1, Safra-1, in north Jordan and in Wadi Sirhan-3 and Jafr-1 in central-east Jordan (Figure 1). Seismic investigations have proven the Araba Complex at depth below the Golan Heights (Meiler et al., 2011). Equivalent rocks also crop out and have been proven in boreholes west of the DST near Eilat (Weissbrod and Sneh, 2002).

Bender (1974) and other authors proposed that the present-day Wadi Araba-Dead Sea-Jordan Valley rift (north-north-east trend) may have been an Ediacaran rift basin. However, presence of other Ediacaran–?early Cambrian extensional basins and grabens in the region (e.g. the Jafr Basin), indicates that there must have been a widespread regional extensional regime in Jordan (see tectono-stratigraphical discussion below).

SAFI GROUP

The Safi Group is the lowermost sedimentary-volcanic unit, and was established in the report accompanying the 1:50,000-scale Karak Map Sheet (Powell, 1988). The group comprises the Saramuj Formation (mostly conglomerate) and the overlying Haiyala Volcaniclastic Formation (Figure 5). It is synonymous with the 'Saramuj Conglomerate' of Blanckenhorn (1912) and Burdon (1959), who were unaware of the younger volcaniclastic sediments exposed farther south near Wadi Abu Barqa (Bender, 1974; McCourt and Ibrahim, 1990). The Araba Complex is synonymous with the 'Saramuj Series' (Burdon, 1959), which included the Saramuj Conglomerate Formation, basic plutonics and dykes. Plates 1a and 1b show the Safi Group bounded by the Araba and Ram unconformities between wadis Abu Barqa and Museimir. The Safi Group is not defined in the subsurface (Andrews, 1991).

SARAMUJ FORMATION

Type and Reference Sections

The formation crops out in the southwest of the Karak Map Sheet adjacent to the Dead Sea (Powell, 1988), and the best exposures are along wadis Qunaia, Maghs and Sa'id (Figure 6). Jarrar et al. (1991) proposed the type section at 31°02'50"N and 35°30'07"E, at an elevation of 293 m below sea level (Figures 1 and 6).

We propose the Ajlun-1 Well (AJ-1) as a sub-surface reference section; reddish-brown conglomerate is recorded overlying brown, reddish-brown and green granite at 3,794.5 m depth (Rabi, 1992) (Figures 1 and 7). The formation has also been described from the North Highlands-1 (NH-1) and Safra-1 (SA-1) in north Jordan (Andrews, 1991).

Distribution

Jarrar et al. (1991) noted that the Saramuj Formation crops out in a wedge-shaped area (2 x 9 km) along the southeastern shore of the Dead Sea (Figures 1 and 6). Dark tones make the formation easily visible on aerial photographs and satellite images.

The subsurface distribution of the Saramuj Formation is poorly documented. It has been reported in exploration wells Ajlun-1 (AJ-1), North Highlands-1 (NH-1) and Safra-1 (SA-1) in north Jordan (Bender, 1974; Andrews, 1991; and in NRA unpublished reports, e.g. Rabi, 1992), but is absent in east Jordan in Wadi Sirhan-3 (WS-3) and Jafr-1 (JF-1). Seismic reflection data from the Golan Heights region suggest that the Saramuj Formation is present about 1 km below ground surface, thickening to the west (Meiler et al., 2011), although this seismic interval includes sediments equivalent to the younger 'Unassigned Clastic Unit' (see Jafr Formation, below). There is some uncertainty concerning the relationship between the polymict Saramuj Formation and younger oligomict conglomeratic units such as the Jafr Formation ('Unassigned Clastic Unit' of Andrews, 1991), Mufaraqad Conglomerates (McCourt and Ibrahim, 1990) and Umm Ghaddah Formation (Amireh et al., 2008); the conglomerates reported in NH-1 and SA-1 wells may be equivalent, in part, to the these younger oligomict conglomerates.

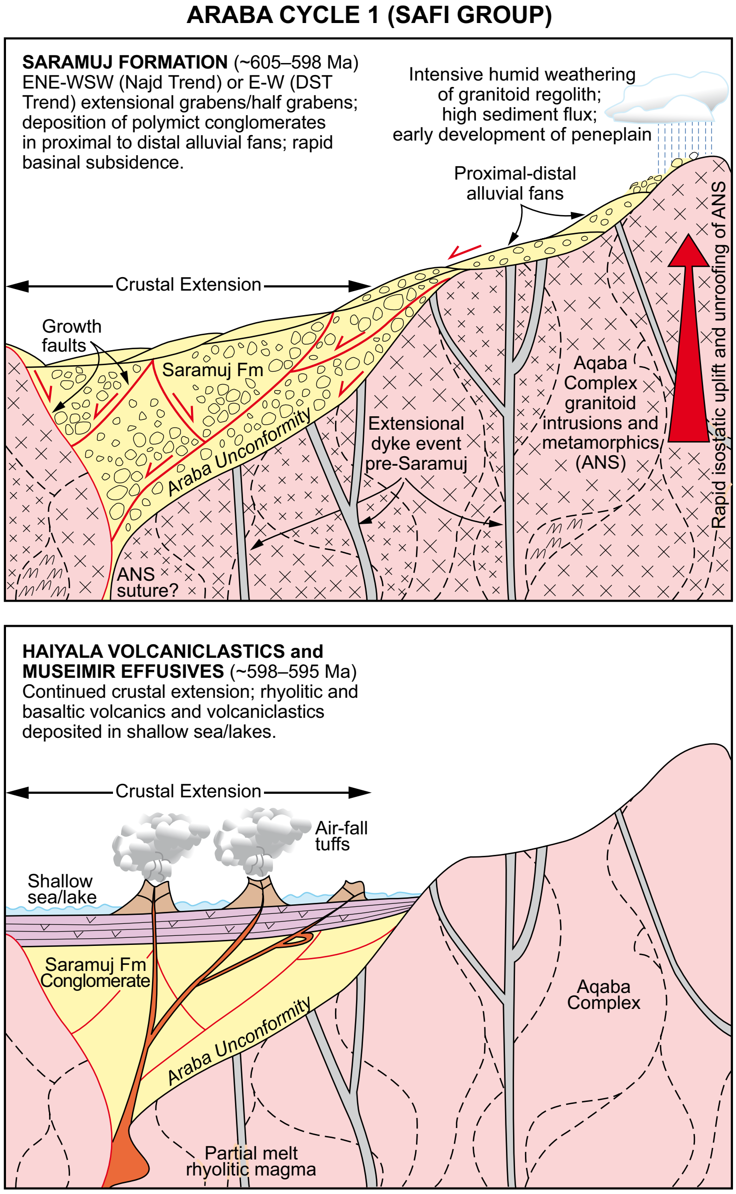


Figure 5: Diagrammatic evolution of the Ediacaran Araba Complex extensional cycles 1 and 2, and the early Cambrian Asfar Cycle. *Continued on facing page.*

Authors and Nomenclature

Burdon (1959) recorded the type outcrop as Wadi Saramuj, but according to the wadi names printed on the 1:50,000-scale topographical sheet (Jordan National Geographical Centre) there are no outcrops of this formation in Wadi Saramuj. It seems likely that the name was assigned by previous authors for outcrops in Wadi Sa'id, located immediately to the north (Powell, 1988). The name is retained, however, because of its regional significance and common usage in the literature.

The formation is synonymous with the 'Saramuj Series' (Blanckenhorn, 1912, 1914), 'Saramuj Conglomerate' (Burdon, 1959), and it has also been described by Lartet (1869), Hull (1886), Blake (1939), Picard (1941), Bender (1974), and formally defined by Powell (1988).

Bender (1974) mapped further outcrops of the formation to the south of Wadi Abu Barqa and, although these are of a similar lithofacies and assumed to be coeval, lithologically they are different in that they do not contain the diverse range of granitoid clasts recorded from the type area. Jarrar et al. (1991) described the formation in four sections including the type section and proposed a depositional model.

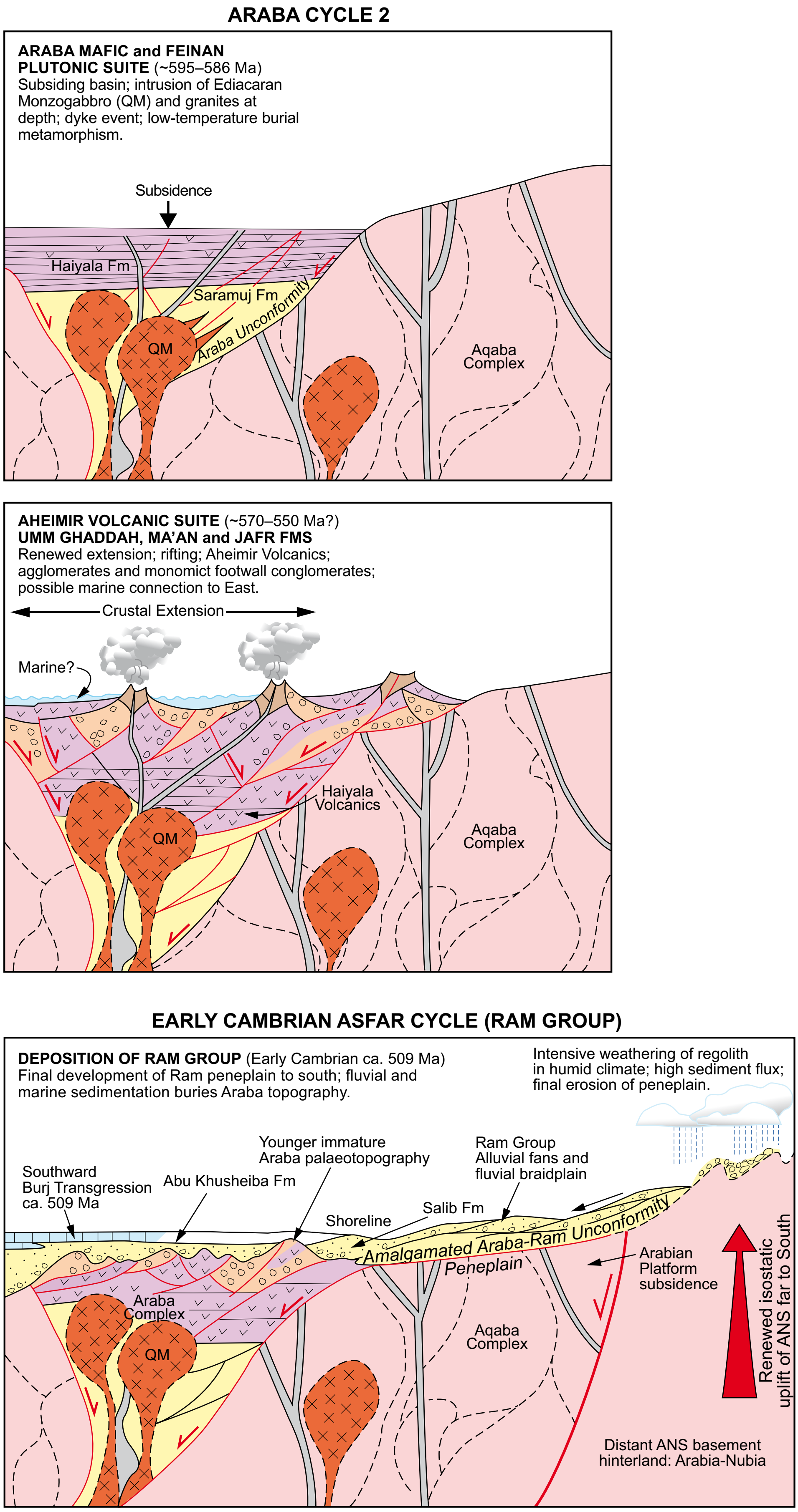


Figure 5: *continued.*

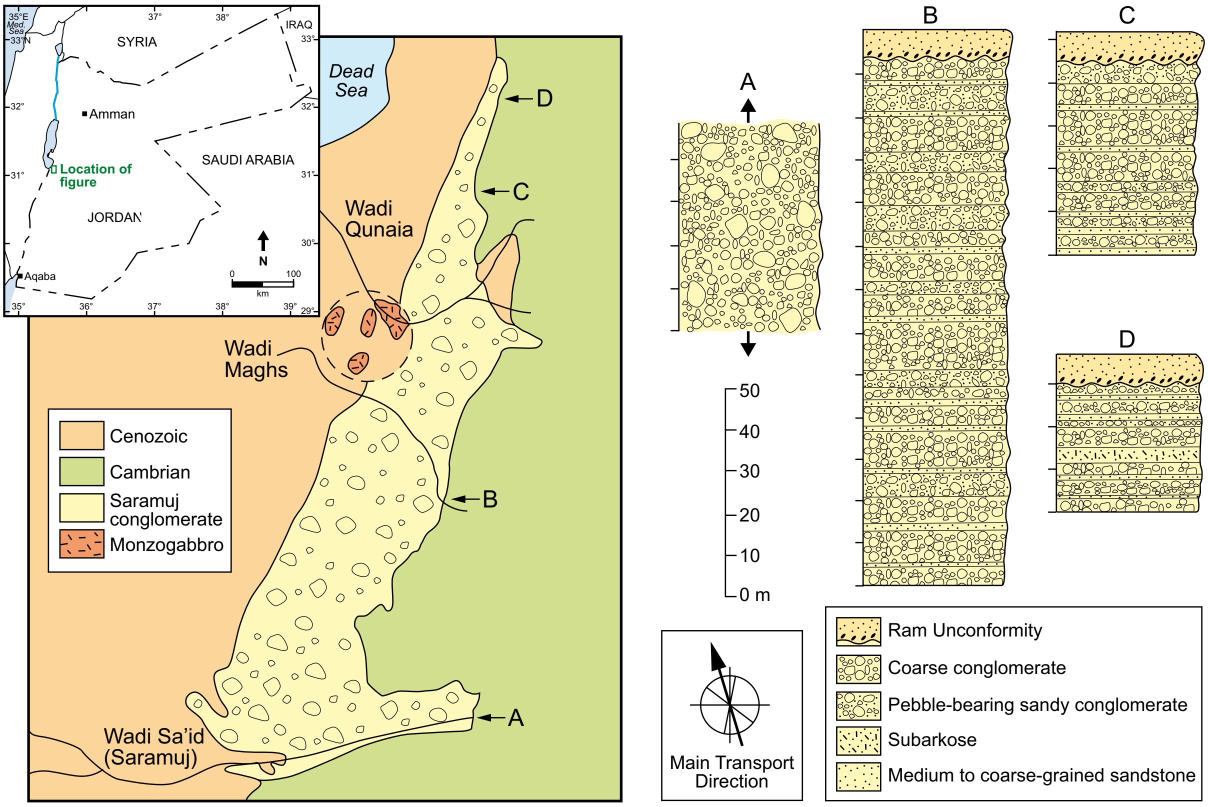


Figure 6: Type locality of the Saramuj Conglomerate. Four representative sections, A, B, C and D and the main direction of transport are shown (after Jarrar et al., 1991).

Lithology

The Saramuj Formation (Powell, 1988; Jarrar et al., 1991) consists predominantly of beds of polymict conglomerate comprising well-rounded, clast-supported, poorly-sorted pebbles, cobbles and boulders with a reddish-brown to dark green-grey coarse-grained to granule-size arkosic matrix, interbedded with beds of low-angle, trough cross-bedded coarse-grained arkosic and lithic sandstone (true arkose, in part) (Plates 7 and 8). Bed thickness is very varied throughout the sequence; some massive conglomerate beds are up to 20 m thick. Andrews (1991) stated that the formation at outcrop includes thin beds of stromatolitic limestones; however, this is not the case.

A distinctive feature of the formation is the presence of bi-modal, pebble-cobble clasts mostly derived from the Aqaba Complex granitoids and their intrusive dyke suite (Plate 9), although in the southern exposure, particularly, clasts of metamorphic rocks, can also be recognised (Powell, 1998; Jarrar et al., 1991). The granite types recognised from their current outcrop in the southern desert include the Yutum Granitic Suite, Filk porphyry of the Urf Suite, foliated granitoids of the Rahma Suite, and Rumman Granodioritic Suite, along with pebbles of porphyry dykes, dolerites and microgranite. Yaseen et al. (2013) dated clasts and matrix from the Saramuj type locality using SIMS techniques and found that the major zircon ages of the matrix fall between ca. 650 to 600 Ma, with two prominent clusters at 624 and 640 Ma and a minor one between 750 and 700 Ma. These ages are consistent with those obtained from the four andesitic, rhyodacitic, granitic and gneiss clasts (624, 642, 650 and 734 Ma. respectively) and reflect local derivation of these clasts. Furthermore, the age of the youngest 10 detrital zircons at ca. 615 Ma represents the maximum age of deposition, which is consistent with the stratigraphic position of the Saramuj Formation.

SARAMUJ FORMATION

Plate 7: Poorly sorted granitic boulders in the Saramuj conglomerate indicating proximity to the source area; Wadi Saramuj, near Safi (see Figure 1 for location). Photo by Gh.H. Jarrar.

SARAMUJ FORMATION

Plate 8: Saramuj Formation exposed above the so-called 'Lot's Cave', which is a Byzantine archaeological site, north of Safi village, Dead Sea Basin (see Figure 1 for location). Note the chaotic, poorly sorted, well-rounded pebbles, cobbles and boulders comprising Aqaba Complex lithologies. Photo by J.H. Powell.

Occasional, rounded and elongate pebble-cobble grade intraclasts of the Saramuj conglomerate, i.e. reworked clasts, are also present (Plates 9c and 10b). Clasts generally have very smooth margins, and pebble point-contacts are ubiquitous except where pressure dissolution has occurred at clast boundaries (Plate 9). Grooves or striations in the surfaces of the clasts that might be indicative of glacial erratics have not been observed at outcrop, nor are there examples of dropstones characteristic of marine glacigenics, thereby precluding origin as a primary glacial deposit. The grey-green colour of the matrix is due to chloritisation and epidotisation of unstable igneous minerals during induration and low-grade burial metamorphism. Coarsening-upward trends are present in ca. 1 m-thick beds, but generally the conglomerate is poorly sorted or unsorted.

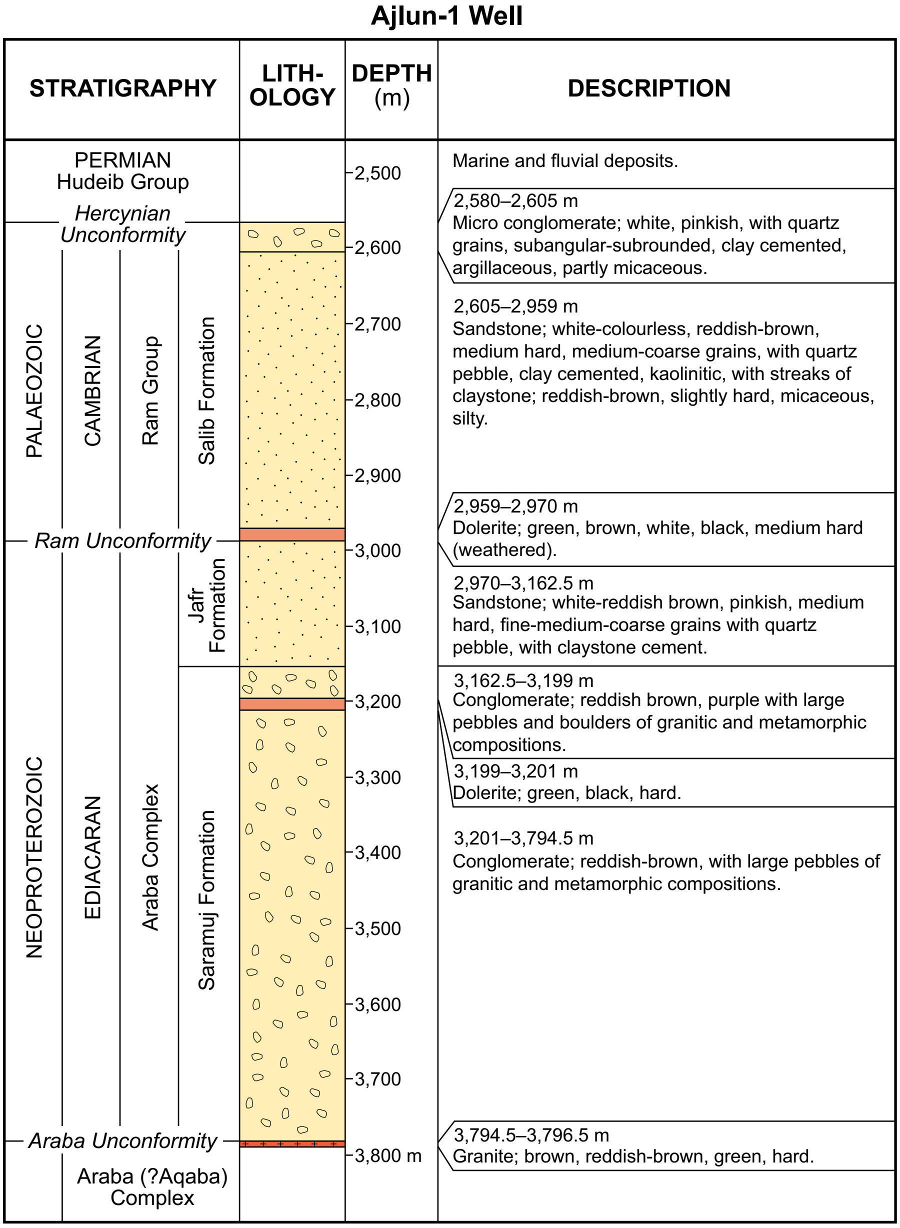


Figure 7: The subsurface type section of the Saramuj Conglomerate Formation is proposed in Ajlun-1 Well between 3,162.5 and 3,794.5 (632 m thick). The dolerite intervals encountered in this and other wells and are interpreted as Triassic. See Figure 1 for location.

The interbedded silicilastics vary from lithic arkose to arkosic sandstone in composition. Trough cross-bedding with low- to very low-grade foresets is typical; the low-angle of the foresets suggests that only the base of the sets are preserved as a result of erosion of most of the these bedforms in a high-energy flow-regime (Plates 9b and 10c). Planar cross-bedding is also present. Palaeocurrent measurements are difficult to determine because of the paucity of exposed bedding-plane surfaces and the eroded nature of the cross-bedding foresets in trough-shaped beds. However, when rotated for tectonic dip the palaeocurrent flow is to the west (for northern outcrop; Powell, 1988) and north and northwest (Jarrar et al., 1991).

In thin section the matrix and the bedded siliciclastics vary from arkose to lithic arkose with > 30% sub-angular feldspar and lithic fragments (quartz and feldspar), together with subrounded quartz grains and opaque minerals (concentrated along bedding laminations). Most of the feldspar grains are partly altered to sericite, and secondary green chlorite is an alteration product. Quartz grain boundaries are slightly indented where in contact, and the feldspars have sutured boundaries.

SARAMUJ FORMATION

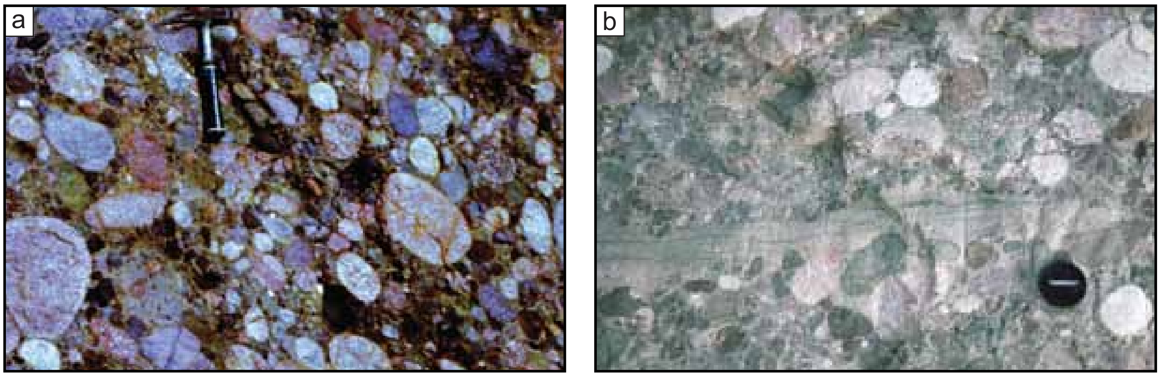
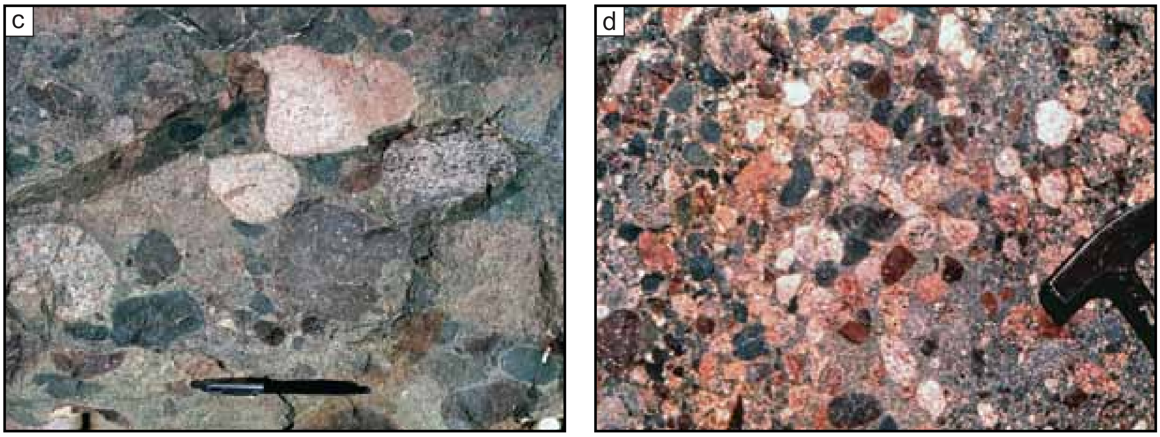


Plate 9: (a) Typical Saramuj Formation conglomerate (hammer 0.33 m long; photo by Gh.H. Jarrar); (b) Saramuj Formation conglomerate with cross-laminated sandstone lens (scoured base) at Wadi Sa'id, near Safi (see Figures 1 and 6 for location). Note the faint imbrication of elongate pebbles (to top right) indicating a high-energy alluvial fan environment. Lens cap: 40 mm diameter. Photo by J.H. Powell.



(c) Saramuj Formation conglomerate showing a variety of mostly rounded pebbles and cobbles consisting of Aqaba Complex granitoids, dyke rocks and porphyry with a coarse-grained lithic arenite matrix. The green colour of the matrix is due to the high percentage of chlorite and epidote that can reach up to 20% of the rock, and which was formed during burial of the formation. Note the elongate intraclast (dark tone, top-left) - a reworked fragment of conglomerate. Pen length is 0.14 m. Photo by J.H. Powell. (d) Coarse-grained conglomerate lithofacies of the Saramuj dominated by sub-angular mafic and felsic volcanics. Note their small size relative to the granitic clasts, reflecting the size of the original clasts in the source area, a result of narrow joint spacing in the volcanic rocks. Photo by Gh.H. Jarrar.

Jarrar et al. (1991) distinguished three lithofacies types.

(1) **Massive clast-supported coarse conglomerates:** Most clasts are between 5 and 30 cm. However, in the southernmost outcrops boulders up to 4 x 2 m have been reported (Plate 7). The thickness of these units can reach up to 30 m. Clasts range from well-rounded to subangular, whereby rounding increases with increasing clast size. Furthermore, granitoids are well-rounded while volcanic clasts tend to be subangular (Plates 9c, d).

(2) **Pebble-bearing sandy conglomerates:** These are matrix-supported pebbly beds in which the grain size of the matrix reaches 4 mm and contain 'floating' pebbles with a maximum clast size of about 10 cm. Beds are up to 2 m thick and show occasional cross-bedding.

SARAMUJ FORMATION

Plate 10: Saramuj Formation (photos by Gh.H. Jarrar). (a) Typical matrix-supported pebbly sandstone facies with floating pebbles of variable composition; bedding is sub-vertical, younging to the right. Lens cap is 40 mm in diameter. (b) Reworked rounded boulders (dark tones) of conglomerate pebbles. Hammer is 0.33 m long.

(c) Trough cross-bedding (perpendicular to current flow) in the sandy lithofacies of the Saramuj Formation. (d) Saramuj conglomerate hornfels in the innermost contact metamorphic aureole surrounding the mozogabbro in Wadi Qunaia (see Figure 6 for location). The igneous clasts are rarely affected, whereas the dominantly dark-green groundmass comprises a mineral assemblage of biotite, hornblende, clino- and orthopyroxene arranged in order of decreasing distance from the contact. Hammer is 0.33 m long.

(3) **Lithic arkosic sandstone:** The lithofacies consists of medium- to coarse-grained sandstones dominated by quartz, alkali feldspars, and lithic fragments (Plate 9). The fine matrix is recrystallised to chlorite and epidote due to anchi-metamorphism; chlorite thermometry gives a burial temperature of 250–300°C (Ghanem, 2009). Assuming a relatively high geothermal gradient at the time of about 50°C/km, a depth of burial of about 5–6 km is suggested (Powell, 1988; Jarrar et al., 1991; Ghanem, 2009). The highly indurated matrix also indicates that the sediments have been buried to a considerable depth.

Thickness

In the type area the base of the formation is not exposed, but the exposed thickness has been calculated at more than 250 m based on a regional dip to the west (Powell, 1988; Jarrar et al., 1991). In the subsurface reference section, Ajlun-1 Well proved 632 m (Figure 7). If the identification of the Saramuj Formation in the NH-1 and SA-1 wells is correct (Bender, 1974; Andrews, 1991) then up to 79 m and 420 m were proven, respectively. Seismic data in the Golan Heights indicates a thickness of up to 1,500 m (Meiler et al., 2011) although this figure probably includes overlying Ediacaran rocks. A maximum thickness of about 400 m is given by Weissbrod and Sneh (2002) for the coeval Eilat Conglomerate.

Boundaries

Lower Boundary: As noted above, the base is not exposed in the type area near Safi, although the lower boundary is exposed in Wadi Abu Barqa, located about 75 km north of Aqaba. Hereabouts, the Saramuj conglomerate rests unconformably (Araba Unconformity) on white–grey porphyritic granite, part of the Aqaba Complex (Jarrar et al., 1991). The lower boundary in AJ-1 Well is marked by conglomerate unconformably overlying granite, the latter probably representing Aqaba Complex basement rather than an Araba Complex intrusive stock (Figure 7).

Upper Boundary: In the type area the upper boundary of the formation is taken at the unconformable boundary (Ram Unconformity) between the conglomerates of the Saramuj Formation and the lower Cambrian Salib Formation (Powell, 1988). The Salib sandstones generally overstep the Saramuj conglomerates and the upper surface of the Saramuj Formation is peneplained. In Wadi al-Mahraka (31°06.446′N; 35°31.689′E) east of the Safi Potash works, Amireh et al. (2008) described the upper Ediacaran Umm Ghaddah Formation locally overlying the Saramuj Formation unconformably. In AJ-1 Well the Ram Unconformity at the base of the Salib Formation is at 3,162.5 m depth (Figure 7).

Near Wadi Abu Barqa, conglomeratic arkoses of similar lithofacies to the type Saramuj Conglomerate are present with abundant subangular to subrounded clasts derived locally from the Turban Granite and the Abu Barqa Metamorphic Suite of the Aqaba Complex. The formation passes upward with a gradational boundary to about 200 m of volcaniclastic sediments comprising coarse-grained tuffs and varved, fissile claystone and siltstone (Haiyala Volcaniclastic Formation) (Jarrar et al., 1991).

Boundary with the Intrusive Qunaia Monzogabbro

The Qunaia Monzogabbro (Ghanem and Jarrar, 2013) crops out between wadis Maghs and Qunaia (Figure 6), after which it was named (Powell, 1988; McCourt and Ibrahim, 1990). About 1.5 km east from the mouth of Wadi Qunaia the monzogabbro has an intrusive contact with the Saramuj Formation; this relationship can also be seen high above the wadi at the southern end of Jibal Samrat Qunaia. At Wadi Qunaia the coarse-grained monzogabbro invades the arkosic matrix of the conglomerate, and the granitic pebble-cobble clasts of the latter are preserved as discrete, rounded xenoliths; rounded blocks of conglomerate are also preserved up to 1 m from the contact (Plate 10d). Intrusive tongues of monzogabbro with irregular margins penetrate beds of coarse-grained, cross-bedded arkosic sandstone. Similar relationships can be observed at the southern end of Jibal Samrat Qunaia, about 100 m above the wadi floor. The contact zone, here, is inclined gently towards the north-northeast. The contact relationships are complicated by extensive, minor faulting and later dyke intrusion, but tongues of very coarse-grained monzogabbro have a contact-metamorphic relationship with the conglomerate.

At the contact zone with the intrusive Qunaia Monzogabbro the quartz grains in the Saramuj matrix are highly sutured with quartz overgrowth, and the feldspar show recrystallisation textures consisting of small equigranular polygonal crystals; biotite, hornblende, and clino- and ortho-pyroxene are also present (Jarrar et al., 1993; Ghanem, 2009). These features indicate thermal contact metamorphism.

Thin sections of coarse-grained lithic or arkosic sandstone (Saramuj Formation) sampled from the contact zone show highly sutured quartz grains, honey-comb mosaics of recrystallised plagioclase crystals, and small, pleochroic, green and mostly brown biotite crystals. The hornblende and the two pyroxenes are restricted to the innermost contact aureole (Jarrar et al., 1993; Ghanem, 2009). These features are absent in the 'normal' Saramuj Formation, and are consistent with a zone of contact (thermal) metamorphism. Bender (1974) erroneously considered the Saramuj Conglomerate as younger than the intrusives and described the contact as a marked erosional unconformity. The younger intrusive relationship of the dyke rocks was, however, noted by Burdon (1959) who lists other intrusive rocks such as augite-nepheline-syenite (Blake, 1939), diabase-porphyrite and an 'eruptive stock' (Picard, 1941) and appinite (Quennell, 1951), which was also inferred to be intrusive. The eruptive stock has been described by Jarrar et al. (1993) and Ghanem and Jarrar (2013) as megaporphyry due to the giant labradorite crystals up to 30 cm long. There are up to 20 thick dykes consanguineous with the monzogabbro. The augite-nepheline-syenite (Blake, 1939) is probably the same as the monzogabbro described, herein.

Age and Stratigraphical Relationships

No fossils or trace fossils have been reported in the Saramuj Formation at outcrop or in the subsurface. It overlies the Aqaba Complex and is therefore younger than the Araba Unconformity (ca. 605 Ma). Yaseen et al. (2013) even placed the minimum depositional age at 615 Ma. Field relationships prove that the Qunaia Monzogabbro intrudes the Saramuj Formation, locally producing contact metamorphism (Powell, 1988; Jarrar et al., 1991) (Plate 10d). The Qunaia intrusion was dated by K-Ar 585 ± 8 Ma (Lenz et al. (1972), by Rb-Sr 585 ± 3 Ma (M. Brook, personal communication, l987, *in* Powell, 1989), and by U-Pb 595 ± 2 Ma (Jarrar et al., 1991, 1993). Therefore the Saramuj Formation, at outcrop, is dated between ca. 605 and 595 ± 2 Ma.

The Qunaia intrusion is itself penetrated by dolerite and thin rhyolitic dykes, which are regionally correlated with the Aheimir Suite dyke event. Nowhere is the Qunaia Monzogabbro in contact with the sediments of the Ram Group; however, dykes lithologically and compositionally similar to those cutting the Qunaia Monzogabbro also cut the Saramuj Formation, but these do not penetrate the overlying Ram Unconformity, indicating a late Ediacaran age for this dyke event.

Depositional Environment

The lithology, grain-size and sedimentary structures indicate that the Saramuj Formation was deposited by a high-velocity, bed-load alluvial system (Powell, 1988; Jarrar et al., 1991). The high degree of rounding of the pebble-boulder clasts indicates that they are far-travelled, or in the case of intraclasts (Plates 9 and 10b), the result of successive reworking of earlier lithified gravels. Occasional rounded clasts of arkosic matrix also indicate re-working of pre-existing gravel matrix. Clast-supported conglomerates such as the Saramuj are indicative of stream-flow, rather than debris-flow, sedimentation in a braided alluvial fan system. However, outcrops in Wadi Saramuj clearly show unsorted, large sub-rounded boulder clasts (1 to 8 m diameter) (Plate 7) that were probably deposited as debris-flow deposits within active proximal alluvial fans located adjacent to active faults (Figure 5). The great thickness of these sediments at outcrop, and presumably from Safra-1 in north Jordan and the Golan Heights, suggests that they were deposited at the margins of a rapidly subsiding basin (a graben or half-graben setting), almost certainly fault-controlled. Preliminary results indicate palaeocurrent flow towards the west and north to northwest. Thick beds of clast-supported conglomerate with interbedded trough-cross bedded arkosic sandstone suggest successive, punctuated, subsidence of a fault-controlled depositional basin with granitoid clasts derived from the uplifted ANS basement country rock located to the south. The proportion of thick conglomerate beds decreases upwards so that arkosic sandstones with thin conglomerate beds predominate in the upper part of the formation indicating a more distal, braided-river lithofacies.

HAIYALA VOLCANICLASTIC FORMATION

Type and Reference Section

This formation is exposed approximately 5.5 km north northeast of Gharandal immediately to the south of Wadi Abu Barqa on the western, lower, slopes of Jabal al-Haiyala (Figures 2 and 4) where the succession dips at between 15 to 25 degrees southeast (McCourt and Ibrahim, 1990; Jarrar et al., 1991) where it unconformably overlies the Saramuj Formation (Figure 8).

Distribution

The formation is informally divided into the A and B members (McCourt and Ibrahim, 1990). They occupy distinct tectonic blocks on the eastern side of Wadi Araba, where the present-day geology is essentially a mosaic of fault-bounded rhombs or lozenges exposed between the Neogene major faults of the Wadi Araba Fault Zone and the Gharandal Fault (Figure 2). Accordingly, the stratigraphical subdivisions (A and B) may only be of local significance. The formation has not been recognised in subsurface.

Authors and Nomenclature

The Haiyala Formation was defined and named by McCourt and Ibrahim (1990). They equate it to the 'Slate Greywacke Series' as mapped by Bender (1968, 1974). They introduced the present name because the rocks are neither slates nor greywackes and the term 'series' as used by Bender differs from that followed by Jordan's National Resources Authority (NRA) and modern stratigraphical procedures (Rawson et al., 2002).

Lithology and Bedforms

Lithologies are described in detail in McCourt and Ibrahim (1990) and Jarrar et al. (1991). The two informal members, although not in continuity, are interpreted as lateral lithofacies variants, described below.

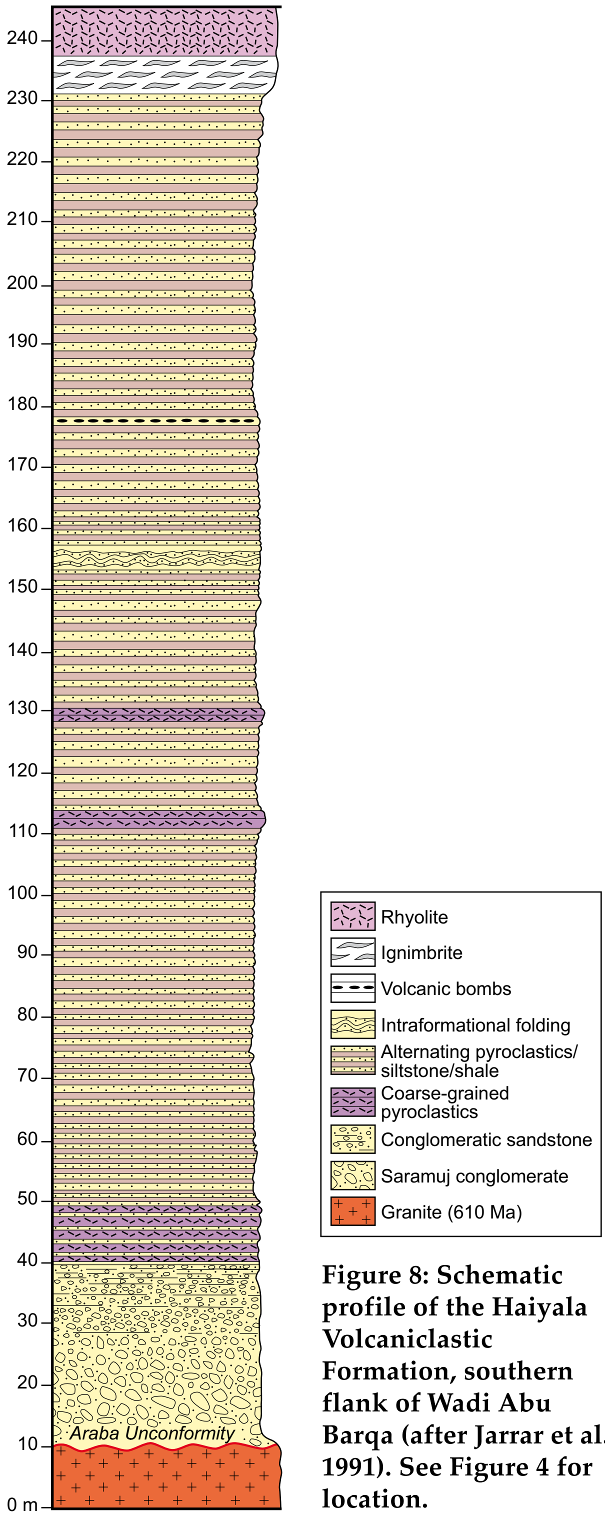


Figure 8: Schematic profile of the Haiyala Volcaniclastic Formation, southern flank of Wadi Abu Barqa (after Jarrar et al., 1991). See Figure 4 for location.

Member A (Figure 8) comprises the main sequence of 200–220 m of steeply dipping volcaniclastic sediments, dominantly coarse-grained tuffs and fissile, finely laminated (possibly 'varved') claystones and siltstones (angular grains of quartz, feldspar and muscovite; Plate 11). The claystones and siltstones are grey-green to reddish-brown, often mottled, and contain fragments of fine-grained brick-red 'felsite' in a tuffaceous matrix. The tuffs (*sensu stricto*) are coarser-grained lithic and lithic-crystal tuffs generally recognised at outcrop due to their purple-green colouration. Thinly bedded sedimentary rhythms, up to 0.60 m thick, are typified by a sharp lower boundary with graded granule to silt-grade pyroclastic fragments intercalated with claystone and siltstone laminae, the latter composed of quartz, feldspar and muscovite, with kaolinite and illite comprising the most common clay minerals. Millimetre-thick laminae are well-developed in the volcanic ash layers, interbedded with fine-grained siliciclastics; laminae are often separated by a sharp erosional, and occasionally scoured, contacts (Jarrar et al., 1991).

Penecontemporaneous folds are present, probably resulting from pyroclastic gravity-flow surges and loading or dewatering during rapid sedimentation events. Upward-fining grading in the coarser

HAIYALA VOLCANICLASTIC FORMATION

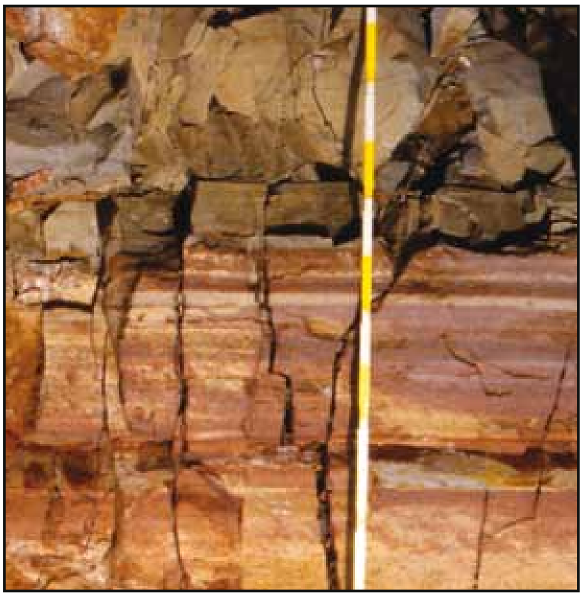


Plate 11: Pyroclastic layers overlain by water-lain mudstones (slates); Haiyala Volcaniclastic Formation. Type locality, southern shoulder of Wadi Abu Barqa (see Figure 4 for location). Photo by Gh.H. Jarrar.

volcaniclastic laminae are up to 1 m thick. Intercalated claystone and siltstone laminae exhibit straight–crested wave ripples, polygonal desiccation cracks (up to 0.20 m across) and circular pits, possibly representing rain-drop impressions (Jarrar et al., 1991).

The pyroclastic rocks are associated with rhyolitic lava flows (Figure 8; Plate 12), and locally with ignimbrite (up to 6 m thick). Pyroclastics include poorly-sorted, fine- to coarse-grained ash tuffs and subordinate lapilli tuffs, both rich in lithic and crystal fragments, up to 60% in abundance. The lithic and crystal fragments reflect the composition of the ANS crust, the former comprising granitoids, volcanics, and subordinate metasediments, and the latter, quartz, sanidine, microcline, muscovite and zircon.

Member B consists of a series of stratified, steeply dipping, green-weathering tuffs and 'ignimbrites' (rhyolites) with thin horizons of volcaniclastic-tuffaceous sandstone exposed in a fault-bounded slice to the east of the main outcrop, where it overlies the granitic basement.

HAIYALA VOLCANICLASTIC FORMATION

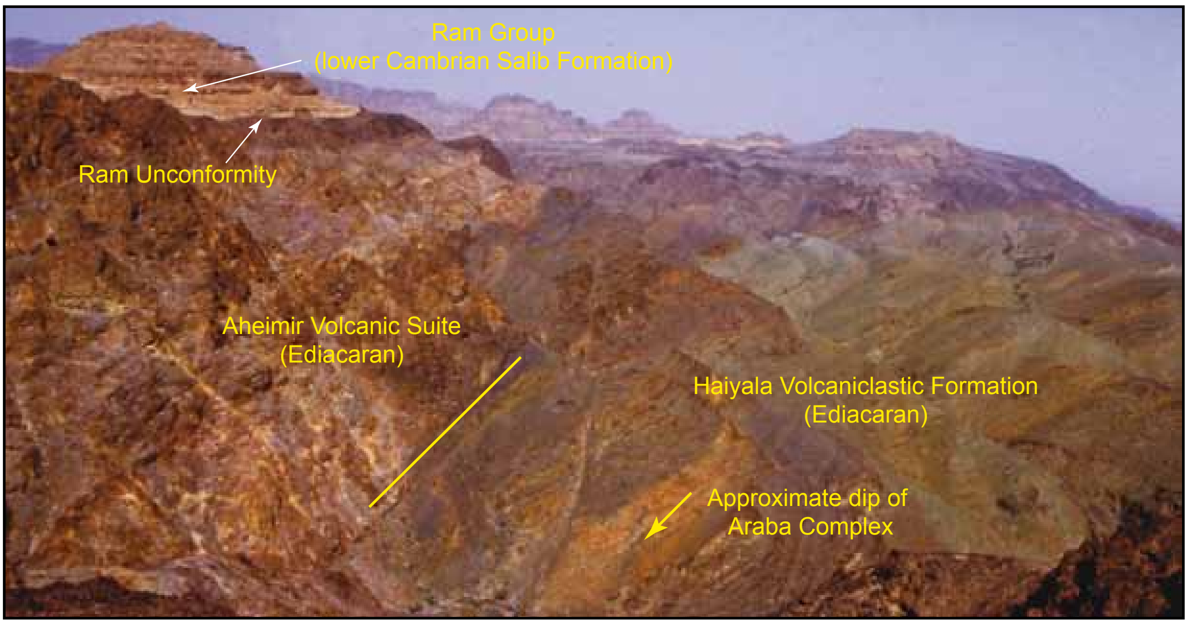


Plate 12: The contact between the Haiyala Volcaniclastic Formation (green tones, right) and the alkali feldspar rhyolites (pale brown, left) of the overlying Aheimir Volcanic Suite on the northern side of Wadi Museimir (see Figure 2 for location). Both units dip south-southeast, and are overlain unconformably by the lower Cambrian Salib Formation. The width of the photograph is several hundred metres. Photo by Gh.H. Jarrar.

Boundaries

Member A has a gradational conformable contact with underlying conglomerates and arkoses interpreted as the lateral, coeval, equivalents of the Saramuj Formation of the type area (Figure 8). Member B overlies granite similar to the Rahma Suite (Aqaba Complex). Like the Saramuj Formation of the type area, it is intruded by rhyolitic dykes, and its upper boundary is a peneplain below the Ram Unconformity.

Depositional Environment

The general lithology, character and sedimentary features suggest deposition as air-fall tuffs and finer-grained volcanic ash in a shallow water body, possibly in a shallow-marine or lacustrine setting (Figure 5). Desiccation cracks and possible rain-drop impressions indicate shallow water and periodic emergence. Scoured basal contacts and penecontemporanous folding and convolute bedding indicate dewatering following rapid sedimentation of volcanic ash, with local downslope scouring and turbidity traction currents during some of these sedimentation events. The overall setting is one of an extensional rifting basin with faults tapping rhyolitic magma that was erupted from volcanic cones, predominantly as air-fall deposits in shallow water bodies.

Age and Regional Correlations

The Haiyala Formation overlies the Saramuj Formation (McCourt and Ibrahim, 1990; Jarrar et al., 1993), which is dated between ca. 605 and 595 ± 2 Ma. It is locally intruded by dykes and small plugs of rhyolites/microgranites attributed to the Aheimir Suite. Jarrar (1992) obtained an Rb-Sr isochron age of 553 Ma for the younger Aheimir Suite; however a single zircon SIMS dating of the flow-folded rhyolites from Wadi Museimir and a composite dyke in Wadi Rahma gave an age range of 600–595 Ma (Jarrar et al., 2012). Recalculating the initial $^{87}Sr/^{86}Sr$ for these rhyolites using the zircon age reduces it ca. 0.7045, very similar to that of the Humrat and Feinan granites for which zircon ages range between 603 ± 5 and 586 ± 16 Ma (Jarrar et al., 2010; Moshtaha, 2011, unpublished PhD thesis).

No Ediacaran fauna has been found, to date, so it is not clear whether the volcaniclastics were deposited in a lacustrine or a shallow-marine environment. Since frond-like marine Ediacaran faunas did not evolve until around 579 Ma (Narbonne et al., 2012) the absence of these fossils may be due either to the fresh-water lacustrine setting or because the formation pre-dates the first appearance of Ediacaran frond-like fossils as suggested by the 600 Ma to 595 Ma zircon age for the younger Aheimir Volcanic Suite, noted above.

AHEIMIR VOLCANIC SUITE, ARABA COMPLEX

Type and Reference Section

The suite is exposed at Wadi Quseib and Wadi Museimir, the road-track from Al Beida to Bir Madkhur, and at Wadi Abu Khusheiba (Figure 2).

Subsurface Reference Section

The Aheimir Volcanic Suite has not been proven conclusively in the subsurface. However, Andrews (1991) described a basaltic volcanic unit ("Unassigned Volcanic Unit") in exploration wells JF-1 and WS-1 in central-east Jordan; these rocks are also interpreted as present on seismic lines (Figures 9 and 10) in rift and half-graben blocks below the Ram Unconformity (see Ma'an Formation, below). This pre-Ram volcanic succession is broadly coeval with the Aheimir Volcanic Suite, i.e. it post-dates the Aqaba Complex and pre-dates the lower Cambrian Ram Group. Amireh et al. (2008) correlated the Aheimir

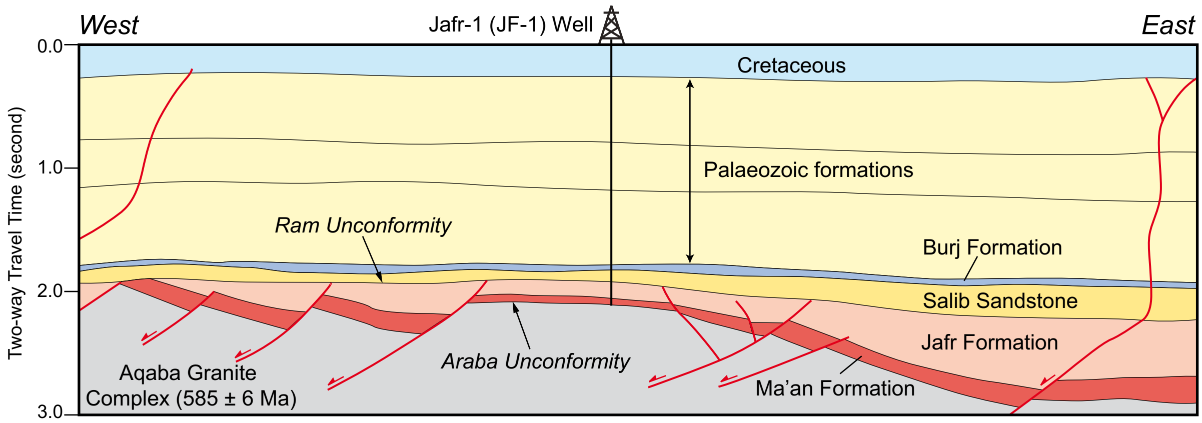


Figure 9: Geometry of half-grabens imaged by seismic data in the Al Jafr area (Jordan Hunt Oil Company, 1989, *in* Andrews, 1991; reproduced by permission of the Natural Resources Authority, Jordan). Jafr-1 Well encountered the lower Cambrian Salib Formation (289.2 m thick) below the middle Cambrian Burj Formation and above the Ediacaran Jafr Formation ('Unassigned Clastic Unit'). The undated basal Ma'an Formation ('Unassigned Volcanic Unit', 126.5 m thick) overlies the Granitic Basement dated at 585 ± 6 Ma (Rb/Sr, Ibrahim and McCourt, 1995; Jarrar et al., 2008). The granite is interpreted as the Aqaba Complex. See Figure 10 for location.

Suite at outcrop, with the subsurface 'Unassigned Volcanic Unit' of Andrews (1991; see below). The correlation is not based on radiometric dating, and the subsurface unit is distinguished separately here (see Ma'an Formation, below).

Distribution

This suite crops out along the eastern side of the Dead Sea Transform (Wadi Araba) extending north and northeast from Gharandal (Wadi Quseib) to Feinan (Figure 2), a strike distance of 65–75 km and varying in width from 2–4 km. The field relationships and outcrop pattern of the Aheimir Suite are highly characteristic in that the outcrop is confined to a narrow elongate fault-fracture zone that either parallels or is coincidental with the present-day Wadi Araba Fault Zone (Dead Sea Transform).

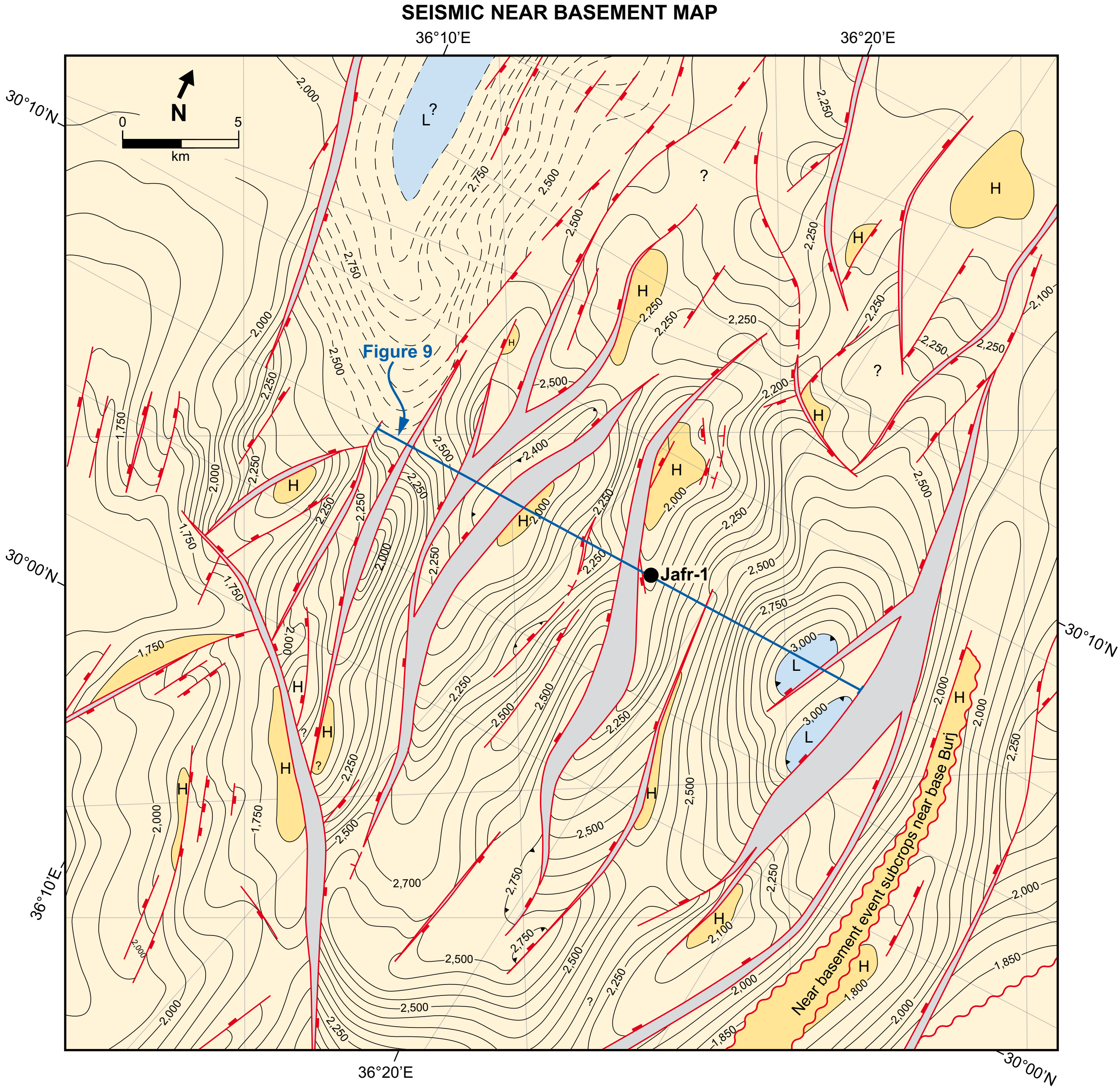
Authors and Nomenclature

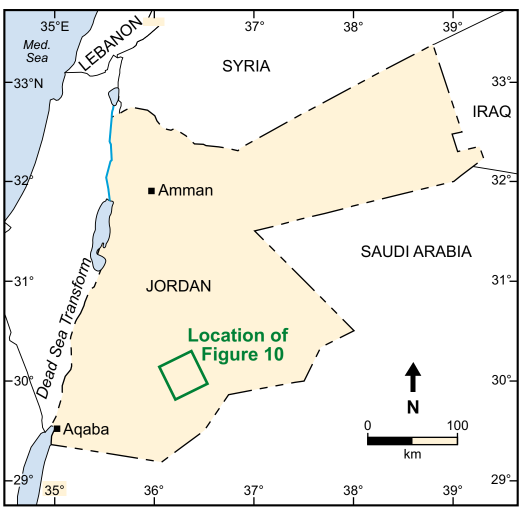
The Aheimir Volcanic Suite was defined by McCourt and Ibrahim (1990); the name derives from the eponymous wadi that intersects Wadi Araba.

Lithology

The suite has been broadly subdivided into: (1) extrusive-intrusive (dominantly rhyolite-microgranite) Quseib Unit; (2) effusive (dominantly 'fragmental') Museimir Formation with (3) locally intercalated Mufaraqad (oligomict) Conglomerate Formation; and (4) rhyolitic porphyrites (dominantly quartz porphyry) of the Al Beida Unit 'Unassigned Volcanic Unit'. It must be emphasised that due to the tectonic complexity of the area in general, and the length of the 'rift-line' in particular, it is very difficult to establish the precise stratigraphical relationships of these units.

The **Quseib Unit**, exposed in wadis Quseib and Museimir, is made up essentially of massive fine-grained porphyritic and non-porphyritic rhyolitic lavas, which have a variably developed, or preserved, banding or fluid structure, intercalated with tuffaceous horizons with abundant ignimbrites. The microgranites and/or dykes cutting their own lavas and pyroclastics are common in both wadis. These are compositionally and mineralogically very similar to the porphyritic rhyolites,





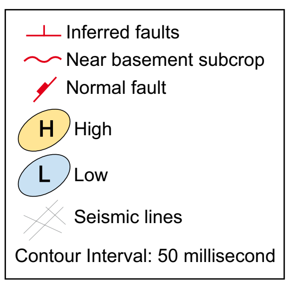


Figure 10: Map of seismic reflection from near the basement in the Jafr region in two-way-time with a contour interval of 50 millisecond (Jordan Hunt Oil Company, 1989; reproduced by permission of the Natural Resources Authority, Jordan). The reflection is tied in Jafr-1 Well to the Ma'an Volcanic Unit or granitic basement (see Figure 13).

AHEIMIR VOLCANIC SUITE

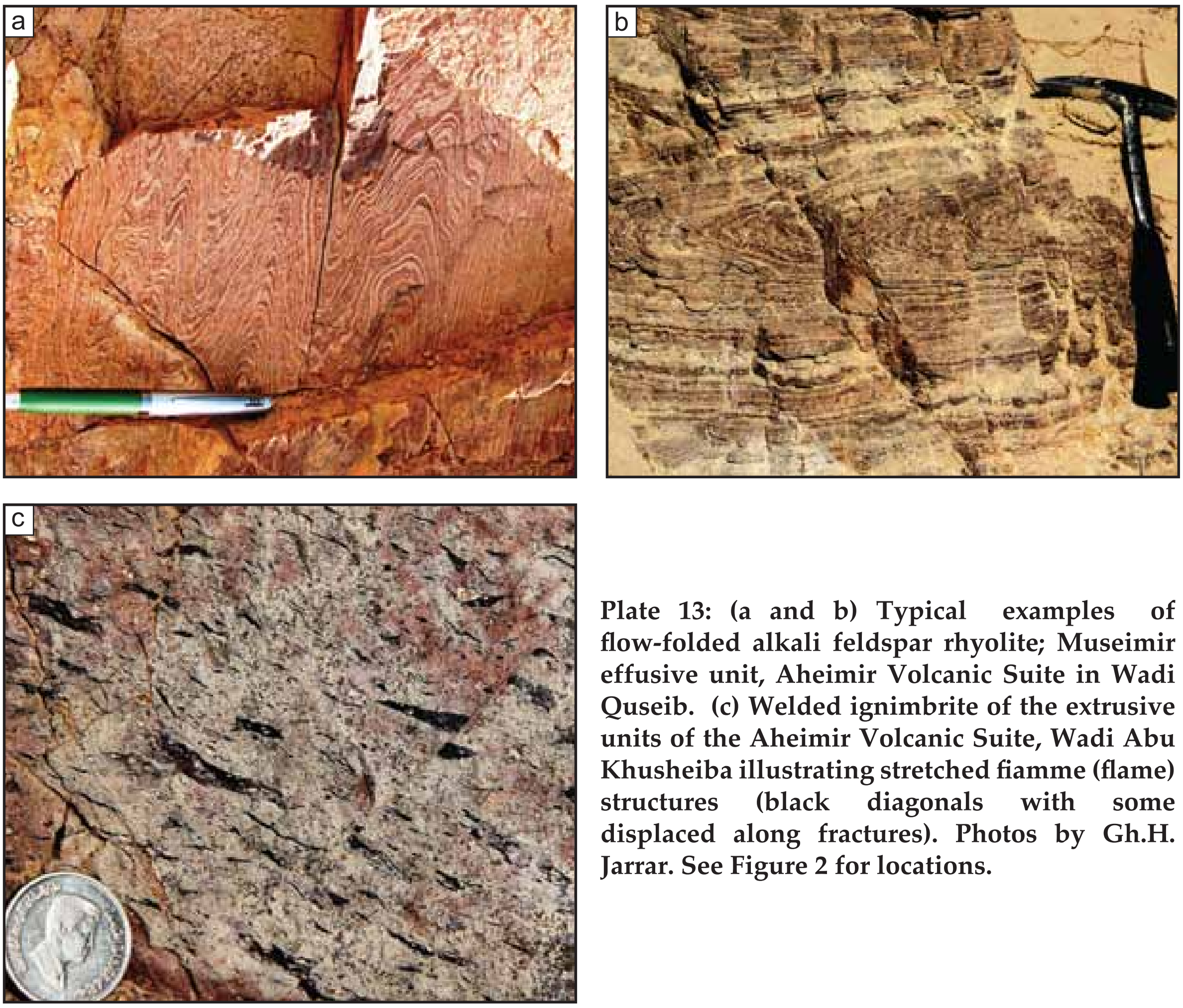


Plate 13: (a and b) Typical examples of flow-folded alkali feldspar rhyolite; Museimir effusive unit, Aheimir Volcanic Suite in Wadi Quseib. (c) Welded ignimbrite of the extrusive units of the Aheimir Volcanic Suite, Wadi Abu Khusheiba illustrating stretched fiamme (flame) structures (black diagonals with some displaced along fractures). Photos by Gh.H. Jarrar. See Figure 2 for locations.

but they have a distinct equigranular, fine-grained, granitic texture. Phenocrysts are subhedral to idiomorphic crystals of clear glassy quartz or red-pink feldspar set in an orange-brown aphanitic matrix. The northern outcrops of the AVS exposed in wadis Abu Sakakin and Borwas are typically peralkaline rhyolites with abundant aegirine, the latter accounting for the occasionally green colour of these rhyolites; according to their geochemistry these are classified as comendites (Jarrar et al., 1992).

The Museimir Formation (McCourt and Ibrahim, 1990**),** exposed along the road-track from Al Beida to Bir Madkhur, comprises fragmental effusives, dominated by lithic tuffs and ignimbrites/welded tuffs, with local agglomerates intercalated tuffaceous sandstones-siltstones and fragmental relatively massive flows of porphyritic felsite-rhyolite. The matrix of the lithic tuffs, that include volcanic breccias, is very fine-grained quartz and potassium-feldspar with high haematite content, possibly representing original glass dust, enclosing angular quartz, feldspar and lithic fragments both volcanic and plutonic in origin. The 'welded tuffs' (*sensu lato*) have some flow structures and also include devitrified glass shards (field identification) generally randomly orientated, but locally parallel and 'welded' together, thus are typical ignimbrites (Plate 13). The overall composition of these effusive rocks is very similar to the more obvious extrusive units, that is, both are essentially granitic (rhyolitic to rhyodacitic).

Some 100 m south of Wadi Abu Khusheiba, the **Mufaraqad Formation** is intercalated with the **Museimir Formation**. At outcrop the Mufaraqad Formation consists, predominantly of oligomict conglomerate comprising angular to subangular, clast-supported, poorly-sorted cobbles and

AHEIMIR VOLCANIC SUITE

Plate 14: Ram Unconformity, west of Petra, looking towards Wadi Araba (see Figure 2 for location), with lower Cambrian Ram Group sandstone (to right) resting unconformably with marked palaeorelief on the dark Aheimir Suite volcanic rocks (Araba Complex). The width of the photo is several 100 metres. Photo by J.H. Powell.

boulders. Clasts comprise either red-weathering granite, derived from the undeformed protolith of the granitic gneiss outcropping in Wadi Barraq; granite dated at ca. 624 Ma (Jarrar et al., 1991), or garnetiferous pelitic schist from the Abu Barqa Suite, often intermixed. The Mufaraqad Formation is intruded by a few dykes varying compositionally from dolerite to pegmatite and quartz porphyry. The contact relationships with the surrounding rocks here is enigmatic; most probably this outcrop represents a volcanic eruptive breccia rather than a conglomerate, and thus is a part of the Aheimir Suite. It might be related to the **Al Beida Unit**, the youngest phase of the Aheimir Suite. The porphyry is fine-grained, red-brown to dark brown with bleby and vitreous quartz phenocrysts and includes quartz keratophyre, orthoclase porphyry, plagioclase quartz porphyry and feldspar quartz porphyry (McCourt and Ibrahim, 1990).

Boundaries

The **lower boundary** of the Aheimir Suite is not discussed in McCourt and Ibrahim (1990), but it is recognised that the Quseib Unit outcropping in wadis Museimir and Quseib forms the lower part of the suite and overlies the Haiyala Volcaniclastic Formation (Plates 1a and 12). The pyroclastics interlayered in the Haiyala volcaniclastics are similar to the extrusive units of the Aheimir Suite. Both Haiyala Formation and the Aheimir Suite form a gently SE-dipping sequence that extends from the southern shoulder of Wadi Abu Barqa to Wadi Quseib.

The **upper boundary**, in particular the unconformity between the massive weathering rhyolites and the overlying lower Cambrian Ram Group (Salib Formation) (Plates 4, 12 and 14), is distinctive in that the characteristic peneplained surface typical of the Aqaba Complex/Ram Group boundary exposed so spectacularly in the Southern Desert is not seen (Powell et al., 2014). In contrast the boundary is marked by an immature palaeotopography with high relief which, from a distance, can give the impression that the rhyolites interfinger with, and/or intrude into, the overlying siliciclastic sediments (c.f. Bender, 1974). In fact, when the contact is examined, this is never the case, and is everywhere an erosional unconformity with pebbles and sub-angular fragments of the Aheimir Suite rocks present in basal conglomeritic sandstone horizons and/or infilling channels in the sediments of the Ram Group (Powell et al., 2014). Furthermore, there is no evidence of contact metamorphism or hydrothermal alteration at the boundary between the volcanics and the overlying Ram Group sandstones, which one would expect if the relationship were an intrusive one. Local contacts exposed on the track-road northwest of Al Beida show the Ram siliciclastic sediments infilling saucer-shape erosional depressions in the underlying palaeotopography (Figure 5; Powell at al., 2014).

Thickness

Jarrar (1992) estimated the thickness of the Aheimir Suite in Wadi Museimir at about 300 m. Since this northeast-trending unit continues for a distance of about 2 km as a ca. 15° SE-dipping sequence of alternating effusive and extrusive rhyolites into Wadi Quseib, the thickness of the Aheimir Suite is estimated at about 550 m.

Age and Regional Correlations

A widespread alkaline rhyolitic dyke event/phase is considered to be younger than the Aheimir Suite (McCourt and Ibrahim, 1990). Dykes, sills and small plugs of rhyolitic-microgranitic material cut, to varying degrees, both the Saramuj and Haiyala formations and very little igneous activity, for example dyking, has been recorded post-dating the Aheimir Volcanic Suite. Based on regional geological evidence, in conjunction with the available (Rb-Sr) age data from the Aheimir Suite and correlated units, McCourt and Ibrahim (1990) suggest a probable age of 550–540 Ma although this Rb-Sr age is now considered to be too young.

Jarrar (1992) obtained a Rb-Sr isochron age of 553 Ma for the Aheimir Suite; however a single zircon SIMS date for the flow-folded rhyolites (Museimir Effusives) gave an age of 598 ± 5 Ma (Jarrar et al., 2012). Based on these disparate geochronological ages and field relationships, the Aheimir Volocanic Suite is definitely younger than the Safi Group (ca. 600 Ma) and older than the Ram Unconformity (ca. 530 Ma). Correlation with the volcanic units proven in WS-3 and JF-1 wells in the Jafr Basin is discussed in a later section. To date, no fossils have been described from the Aheimir Suite.

UMM GHADDAH FORMATION

Type and Reference Section

The type section of the Umm Ghaddah Formation is located in Wadi Umm Ghaddah central Wadi Araba (30°26.0′ N, 35°22.36′ E; Figures 1 and 11, Table 2), where the formation is 60 m thick (Amireh and Abed, 2000; Amireh et al., 2008). This formation has been described by Jarrar et al. (1991) as a monomict conglomerate that consists of rhyolitic pebbles, cobbles, and boulders derived from the Aheimir Suite; nevertheless, it had not been given a formal name. Reference sections given by Jarrar et al. (1991) are Wadi Zubda, shown on the Geological Map of Bender (1974; Gharandal Sheet), and in Wadi Quseib where about 20 metres are exposed in a small basin of about 100 metres wide.

Table 2
Thickness of the Umm Ghaddah Formation

Outcrop	Thickness (m)	Underlying Unit
Wadi Umm Ghaddah	60	Aheimir Volcanic Suite
Wadi Abu Khusheiba	up to 15	Aheimir Volcanic Suite
Wadi al-Mahraka	30	Saramuj Formation
Wadi Quseib	ca. 20	Aheimir Volcanic Suite

Subsurface Reference Section

In the subsurface Jordan Hunt Oil Company (1989, unpublished report, *in* Andrews, 1991) identified a rock unit in the Jafr-1 (JF-1) and Northern Highlands-1 (NH-1) wells (Figure 1), and named it the 'Unassigned Clastic Unit'. Amireh and Abed (2000) and Amireh et al. (2008) proposed correlating this unit to the Umm Ghaddah Formation (see later discussion).

Distribution

The formation is recognised by Amireh and Abed (2000) in Wadi Umm Ghaddah (30°26.0′ N, 35°22.36′ E), and in Wadi al-Mahraka (31°06.446′ N, 35°31.689′ E) just east of the Potash Factory near the Dead Sea (Figure 1). Amireh and Abed (2000) correlated the Umm Ghaddah Formation and 'Unassigned Clastic Unit' of Jordan Hunt Oil Company (*in* Andrews, 1991) and interpreted it in six wells: Ajlun-1, Fuluq-1, Hammar-2, Jafr-1, North Highlands-1, Wadi Ghadaf-2 and Wadi Sirhan-3 (Figure 1).

Authors and Nomenclature

The name 'Umm Ghaddah Formation' was introduced and defined by Amireh and Abed (2000) to describe the unmetamorphosed siliciclastic sequence underlying the lower Cambrian Salib Formation (Ram Group).

Lithology, Facies Types and Facies Associations

The Umm Ghaddah Formation consists of two facies associations A and B: Facies Association A is almost entirely made of grain-supported, conglomeratic rhyolite clasts, and consists of four facies types (A1 to A4). Facies Association B is essentially made of lithic sandstones and consists of three facies (Sp, Sh and St). These are summarised here from Amireh et al. (2008).

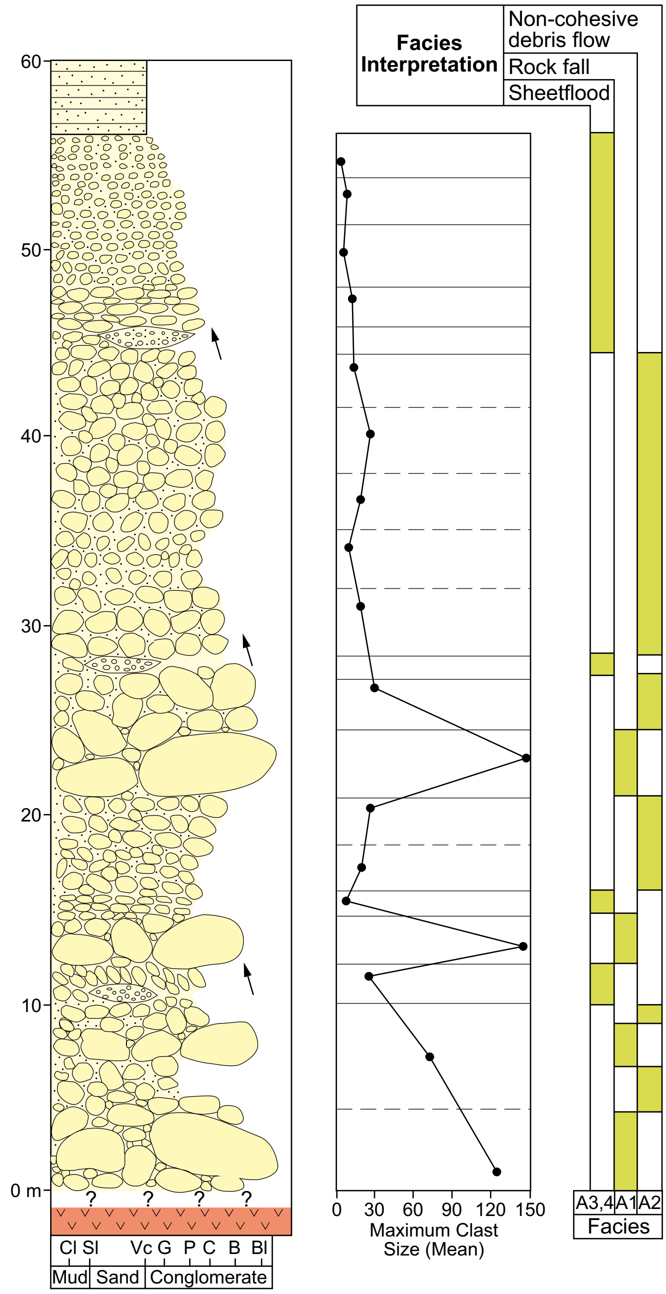


Figure 11: Type section of the Umm Ghaddah Formation in Wadi Umm Ghaddah showing lithologies, sedimentary structures, grain-size and facies interpretation. Lower arrow indicates pebble imbrication; central and upper arrows indicate the orientation of channel axes. The formation overlies the Aheimir Volcanic Suite (reproduced from Amireh et al., 2008, with permission of Elsevier). See Figure 1 for location.

Facies A1 consists of massive, clast-supported (less than 10% sandy matrix), very poorly-sorted, sandy, coarse cobble to block conglomerate. The clasts are randomly oriented, invariably subrounded to rounded, and vary in shape from discoidal to oblate. This facies occurs in the lowermost 25 m interval of the formation in the type locality (Figure 11) and in its lowermost part at Wadi Abu Khusheiba. Sedimentary structures and internal stratification are not visible in this facies. Clasts are

UMM GHADDAH FORMATION: FACIES A1 AND A2

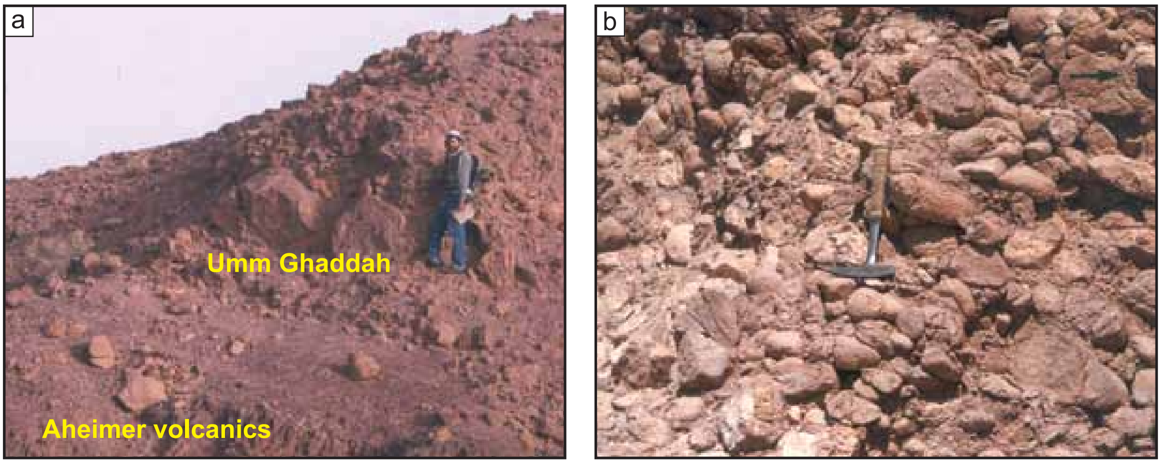


Plate 15: Umm Ghaddah Formation in Wadi Abu Khusheiba (see Figure 2 for location). (a) Facies A1 (Belal Amireh 180 cm), and (b) Facies A2 (hammer 30 cm), (reprinted from Amireh et al., 2008, with permission of Elsevier).

up to 5.5 m in size, and the mean diameter of the 10 largest clasts within each unit varies from 70–150 cm (Plate 15a). Grain-size analysis of the matrix reveals that it ranges from silt to medium pebbles, and is poorly sorted. The granule, fine pebble and medium pebble fraction accounts for 42 weight% of the matrix (sand 54% and silt 4%). No clay has been found in this fraction. Facies A1 has a sandy (slightly silty) matrix that makes up less than 10% of total rock volume.

Facies A2 is clast-supported with variable content of sandy matrix ranging from 10–25%. It is ungraded to inversely graded, and disorganised (Plate 15b). Clasts are randomly oriented, rounded to well-rounded, discoidal to oblate-shaped, very poorly-sorted, sandy, pebbly, cobble to boulder-grade (Figure 11). This facies is the most abundant in the type locality. It is similar to the Facies A1 in that there are no internal sedimentary structures or external stratification in the beds, but it is characterised by having smaller-sized clasts and containing a more sandy matrix. Mean grain size of the 10 largest clasts varies from 7–30 cm (Figure 11). The matrix consists of poorly sorted silt to medium pebbles. The granule, fine and medium pebbles account for 44–58% (40–54% sand, 2% silt).

Facies A3 consists of clast-supported conglomerate with a sandy matrix varying from 10–30%. Beds are ungraded, poorly sorted and consist of sandy, pebbly, fine- to coarse-grade cobble conglomerate (Plate 16). Clasts are parallel-oriented, subrounded to rounded and discoidal to oblate. In the Wadi Umm Ghaddah section this facies occurs at 15 m above the base of the formation and in the upper 15 m (Figure 11). It is crudely stratified (Plates 16b, d). In Wadi Umm Ghaddah it shows clast imbrication, revealing a north-northwest dispersal direction (Plates 16c, d). This facies has sharp but non-erosional lower boundaries. Mean size of the 10 largest clasts is 7 cm (Figure 11). The matrix ranges from silt to medium pebble-grade and is poorly sorted. The granules, fine and medium pebbles account for 33–55% (44–65% sand, 1–25% silt).

Facies A4 is a lenticular to channel-shaped conglomerate (Plate 17). It is clast-supported with 20–40% sandy matrix. This facies is largely ungraded, internally stratified, moderately sorted and consists of sandy, granular to pebble-grade conglomerate. The clasts are subrounded to rounded and discoidal, oblate to prolate in shape. Three units of this facies are encountered within the lower, middle and upper parts of the formation in Wadi Umm Ghaddah (Figure 11). The lenses or channels vary in width from 10 to 18 m, and up to several decimetres in thickness (Plate 17). The bases of these lenses and channel-fills are either convex downward or irregular, whereas their tops can be flat (Plate 17) or irregular. The axes of these lenses or channels are dominantly NNW-trending. There is a shale layer (Fm; 10–15 cm thick) in Wadi Abu Khusheiba interbedded within facies A2 and A3 (Plate 17), consisting of kaolinite and illite.

UMM GHADDAH FORMATION: FACIES A3

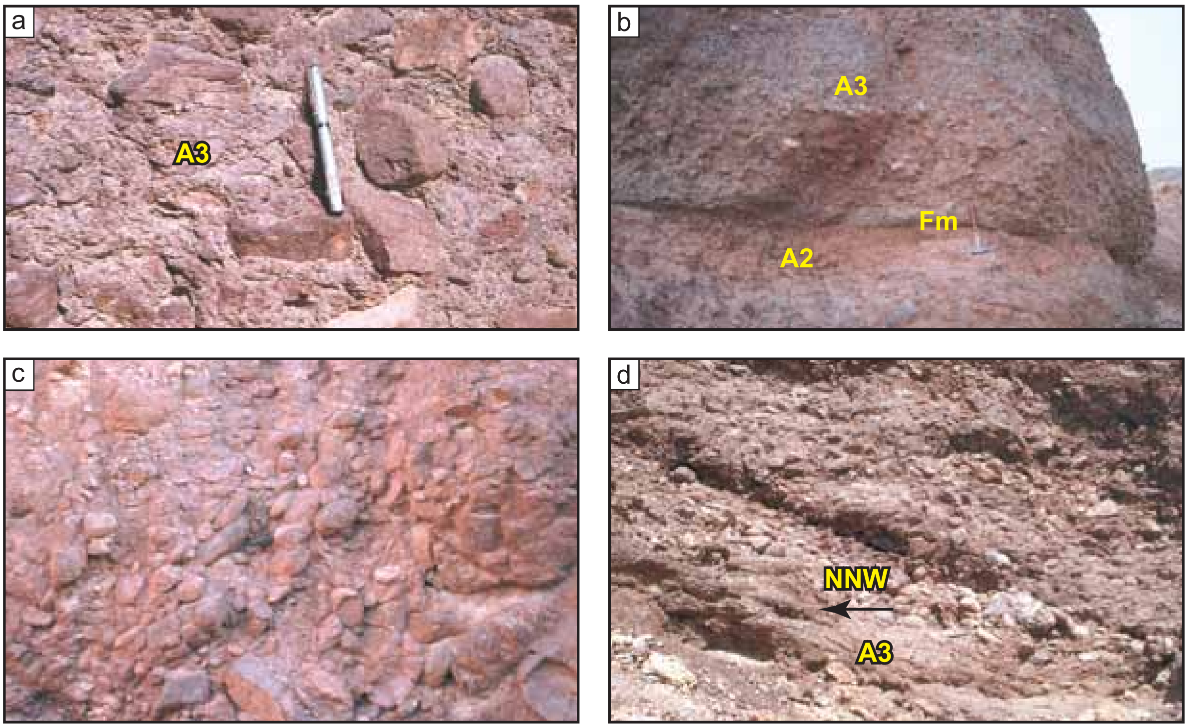


Plate 16: Alluvial fan Facies A3 of Umm Ghaddah Formation (see Figure 2 for locations). (a) Wadi Umm Ghaddah with 30% sand matrix; (b) Wadi Abu Khusheiba showing similar stratification (Fm is a shale layer); (c) Well-developed imbrication, Wadi Umm Ghaddah; (d) Imbricated cobbles (arrow) from Wadi Umm Ghaddah (reprinted from Amireh et al., 2008, with permission of Elsevier).

UMM GHADDAH FORMATION: FACIES A4

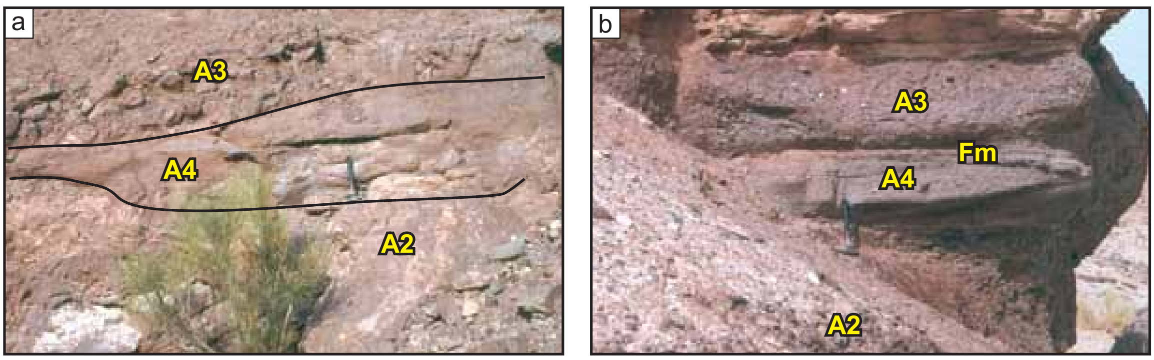


Plate 17: Alluvial fan Facies A4 of Umm Ghaddah Formation (see Figures 1 and 2 for locations; hammar for scale 0.30 m long). (a) Channel infill of Facies A4 truncating Facies A2, and characterised by a downward convex base and a flat top. Direction of channel axis is towards the NNW, Wadi Umm Ghaddah. (b) Channel infill of Facies A4 characterised by downward convex base and top, and having an axis orientation towards NNW, Wadi Abu Khusheiba. The channel is incised in Facies A2 and is overlain by a shale layer (Fm) (reprinted from Amireh et al., 2008, with permission of Elsevier).

The lower 25 m of the formation in Wadi Umm Ghaddah is characterised by the large clasts of Facies A1, whereas the upper 35 m exhibit a gradual decrease in clast size, showing an overall fining-upward tendency (Figure 11). On the other hand, in Wadi Abu Khusheiba, five outcrops are characterised by several coarsening and fining-upward units.

Facies Association B is predominantly lithic sandstone as seen in the Wadi al-Mahraka outcrop (Figure 1). A relatively minor amount of coarse-grained pebbly material of Facies Association A is still present in this outcrop as seen in Figure 12. At Wadi al-Mahraka, Facies Association B shows three sandstone lithofacies:

- **Sp**: planar tabular cross-bedded (Plate 18a),
- **Sh**: horizontally laminated sandstone (Plate 18a),
- **St**: trough cross-bedded (Plate 18b).

Sp is the major lithofacies having unit thicknesses of 20–90 cm. The Sp and St lithofacies are composed of pebbly, medium-grained, poorly-sorted sandstone, whereas the Sh lithofacies is made of fine-grained, well-sorted sandstone.

Grain-size analysis of the dominant Sp lithofacies reveals fine pebble to silt-grade with a mode at medium sand, and is poorly sorted. The fine pebbles and granules account for 11%, sand 87% and silt 2%. No clays have been detected. Microscopic analysis shows that the sand grains are subrounded to rounded and of moderate to high sphericity.

The sandstones represented by these three lithofacies constitute sand-bodies 1–5 m thick that extend laterally across the entire width of the outcrop. Some of these sheet sandstone bodies have a basal gravel lag and exhibit an upward-fining trend. The palaeocurrent direction (Figure 12) is north-northeast and northeast.

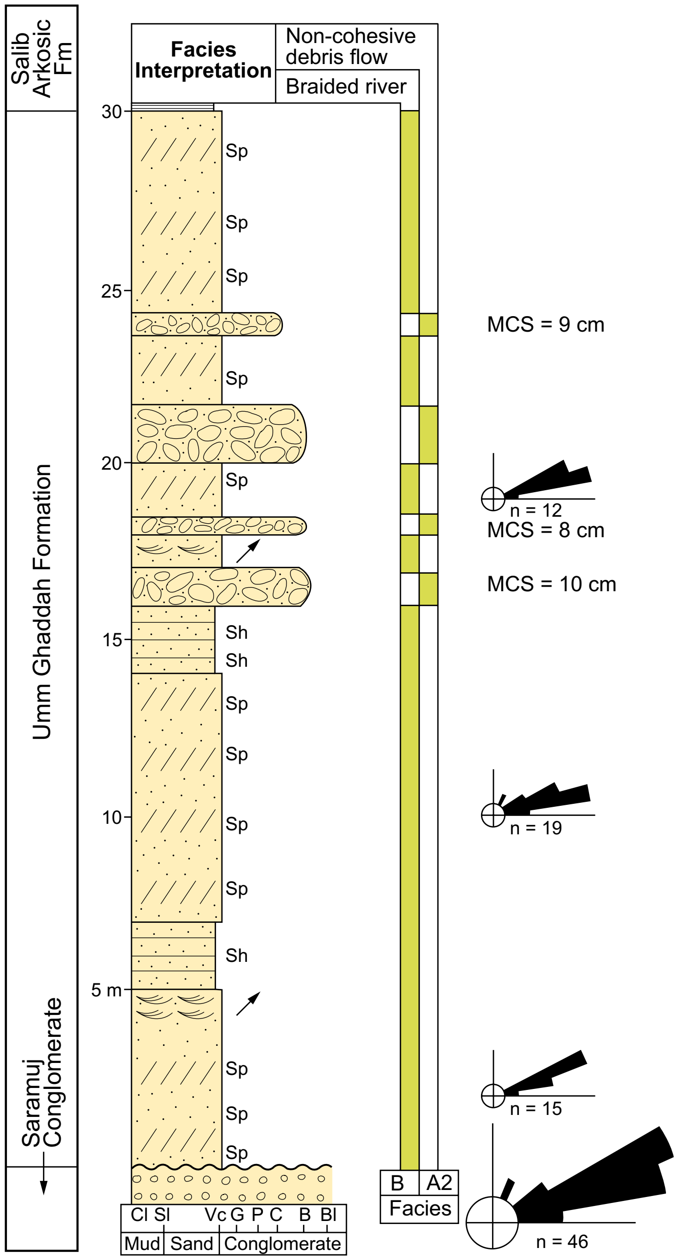


Figure 12: Columnar section of the Umm Ghaddah Formation in Wadi al-Mahraka with grain size, sedimentary structures, and palaeocurrent measurements. Sp, Sh and St represent sandstone facies with planar, horizontal and trough bedding. The two arrows indicate palaeocurrent direction. The rose diagram at lower right represents the total Sp cross-bedding measurements. M.C.S. indicates maximum clast size (reproduced from Amireh et al., 2008, with permission of Elsevier). See Figure 1 for location.

Depositional Environment

The Umm Ghaddah Formation is interpreted to have been deposited in alluvial fans, both as proximal and distal lithofacies, in a continental setting. The proximal facies were deposited at or adjacent to syn-depositional rift or half-graben bounding faults in wadis Abu Khusheiba, Umm Ghaddah and Quseib. The proximal lithofacies are represented by the coarse-grained, clast-supported conglomerates of **Lithofacies Association A**. **Facies A1 and A2** represent proximal alluvial fan facies, deposited by sediment-gravity flow processes including mainly cohesionless debris-flows (sub-aerial, high-viscosity debris flow) (Plate 19). The two facies were generated from the graben scarp by bedrock cliff-failure and moved downward by the influence of gravity, and tumbled directly at the

UMM GHADDAH FORMATION: FACIES ASSOCIATION B

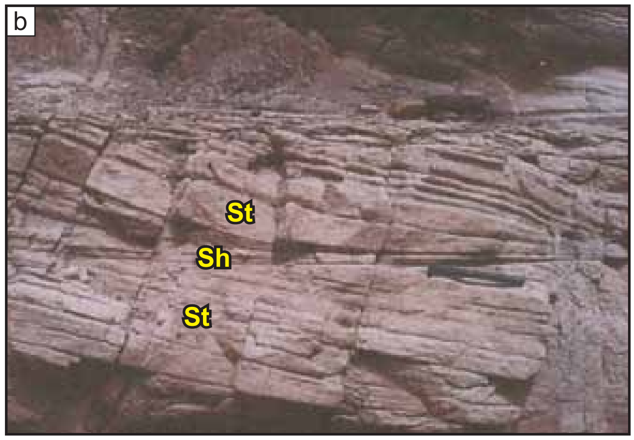


Plate 18: Braided river facies in Wadi al-Mahraka (see Figure 1 for location). (a) Planar tabular cross-bedding (Sp) and horizontal stratification (Sh) of Facies Association B; (b) Two sets of trough cross-bedding (St) with interbedded thin unit of Sh (reprinted from Amireh et al., 2008, with permission of Elsevier).

UMM GHADDAH FORMATION: FACIES ASSOCIATION A

Plate 19: Typical clast-supported monomict conglomerate, Umm Ghaddah Formation, Wadi Quseib (see Figure 2 for location). The clasts are of local provenance as is typical for this formation. Hammar for scale 0.33 m long. Photo by Gh.H. Jarrar.

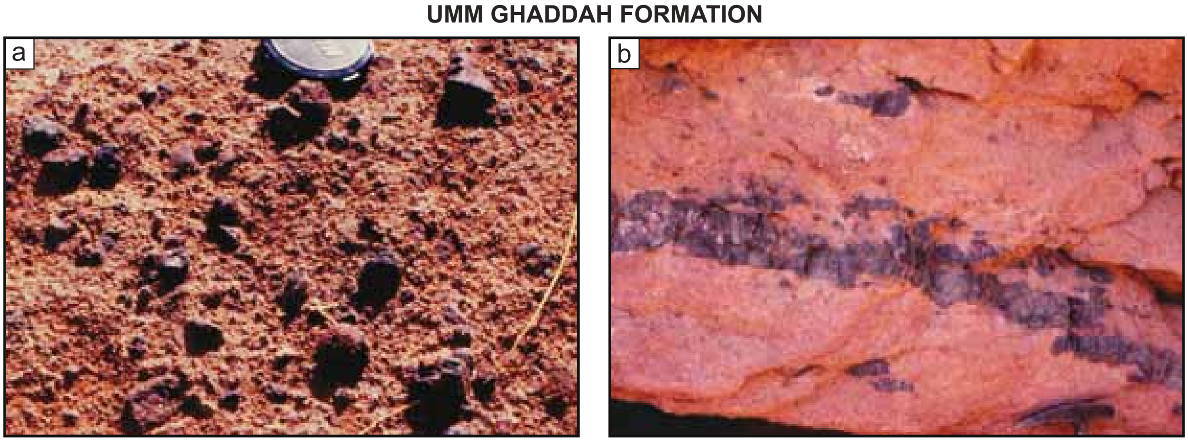


Plate 20: (a) Manganese nodules in Umm Ghaddah Formation. (b) Manganese layers overlying an impermeable claystone bed in the sandy lithofacies of Umm Ghaddah Formation at the type locality (see Figure 2 for location). Photo by Gh.H. Jarrar.

base of the fault scarp or rolled over or bounced a little distance to the proximal fan. The large blocks, 5.5 m in diameter, may have been sourced by rock fall. This interpretation is based on the very low fine-grain matrix (< 10% and < 25% in facies A1 and A2, respectively), the absence of stratification, and the absence of imbrication. Jarrar et al. (1991) reported the occurrence of thick manganese seams (up to 5 cm thick) and pebbles and cobbles thereof, in the sandy facies of the conglomerate (Plate 20). The manganese enrichment is connected to a fluviatile depositional regime and is concentrated above impermeable clay horizons.

Facies A3 consists of smaller clast size and higher fine-grained matrix (up to 3%). Facies A3 was most likely formed by sheet floods in the mid- to distal alluvial fan. This interpretation is supported by: (1) presence of stratified gravels and sands, (2) clasts that are parallel to bedding planes, (3) sheet-like geometry, (4) moderate sorting of clast-supported pebbles and cobbles, and (5) absence of cross-bedding.

Facies A4 is a lenticular to channel-shaped conglomerate. It is clast-supported with up to 40% sandy matrix. This facies is largely ungraded, internally stratified, moderately sorted and consists of sandy, granular to pebble-grade conglomerate. Faint internal stratification and lamination are interpreted as incised channel-fills. They may represent an extension of the drainage-basin feeder channel onto the fan or a cut-and-fill structure by channels entrenched only a short distance downslope from the fan apex. Another interpretation could be the deposition in incised shallow channels in the sheet-flood deposits of distal fan during waning flood discharge or recessional flood clear-water flows. The channel-fills indicate north-northwestward runoff from the fan apex to the fan margin.

Facies Association B represents the distal braided-river deposits of alluvial fans. This facies dominates the Wadi al-Mahraka section. It is dominated by lithic arenites with minor interbedded horizons of A3 and A4. Also finer argillites of siltstones and claystones are also recorded. Facies association B is characterised by the presence of various types of cross bedding; the major type is the planar tabular cross-bedded (Sp), with less abundant trough cross-bedded (St), and horizontally laminated sandstone (Sh). The three lithofacies constitute sandstone sheet, 1–5 m thickness extending laterally across the entire width of the outcrop in Wadi al-Mahraka. These sandstone sheets usually start with a planar to slightly irregular base that might truncate the underlying sheet. Some of these sheets have a basal gravel lag and exhibit an upward-fining trend. The overall stacking is an upward-fining pattern, especially in the thick successions.

It is likely that the axes of the Umm Ghaddah rift basins were oriented north-northwest to northeast as indicated by (1) the palaeoflow in the Facies Association B at Wadi al-Mahraka measured from

UMM GHADDAH FORMATION

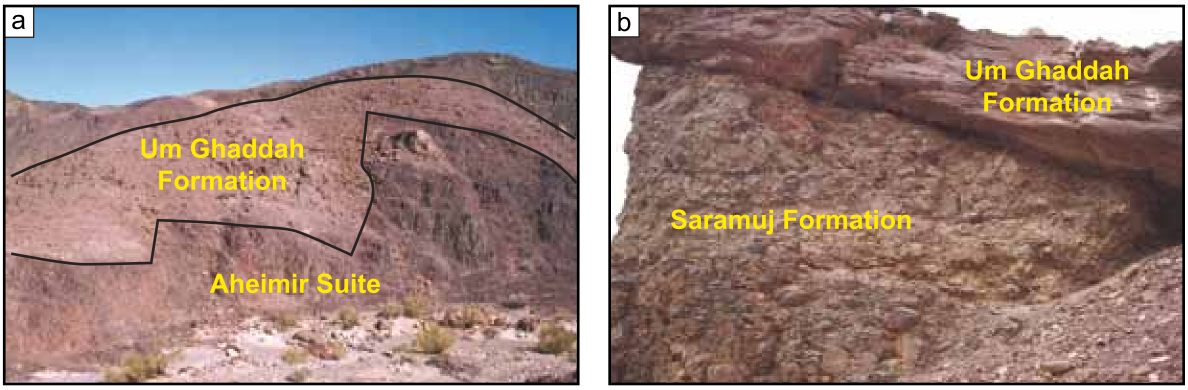


Plate 21: Lower boundary of Umm Ghaddah Formation, (a) overlying the Aheimer Volcanic Suite (AVS), width of the exposure is 500 m, (b) overlying the Saramuj Formation in Wadi al-Mahraka (see Figure 1 for location). (Reprinted from Amireh et al., 2008, with permission of Elsevier)

cross bedding is towards the southeast, (2) the north-northeast trending 70 km-long Aheimir volcanic exposure, and (3) the north-northeast trend of the three Umm Ghaddah outcrops that are dominated by volcanic pebble clasts locally sourced from the footwall volcanics of the Aheimir Suite. The alluvial Facies Association A was deposited normal and adjacent to the bounding rift faults, while Facies Association B was deposited parallel to the rift axis.

Boundaries and Thickness

The Umm Ghaddah Formation unconformably overlies the Aheimer Suite in Wadi Abu Khusheiba outcrops and Wadi Umm Ghaddah type section (Figure 11, Table 2, Plates 15a and 21a), and Wadi Quseib, where the conglomerates of Facies Association A are almost completely made of the Aheimer volcanic rocks. In Wadi al-Mahraka it overlies the Saramuj Formation (Plate 21b).

The upper boundary is marked by the unconformable lower Cambrian Salib Formation (Ram Group), which can be easily recognised in the outcrops of wadis Abu Khusheiba and Umm Ghaddah because of the distinctive rhyolite-dominated clasts of the Umm Ghaddah Formation.

Age

No body fossils or trace fossils have been reported from the Umm Ghaddah Formation at outcrop or in the subsurface. It is younger than the Aheimer Volcanic Suite (minimum age 598.2 ± 3.8 Ma) (Jarrar et al., 2012) because it consists mostly of clasts derived from these volcanics, especially the alluvial fan lithofacies. It is older than the Ram Unconformity (ca. 530 Ma).

ARABA COMPLEX IN THE SUBSURFACE

The Araba Complex has been proven in a number of exploration wells in east-central Jordan (Jafr-1 and Wadi Sirhan-3) and in north Jordan (Ajlun-1, North Highlands-1 and Safra-1; Figure 1). Jafr-1 also ties in with a broadly east-west orientated seismic line (unpublished report by Jordan Hunt Oil Company, 1989, *in* Andrews, 1991) (Figures 9, 10 and 13). Coeval rocks have also been reported from deep seismic imaging in the Golan Heights (Meiler et al., 2011). Precise correlation between the rocks units described here, at outcrop, and the subsurface units is somewhat tentative due to the paucity of information on the lithologies, at depth, and the reliance on interpreting wireline log signatures in the predominantly volcanic-volcaniclastic-siliciclastic succession where identification of conglomerate clast provenance is critical in unravelling the pulsatory sedimentary fill of these extensional basins (e.g. distinguishing Saramuj Formation polymict granitoid conglomerate from Aheimir Suite and Umm Ghaddah Formation oligomict volcanic conglomerates). Consequently, the sequences encountered in the Jafr Basin and north Jordan exploration wells are described, here, for each well, to highlight similarities and divergence from the type outcrop area. This is followed by discussion of tentative correlation between the outcrop and the subsurface.

Jafr-1 Well (JF-1)

Granite 'Basement' (Aqaba or Araba Complex)

The Jafr-1 Well in east-central Jordan encountered coarse-grained crystalline granite at 4,027.1 m and drilled through it for 20.1 m before stopping at a total depth 4,047.2 m (Figures 9, 10 and 13, Table 3). The granite is overlain by 6.7 m of granite 'wash' (interpreted here as weathered regolith) and sandstone between 4,020.4 and 4,027.1 m. A sample from the granite gave a Rb-Sr age of 585 ± 6 Ma (Andrews, 1991); the Rb-Sr age of the granite places it in the early Ediacaran, although on regional evidence Rb-Sr ages are generally younger by about 10 to 20 million years than U/Pb zircon ages (Jarrar et al., 2013). If the age quoted above is correct then the 'granite' may be part of the Feinan-Humrat-Mubarak Suite (586.2 ± 5 Ma to 600 ± 5 Ma U/Pb) or perhaps the Qunaia Monzogabbro (595 ± 2 Ma) intrusive phase. The tentative intrusive age suggests that the 'granite' is part of the granitoid Araba Complex (ca. 610–550 Ma). However, this age may be too young because the continuous granitoid basement proven by the Jafr seismic data and the presence of weathered granite 'wash' at the boundary in Jafr-1 Well (Figure 13) suggests a period of weathering occurred during development of the basal Araba Unconformity (≥ 605 Ma) on the underlying regional Aqaba Complex granitoids, i.e. prior to the deposition of the Ma'an Volcanic Formation.

Ma'an Volcanic Formation (formerly 'Unassigned Volcanic Unit')

Above the granite 'wash' and sandstone, between 3,893–4020.4 m, Jafr-1 encountered a 126.5 m-thick purple-brown to brown, very finely crystalline volcanic unit with frequent phenocrysts and masses of haematite (Figures 9 and 13, Table 3). Jordan Hunt Oil Company (1989, unpublished report *in* Andrews, 1991) named this interval the 'Unassigned Volcanic Unit', but it is here defined as the **Ma'an Volcanic Formation**, defined and named after the Ma'an Governorate that includes the Jafr area. At several horizons a red colouration reflects oxidation and deep weathering, here interpreted as weathered palaeosol horizons (bole). Paleoservices (1989, unpublished report, *in* Andrews, 1991) described textures from cuttings as trachyte flows, calcite-filled amygdales, flattened volcanic shards embedded in volcanic glass, large early-phase phenocrysts, lithic fragments and reworked textures, and *in situ* surface weathering. An analysis of thorium-uranium ratios also suggests the presence of four volcanic rock types, which may occur within a composite sequence of lava flows and tuffs.

Andrews (1991) reported that K-Ar age determination in Jafr-1 and Wadi Sirhan-3 yielded 403 Ma and 374 Ma, respectively, for the Ma'an Volcanic Formation. They correctly considered these ages as unrealistically young, as is typically the case for weathered basalts due to argon loss. By stratigraphical position, the Ma'an Volcanic Formation is younger than the underlying granite encountered in Jafr-1 dated at 585 ± 6 Ma, and older than the overlying, undated Jafr Formation (formerly 'Unassigned Clastic Unit'; see below). The geoseismic interpretation in Figure 9 suggests that the Ma'an Volcanic Formation was erupted in an active rift or half-graben setting in the Jafr area.

Jafr Formation (formerly 'Unassigned Clastic Unit')

Above the Ma'an Formation, Jafr-1 encountered between 3,625.6–3,893.9 m (2,754.8–3,023.1 m below sea level) a 268 m-thick siliciclastic succession, which Jordan Hunt Oil Company (1989, unpublished report *in* Andrews, 1991) named the 'Unassigned Clastic Unit'. The unit is formalised and defined here as the "Jafr Formation" named after the town of Al Jafr (Figures 9 and 13, Table 3). The basal part of the unit contains volcanic fragments derived from the underlying Ma'an Formation and thus the geophysical log boundary is not sharp, although the change in lithology was identified from cuttings and the overall gamma-ray log response (Figure 13).

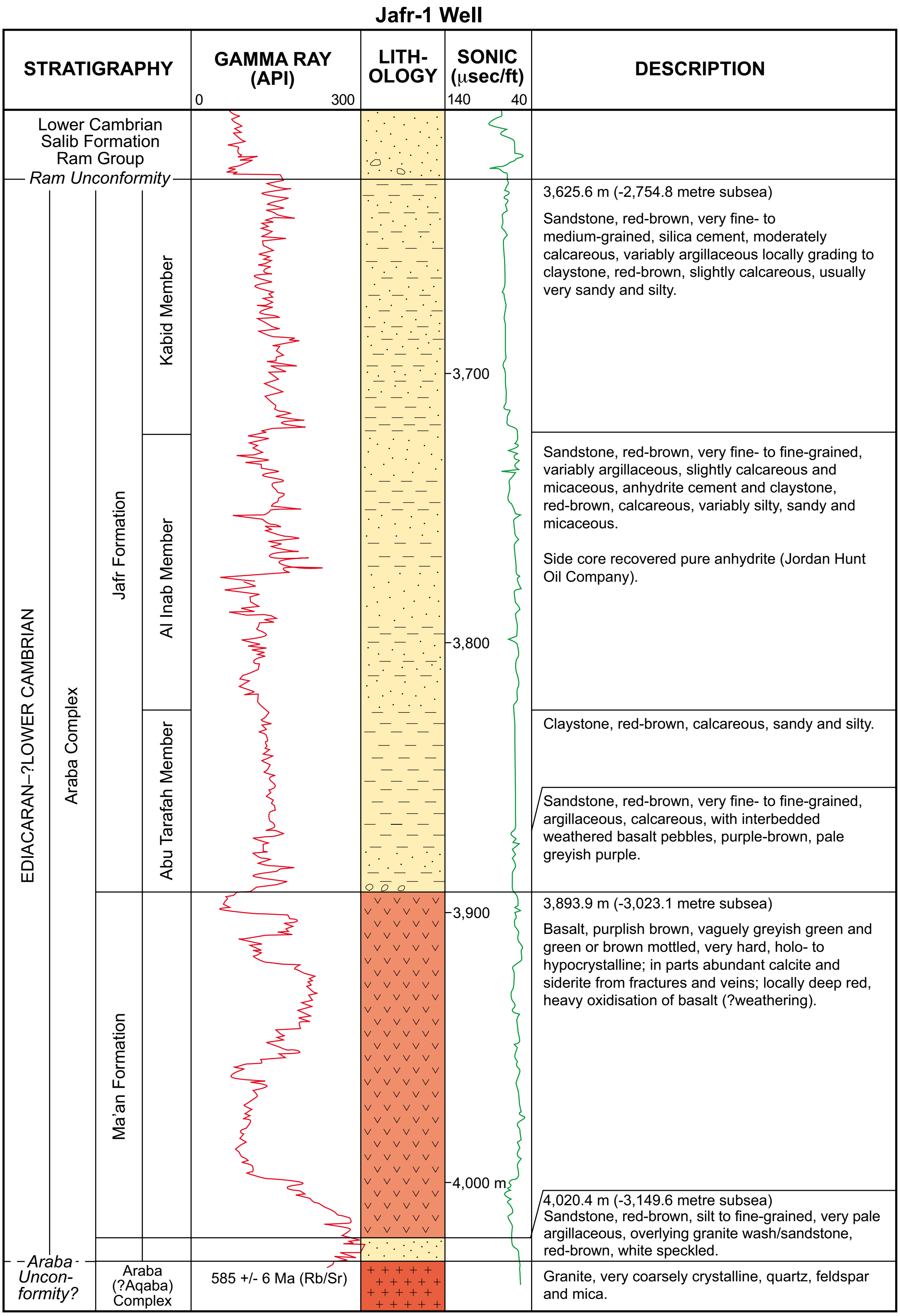


Figure 13: Reference section of the Ma'an Formation (previously 'Unassigned Volcanic Unit') and Jafr Formation (previously 'Unassigned Clastic Unit') in Jafr-1 Well (30°06'15.6"N, 36°21'14.0"E; modified from Jordan Hunt Oil Company, 1989; Andrews, 1991; reproduced by permission of the Natural Resources Authority, Jordan). See Figures 9 and 10 for location.

Table 3
Jafr-1 Well (after Andrews, 1991; this study)

Unit		Top (m)	Base (m)	Thickness (m)	Age
Burj Formation		3,275.4	3,336.4	61.0	mid-Cambrian (509 Ma)
Salib Formation		3,336,4	3,625.6	289.2	early Cambrian (≤ 530 Ma)
Jafr Formation ('Unassigned Clastic Unit')		3,625.6	3,893.4	268.2	late Ediacaran ≥ 550 Ma?
	Kabid Member	3,625.6	3,697.4	72	Ediacaran
	Al Inab Member	3,697.4	3,797.4	101	≤ 560 Ma?
	Abu Tarafah Member	3,797.4	3,893.9	96	Ediacaran
Ma'an Formation ('Unassigned Volcanic Unit')		3,893.4	4,020.4	126.5	Ediacaran
Granite wash		4,020.4	4,027.1	6.7	Ediacaran
Granite		4,027.1	4,047.2 (TD)	20.1	585 ± 6 Ma (Rb-Sr)

The Jafr Formation was divided on the basis of geophysical logs into three informal subunits by Andrews (1991), here described, in upward sequence, as formal members (Figure 13):

- **Abu Tarafah Member** (72 m thick)**:** The base of the lower unit is marked by re-deposited fragments or pebbles of weathered basalt. The overlying rocks are dominated by hard, red-brown, argillaceous, haematitic, laminated, very fine- to medium-grained sandstones. Side-wall cores indicate very calcareous cement at a number of levels. The name is derived from Wadi Abu Tarafah (also spelled Tarafa or Tarf'ah), which flows in to the Jafr Basin, south of Al Jafr.

- **Al Inab Member** (101 m thick) consists of red-brown, hard, very fine- to fine-grained sandstone interbedded with, or cemented by anhydrite. Side–wall cores generally indicate a slightly calcareous cement. A side-wall core at 3,730.45 m (12,239 ft) recovered from the upper part of the member and was described as a white to colourless, very fine (sugary) crystalline calcitic anhydrite with micro-breccia features. It tested positive for barium chloride ($BaCl_2$). Occasional red-brown claystone is also present. The name is taken form Wadi al-Inab (also spelled 'Unab') located southeast of Al Jafr.

- **Kabid Member** (95 m thick); the upper unit consists of well-sorted, red-brown, fine- to medium-grained sandstones, micaceous in part, and with a slightly calcareous or dolomitic cement, interbedded or grading to red-brown sandy or silty claystones. The name is taken from Wadi Kabid located southwest of Al Jafr.

No fossils have been found in the Jafr Formation but from its stratigraphical position it is younger than the Ma'an Formation (ca. 585 ± 6 Ma) and older than the bounding Ram Unconformity (ca. 530 Ma).

The depositional settings for the three members encountered in Jafr-1 were interpreted by Paleoservices (1989). No cores were cut through this interval, so the environments of deposition are deduced only from broad lithological assemblages, sparse side-wall cores and geophysical log responses. Paleoservices (1989) considered that the lower Abu Tarafah Member was deposited in a fluvial continental environment, the middle Al Inab Member in a marginal-marine/sabkha environment, followed by a return to continental deposition (Kabid Member). A possible marine incursion is indicated by the carbonate/anhydrite cemented lithologies in the Al Inab Member and by an influx of silty-sandy claystones and well-sorted, fine-grained sandstones in the lower part of the Kabid Member.

Based on the occurrence of pure anhydrite in a side-wall core, intercalated brecciated anhydrite and carbonate cements in the Al Inab Member, the present authors interpret a restricted sabkha to marginal-marine setting for the middle member of the Jafr Formation (Figure 13). It is likely that a marginal-marine setting persisted during the deposition of the uppermost Kabid Member, which is characterised by slightly calcareous/dolomitic siltstones.

Salib Formation

Above the Jafr Formation, the base of the Salib Formation is marked at 3,625 m by a conglomerate unit, and on seismic sections the base of this unit is clearly a major erosional surface, truncating the older, faulted succession (Andrews, 1991). Amireh et al. (2008) described this conglomerate as a lag deposit dominated by quartz in Jafr-1, and added that it is not always present in the lowermost Salib in the wells they studied or at outcrop. In general, they emphasise that the sandstones of the Jafr and Umm Ghaddah formations are lithic arenites whereas the Salib sandstones are arkosic arenites. The pebbles and granules in the basal pebbly sandstone facies in the Salib Formation consist dominantly of quartz while in the Jafr Formation they are mainly rhyolitic rock fragments derived from the underlying volcanic formation. The gamma-ray log response decreases across the boundary (Figure 13) reflecting the decrease in lithic clasts in the Salib Formation. The Salib Formation is 289.2 m thick between 3,364.4–3,625 m depth in this well and is overlain by the marine middle Cambrian Burj Formation (61 m thick) between 3,275.4–3,336.4 m (Powell et al., 2014).

North Highlands-1 Well

The North Highlands-1 Well was drilled near the Syrian border (Figure 1, Table 4). Between 3,938 m and total depth (TD) at 4,017 m it encountered a section (79 m thick) consisting of reddish-brown and purple conglomerate with pebbles and boulders of granitic and metamorphic composition set in a matrix of fine to coarse, angular quartz and feldspar grains (unpublished NRA reports, *in* Powell, 1988; Andrews, 1991). Andrews (1991) assigned this section to the Saramuj Formation, and reported that the Ma'an Formation ('Unassigned Volcanic Unit') is not present between the Saramuj Conglomerate and Jafr Formation ('Unassigned Clastic Unit').

It is not clear whether this pebble conglomerate with granitic and metamorphic clasts correlates with the Saramuj Formation or the younger Umm Ghaddah Formation. Amireh and Abed (2000) interpreted this section as volcanic rocks, but this does not fit with the description of polymict granitic and metamorphic clasts, presumably derived from the ANS basement, which is characteristic of the Saramuj Formation at outcrop. The gamma-ray log from TD to the Ram Unconformity varies from 60–130 API and does not distinguish between the basal conglomerate and Jafr Formation. Accordingly, NH-1 does not show any major change across the boundary between the Saramuj Formation and the overlying Jafr Formation, but according to the Andrews (1991) the conglomeratic lithology of the Saramuj Formation is distinctive below this boundary. No sonic log was run through this interval.

Table 4
North Highlands-1 Well (after Andrews, 1991)

Unit	Top (m)	Base (m)	Thickness (m)	Age
Burj Formation with dolerite	2,193.5	2,394.0	122.5 (78 m dolerite)	early mid-Cambrian (ca. 509 Ma)
Salib Formation	2,394.0	2,965.0	531.0	early Cambrian
Jafr Formation ('Unassigned Clastic Unit')	2,965.0	3,938	973.0	Ediacaran ≥ 550 Ma?
Upper Subunit	2,965	3,155	190	Ediacaran ≤ 560 Ma?
Lower Subunit	3,155	3,938	785	Ediacaran
Saramuj Formation	3,893	4,017 (TD)	> 79.0	ca. 595 Ma

Note: the age of the dolerite (possibly a sill) is uncertain; it may be Mesozoic in age.

Above the conglomeratic section, the well encountered the Jafr Formation ('Unassigned Clastic Unit') between 2,965–3,938 m below surface (937 m thick), which consists of two subunits (Andrews, 1991), as follows:

- **Lower Subunit** (785 m thick), is described as argillaceous, micaceous sandstone.
- **Upper Subunit** (190 m thick) has an overall fining-upwards trend with red-brown argillaceous, micaceous, fine- to medium-grained sandstone dominant at the base. Red-brown micaceous siltstone is dominant at the top.

The subunits are probably coeval with the three members of the Jafr Formation recorded in JF-1 well, but there is no record of carbonate or anhydrite lithologies that characterise the Al Inab and Kabid members in the Jafr Basin.

The NH-1 Well encountered several dolerite intervals ranging in thickness from a few metres to 10s of metres in the Ediacaran, Palaeozoic and Triassic sections. The dolerites are not encountered above the Triassic Ma'in Formation in Jordan, but regional evidence indicates the intrusives are Late Jurassic in age (Lang and Mimran, 1985). Between 2,193.5 m and 2,394 m the well encountered an interval of siltstone, dolomite and limestone, which are assigned to the Burj Formation, and 122.5 m thick. The rest of the section consists of several intervals of dolerite, one of which is nearly 30 m thick.

Ajlun-1 Well (AJ-1)

Also located in north Jordan, Ajlun-1 Well was not apparently available for inclusion in the summary bulletin by Andrews (1991). The gamma-ray and sonic logs and sparse lithological descriptions reveal important stratigraphical information (Figure 7, Table 5).

AJ-1 encountered conglomerates between 3,162.5 m and 3,794.5 m depth (Figure 7), unconformably overlying 'basement' from 3,794.5 m to 3,796.5 m (TD); the latter is described as "brown, reddish-brown, and green hard granite" and identified as the Aqaba Complex (Rabi, 1992). The conglomerate interval (632 m thick) is attributed to the Saramuj Formation and consists of reddish-brown and purple conglomerate with large pebbles and boulders of granitic and metamorphic composition. This represents the thickest section for the Saramuj Formation in Jordan, and is the first well to unequivocally identify the formation in the subsurface; it thus provides a useful reference section. Its stratigraphical position above the Aqaba Complex (from which its component clasts were derived) and below the probable Jafr Formation (see below) and overlying Salib Formation (early Cambrian age) suggests an Ediacaran age for the Saramuj Formation in this well. The thickness of the Saramuj Formation in this well in north Jordan is consistent with regional thicknesses interpreted from seismic investigations to the north, in the Golan Heights (Meiler et al., 2011).

Table 5
Ajlun-1 Well (after Rabi, 1992)

Unit	Top (m)	Base (m)	Thickness (m)	Age
Permian Hudeib Formation	-	2,580	-	Permian
Salib Formation	2,580	2,959	379	early Cambrian
Dolerite sill	2,959	2,970	11	intrusive
Jafr Formation ('Unassigned Clastic Unit')	2,970	3,162.5	192.5	late Ediacaran
Saramuj* Formation	3,162.5	3,794.5	632*	late Ediacaran
Aqaba Complex Granite	3,794.5	3,796.5	2 +	Cryogenian to early Ediacaran

Note: * includes 2 m-thick dolerite sill from 3,199–3,201 m. Note: the age of the dolerite (possibly a sill) is uncertain; it may be Mesozoic in age.

The interval from 2,975/2,985 m down to the top of the Saramuj Formation at 3,162.5 m has distinctive gamma-ray and sonic log signatures, clearly different from both the underlying Saramuj Formation and the overlying Salib Formation, as observed by Amireh and Abed (2000). This interval (187.5 m thick) is characterised by both a very uniform and relatively higher sonic profile, along with a lower amplitude gamma-ray response, as compared to the 'saw-tooth' gamma-ray and sonic profiles in the underlying Saramuj Formation and also the overlying Salib Formation. Lithological descriptions are sparse and it is described as: "white, pinkish to reddish-brown with fine- to medium quartz pebbles and claystone cement". Rabi (1992) included this interval within the Salib Formation, but the distinctive geophysical signatures indicate a more indurated, harder lithology with, perhaps, strong carbonate cements (i.e. higher gamma). Similar gamma-ray and sonic signatures are seen in the fine-grained carbonate-cemented Jafr Formation, especially the lowermost Abu Tarafah Member (Figure 13). The higher sonic response over this interval might also be due, in part, to the induration resulting from burial diagenesis, which is consistent with burial of the Ediacaran succession prior to uplift and erosion in early Cambrian times. Again, there are no age indicators, but the stratigraphical position above the Saramuj Formation and below the Salib Formation indicate a late Ediacaran age. We tentatively correlate this unit with the Jafr Formation as described in Jafr-1 well. The lithology is inconsistent with this unit representing the conglomeratic Umm Ghaddah Formation (Amireh and Abed, 2000).

The lower Cambrian Salib Formation was proven between 2,580 m and 2,959 m depth, unconformably overlain by the Permian Hudeib Group (Rabi, 1992; Figure 13). Lithologies comprise "white, pinkish, reddish-brown and colourless, medium-grained sandstone with quartz pebbles"; it is partly argillaceous with clay cements. The gamma-ray and sonic signatures along with sparse lithological descriptions indicate that the formation fines upward with a greater proportion of thin claystone beds from about 2,760 m to 2,580 m (base of Hudeib Formation). The marine Burj Formation was not encountered in this well, indicating a regional thickening of the Salib Formation to the north, consistent with the regional pattern for the lower Cambrian succession (Powell et al., 2014).

The boundary between the tentative Ediacaran Jafr Formation and the overlying lower Cambrian Salib Formation in this well is marked by a dolerite (11 m thick); a thin 2 m-thick dolerite is also present at lower depths from 3,199–3,201 m within the Saramuj Formation. As noted above for the NH-1 Well, we interpret these as dolerite sills of Mesozoic age which, along with feeder dykes, were intruded in north Jordan during Late Jurassic times, certainly prior to the Early Cretatceous unconformity (Bandel and Khoury, 1981; Lang and Mimran, 1985; Powell and Moh'd, 1993).

Safra-1 Well

Safra-1 Well is located to the southeast of Amman in north Jordan (Figure 1). Bender (1974, *in* Andrews, 1991) reported a 420 m-thick section, between 2,130–2,550 m, consisting of conglomeratic sandstone, arkosic sandstone and slate. It overlies "granite" between 2,550 m with a total drilled depth of 2,582 m, and underlies the lower Cambrian Salib Formation. No volcanic units occur in this section. Because geophysical logs are not available for this well, Andrews (1991) did not consider it as a representative reference well. It is unclear to the present authors whether the Saramuj Formation identified in Safra-1 may in fact be the younger Jafr Formation ('Unassigned Clastic Unit' or perhaps the Umm Ghaddah Formation) encountered in Jafr-1 and North Highlands-1.

Wadi Sirhan-3 Well

Andrews (1991) reported that in Wadi Sirhan-3 (Figure 1, Table 6) a red-brown alkali olivine basalt (> 120 m thick) was encountered between 4,460 m and total depth (TD) at 4,580 m. In this report it is named the Ma'an Formation, as in Jafr-1, and it also shows extensive replacement by iron oxides. Andrews reported that the lower Cambrian Salib Formation overlies this unit. In contrast, Amireh and Abed (2000) interpreted the 'Unassigned Clastic Unit' (presumed correlative of the Umm Ghaddah Formation) between 4,200–4,216 m and 4,370–4,376 m.

Table 6
Wadi Sirhan-3 Well (after Andrews, 1991)

Unit	Top (m)	Base (m)	Thickness (m)	Age
Burj Formation	3,614.0	3,710.0	96.0	early mid-Cambrian (ca. 509 Ma)
Salib Formation	3,710.0	4,460.0	750.0	early Cambrian
Jafr Formation ('Unassigned Clastic Unit')	absent	absent	0.0	Ediacaran
Ma'an Formation ('Unassigned Volcanic Unit')	4,460.0	4,580.0 (TD)	>120	Ediacaran

REGIONAL CORRELATION

As noted above, correlation of the Araba Complex units from the well-exposed, fault-bounded outcrops adjacent to Wadi Araba with the succession proven in widely spaced exploration wells in central-eastern (JF-1 and WS-3) and north Jordan (AJ -1, NH-1 and SA-1) is uncertain. There is little core material available, which means that the often subtle, but important, lithological characteristics, such as conglomerate clast composition that define these units at outcrop are sparse or poorly described. Furthermore, correlations are reliant on geophysical wireline log characteristics of these predominantly siliciclastic sedimentary rocks which lack distinctive gamma-ray signatures and, in some cases, even basic sonic and gamma-ray logs are not available.

Consequently, in the Jafr area we have tentatively defined the sub-surface units termed the former 'Unassigned Volcanic Unit' and the stratigraphically younger 'Unassigned Clastic Unit', as the Ma'an Formation and Jafr Formation, respectively. Should new seismic and exploration well data become available it may be possible to be more certain about the identification and correlation of these units in the region.

The stratigraphical and tectono-structural position (extensional grabens and half-grabens) of the Jafr Formation (Figures 9 and 10) suggests correlation with the lavas and effusive rocks of the Aheimir Volcanic Suite (Amireh and Abed, 2000). However, it is not clear whether the Ma'an Formation in the sub-surface is equivalent to the Quseib Rhyolite, Museimir Effusives or the Al Beida Rhyolite, or perhaps all of these volcanic units as seen at outcrop. If the granite and weathered regolith underlying the Ma'an Volcanic Formation in JF-1 belongs to the Araba Complex then the lower part of the Araba Complex (Safi Group and associated intrusives) is missing here and in WS-3. However, as noted above, the granite and weathered regolith may represent the older regional Aqaba Complex granitoid basement; if this the case then the Ediacaran rocks are represented by only the upper part of the Araba Complex in the Jafr area.

Absence of the Jafr Formation in WS-3 is probably due to erosion of this siliciclastic unit on the uplifted shoulders of half-grabens or horst blocks in the Jafr area (Figures 9 and 10). Amireh and Abed (2000) correlated the Umm Ghaddah Formation with the Jafr Formation (then the 'Unassigned Clastic Unit'). However, the Umm Ghaddah Formation at outcrop is predominantly coarse-grained conglomerate and coarse-grained sandstone deposited in alluvial fan to braided-river environments, in a localised footwall tectonic setting. In contrast, the Jafr Formation in the sub-surface (JF-1) lacks conglomerates, except for minor re-worked fragments of the underlying volcanic rocks at the base and, in contrast, predominantly comprises fine- to medium-grained siliciclastics together with claystones, siltstones, anhydrite along with carbonate cements. These lithologies, present mostly in the middle and upper part of the formation, suggest a low-gradient alluvial plain passing to a coastal plain or shallow-marine setting, in contrast to the alluvial fan setting of the Umm Ghaddah Formation at outcrop.

The Umm Ghaddah outcrop and Jafr subsurface lithofacies, if coeval, may represent end-members of a fault-bounded upland terrain (e.g. Umm Ghaddah) passing eastwards to a coastal-plain or

Table 7
Correlation of the Cryogenian, Ediacaran and lower Cambrian units in Jordan and adjacent areas

AGE			JORDAN (see references herein)		SAUDI ARABIA (Al-Husseini, 2014) *Northwest*	*Central*		SINAI, NEGEV and TIMNA (Weissbrod and Sneh, 2002; Eyal et al., 2014; Beyth et al., 2014; Abu El-Enen and Whitehouse, 2013)
PALAEOZOIC	Cambrian	Ram Group (part)	Burj Formation (ca. 509 Ma)	Tayma Group (part)	Burj Formation		Yam Suf Group (part)	Timna Formation
			Salib Sandstone Formation		Siq Sandstone Formation			Amudei Shelomo Formation
	541 Ma	*Ram Unconformity (ca. 530 Ma)*						
NEOPROTEROZOIC	Ediacaran	Araba Complex	Umm Ghaddah/Jafr formations Mufaraqad Conglomerate Ma'an Formation Aheimir Volcanic Suite Feinan-Humrat-Mubarak Granitic Suite Araba Mafic Suite Qunaia Monzogabbro	Jibalah Group	Muraykhah Formation Rubtayn Formation	Jifn Formation		Zenefim Formation and Taba Formation Amran Igneous Suite of Eilat and St. Katherina (alkali feldspar rhyolites flows and pyroclastics) St. Katherina Ring Complex, Central Sinai Peninsula
		Safi Gp	Haiyala Volcaniclastic Formation Saramuj Conglomerate Formation			Umm al-Aisah Formation		Roded tuff/conglomerate Mapalim Formation Eilat Conglomerate
		Araba Unconformity (ca. 605 Ma)						
	Ediacaran 635 Ma Cryo-genian 850 Ma	Aqaba Complex	Yutum Granitic Suite Rumman Granodioritic Suite Urf Porphyritic Suite Darba Tonalitic Suite Rahma Foliated Suite Duheila Hornblendic Suite Abu Saqa Schist Buseinat Gneiss Suite Janub Metamorphic Suite Abu Barqa Metamorphic Suite		Salih Formation Habd Complex Misyal Formation Sulaysil Formation Shar/Mass Complexes Saluwah Group Bayda Group Imdan Complex Zaam Group	Shammar Group		Batholiths of calc-alkaline granitoids Shahmon metabasites Taba Metamorphic Complex, NE Sinai Eilat Metamorphic Complex Feiran-Solaf Metamorphic Complex, NW Sinai

shallow-marine setting in central Jordan (Jafr Formation) and hence a possible link to the Ediacaran Mozambique Ocean that is more widespread in the Arabian Platform to the southeast (e.g. Jibalah Group) (Johnson et al., 2013). Alternatively, the outcropping Umm Ghaddah Formation may represent a localised footwall alluvial deposit, whereas the Jafr Formation represents a separate, more widespread marine transgression that advanced from the southeast. A similar scenario is indicated by the marine Ediacaran Jibalah Group in extensional rifted basins such as the Antaq Basin in Saudi Arabia (Nettle et al., 2014; Johnson et al., 2013). In summary, until additional subsurface data becomes available to firmly establish this correlation we prefer to maintain the outcrop and sub-surface formations as distinct formations.

In the type area, the lithology and low-grade burial metamorphic characteristics of the Saramuj Formation are very distinctive. Although the presence of the Saramuj Conglomerate in the lower part of NH-1 Well in north Jordan was reported by Bender (1974) and further discussed by Andrews (1991), Amireh and Abed (2000) regarded these basal conglomeratic sandstones as representing the Umm Ghaddah Formation. However, the description of granitic and metamorphic pebbles and boulders set in a matrix of fine- to coarse-grained arkosic matrix favours correlation with the Saramuj Formation of the type area. Furthermore, the presence in AJ-1 Well of a thick sequence of Saramuj Formation conglomerates unconformably overlying Aqaba Complex granite, and in turn, overlain by the Jafr Formation, indicates a thick succession of extensional rift related fanglomerates in north

Jordan. Attribution of the 420 m-thick conglomeratic arkosic sandstone in SA-1 overlying granite has been interpreted as representing the Saramuj Formation (Bender, 1974; Andrews, 1991), but there are no available geophysical wireline logs for this well and this interval may be equivalent to the Jafr Formation ('Unassigned Clastic Unit') encountered in JF-1 and NH-1.

Correlation of the Araba Complex with rocks exposed on the west side of the Dead Sea Transform (DST) is more certain. The succession in the Eilat-Negev area is offset by about 105–110 km Neogene left-lateral shear on the DST (Freund et al., 1970), so that the rocks outcropping around Eilat are broadly offset from the southern Dead Sea (Safi) area, the type area for the Saramuj Conglomerate (Figure 1). The Eilat Conglomerate (Weissbrod and Sneh, 2002) is broadly equivalent to the Saramuj Conglomerate and is similarly overlain by volcanics and rhyolite dykes that are probably coeval with part of the extensional volcanic pulse represented by the Aheimir Volcanic Suite. The uppermost Zenefim Formation includes conglomerates and sandstone thought to be coeval with the Umm Ghaddah Formation (Weissbrod and Sneh, 2002; Amireh et al., 2008). On both sides of the DST the top of the Ediacaran succession is marked by the lower Cambrian Ram Unconformity (base of the Ram Group and Yam Suf Group) (Table 7).

Discussion of the Tectono-stratigraphical Evolution of the Araba Complex and Regional Arabian Plate Correlation

The general tectono-sedimentary setting for the Ediacaran successions across the Arabian Plate is one of fault-bounded basins, generally following the NW-trending Najd Fault System (Stern, 1985, 1994; Al-Husseini, 2011, 2014; Johnson et al., 2011, 2013; Nettle et al., 2014). These 'Jibalah basins' generally represent NW-SE, pull-apart extensional rifts that developed in a transpresional or transtensional regime across the terrains of the ANS at the end of the amalgamation of the East African Orogen (Stern, 1994; Kusky and Matsah, 2003; Johnson et al., 2011, 2013). These basins were infilled during the Ediacaran Period with alluvial, marginal marine, volcanic and volcaniclastic successions. Late Cryogenian to Ediacaran sedimentary and volcanic rocks were thus deposited on actively deforming, or in the case of the Araba Complex, on sutured terrains (Johnson et al., 2013). Rifting, burial, uplift and exhumation of the Aqaba Complex resulted in local unconformities and syntectonic intrusion (e.g. Safi Group, Feinan Suite and Qunaia intrusion). The overall tectono-stratigraphical setting of the Araba Complex is similar to the Hammamat Group in Egypt (Fowler and Osman, 2013) and the Jibalah basins of Saudi Arabia, in that they are characterised by basal polymict conglomerates, basalt, rhyolite, rhyodacite and low-grade or no metamorphism, and in the case of the Jafr Formation fine-grained carbonate cemented siliciclastics and marginal marine/sabkha anhydrite. Importantly, these Ediacaran successions rest with basal unconformities on the amalgamated ANS granitoid basement.

In the east of the ANS (e.g. Central Saudi Arabia and Oman) the Jibalah basins include marine strata, with typical Ediacaran frond-like biota (Amthor et al., 2003; Miller et al., 2008; Nettle, et al., 2014; Vickers-Rich et al., 2010, 2013). The Jibalah Group ranges from mid- to late Ediacaran age (Al-Husseini, 2014) and is, therefore, coeval with the upper part of the Araba Complex and the Huqf Supergroup in Oman (Loosveld et al., 1996; Forbes et al., 2010). The Ediacaran basins of the ANS provide an insight to the growing worldwide evidence for the evolution of Ediacaran biota in the marine realm (Knoll et al., 2004; Narbonne et al., 2012), and although Ediacaran fossils have not been reported from the Jordan succession, the age of the younger part of the succession (ca. 560 Ma) falls within the window of evolution of Ediacaran biota.

The geometry of Jibalah Group basin-fill in the Antaq Basin of Central Saudi Arabia (Nettle et al., 2014) and associated basins, is very similar to that of the Araba Complex described herein. Typically, they comprise basal polymict or oligomict alluvial conglomerates and associated siliciclastics (Saramuj Formation = Rubtayn Formation) overlying ANS granitoids (Aqaba Complex, ca. 630–610 Ma in Jordan). The middle part of the succession in both the Antaq Basin, and at outcrop in Jordan comprises volcanic and volcaniclastic rocks (Aheimer Volcanic Suite = Badayi Formation) that, in turn, pass up to coarse- and fine-grained siliciclastics, locally (Jafr area) with carbonate cements (Umm Ghaddah/Jafr Formation = Muraykhah Formation). In the Antaq Basin, the marine part of the succession is represented by claystone, siltstone and fine-grained sandstone and carbonates arranged in 5–20 m-thick transgressive-regressive cycles, with the carbonates marking the marine flooding surfaces (Nettle et al., 2014). This stratigraphical signature is remarkably similar to the siliciclastic-carbonate-anhydrite succession reported from the Al Inab Member (Jafr Formation) in JF-1 Well. Furthermore, the Jibalah Group in the Dhaiqa Basin (Midyan Terrane), which is the nearest Jibalah Basin to Jordan (Figure 3) includes massive limestone with a youngest age of 560 ± 4 Ma based on detrital zircons (Vickers-Rich et al., 2010), a possible correlative of the marine Jafr Formation.

Although the overall tectono-stratigraphical signature of the Araba Complex and Jibalah Group in the Antaq Basin differ in some respects (i.e. the Safi Group, and Qunaia and Feinan-Humrat intrusives are older than the later rifted succession and are not represented in the Antaq Basin), there is some correspondence between the Jafr Formation (subsurface Jafr Basin, east Jordan) and the marine Ediacaran fossil-bearing Muraykhah Formation at the top of the Antaq sequence, suggesting a possible link between the two basins. Furthermore, the presence in AJ-1 (north Jordan) of similar fine-grained siliciclastics, tentatively assigned to the Jafr Formation suggests more widespread development of this lithofaies. An alternative hypothesis is that the basins developed in isolation, but evolved with typical Jibalah Basin stratigraphical signatures of extension (transtension) – siliciclastic infill – basalt/rhyolite volcanicity and volcaniclastics – marine flooding.

As noted above, the Araba Complex includes early Ediacaran igneous rocks units not seen in the Antaq Basin and, furthermore, records a more complex geological history that includes at least two cycles of extension, basin-fill and volcanicity (Figure 5). Johnson et al. (2013) sub-divide ANS Ediacaran basins into (a) terrestrial and (b) mixed terrestrial to shallow-marine. The Safi Group, which includes the Saramuj Conglomerate, Haiyala Volcaniclastics and syntectonic Qunaia and Feinan-Humrat intrusions formed in a terrestrial setting, but the presence of probable marine strata in the younger Jafr Formation, which may be co-eval with the terrestrial Umm Ghaddah Formation, suggests a mixed terrestrial to shallow-marine setting. If the Saramuj/Eilat conglomerate is present beneath the Golan Heights as suggested by deep seismic reflection data (Meiler et al., 2011) and borehole evidence in north Jordan (AJ-1 and NH-1), then Ediacaran Jibalah-type basins must be more widespread, below Phanerozoic cover rocks, in the northern Levant.

The Araba Complex cycle was outlined by Abed (2005) – termed the Najd Fault Cycle (ca. 641–541 Ma) following Al-Shanti (1993). Here, we retain the term Araba Complex for this cycle and recognise two sub-cycles. The first Araba sub-cycle (Safi Group) follows amalgamation of the granitoid ANS in the Levant, ca. 610 Ma (Figure 5). Uplift of the ANS basement may in part be related to isostatic re-bound (crustal buoyancy) of the shield following the Marinoan Glaciation which may have covered all or much of the Earth (Hoffman and Schrag, 2002; Hoffman and Li, 2009) including the ANS. Isostatic uplift was followed by extension and/or transtension that produced fault-bounded grabens or half-grabens with rapid deposition of clast-supported conglomerates and siliciclastics in the hanging wall of active faults in alluvial fan, and subsequently, braided-stream settings (Saramuj Formation). The age of the Saramuj Formation conglomerate and its included granitoid and metamorphic clasts (Aqaba Complex) indicates that the amalgamated granitoid basement hinterland was undergoing rapid uplift and erosion by at least 605 Ma (Jarrar et al., 2003, 2013), resulting in initial peneplanation of the basement hinterland. This first erosional phase pre-dated, and was later subsumed in a palaeogeomorphological sense, into the early Cambrian Ram Unconformity, ca. 530 Ma) (Powell et al., 2014). Some authors have argued that this erosional phase reduced the source-rock hinterland ANS to near sea level (Avigad and Gvirtzman, 2009). The Haiyala Volcaniclastics overlying the first-subcycle Saramuj conglomerates might, therefore, have been deposited in a shallow-marine setting near sea level, rather than in intermontaine lakes.

Well-rounded, polymict granitoid and metamorphic clasts typical of the Saramuj Formation, derived from the adjacent ANS highlands, might suggest a glacigenic origin during the Marinoan Glaciation (650–635 Ma) but, as noted by Powell (1988) and Jarrar et al. (1991), no glacial or glacio-marine features such as deformed bedding below drop-stones, glacial faceting or glacial striae have been observed. Furthermore, the conglomerate includes granitoid clasts whose intrusion ages (ca. 650–610 Ma) post-date the Marinoan Glaciation, thereby precluding a glacigenic origin for the Saramuj

Formation. The subsequent Gaskiers Glaciation (ca. 582 Ma) is too young to be a dynamic source for the conglomerates. We prefer an active extensional fault-bounded alluvial model, with high sediment flux and rapid basin subsidence to accommodate the thick conglomerate succession.

The extensional, basin-fill phase was followed by the intrusion of a bi-modal igneous suite (Qunaia-Feinan Humrat) and the eruption of their volcanic counterparts, basaltic lavas and volcaniclastics (Haiyala Volcaniclastic Formation and the Aheimir Volcanic Suite) tapping a relatively shallow magma along an ANS suture zone. However, as noted above, it is not certain if these volcaniclastic rocks were deposited in a marine environment or in lakes. The overall setting is similar to that proposed for the terrestrial-type basin characterised by an extensional tectonic regime with graben formation and subsequent bi-modal volcanism seen in the Hammamat basins of Egypt (Fowler and Osman, 2013). To date, no Ediacaran frond-like fossils have been reported from these rocks, but their age is probably earlier (based on the intrusive Qunaia Monzodiorite; 595 ± 2 Ma) than the first appearance of this biota at around 575 Ma (Narbonne et al., 2012); alternatively if the depositional setting was lacustrine then marine Ediacaran faunas would not be present.

The first Araba sub-cycle (Safi Group) was subsequently buried to ca. 4–5 km depth (Powell, 1988; Jarrar et al., 1991), which is manifested in burial diagenesis and very low-grade metamorphism of the Saramuj lithologies; these features include suturing and dissolution at pebble contacts, induration and low matrix porosity, and epidotisation/chloritisation of the arkosic matrix (Ghanem, 2009). Intrusion of the Qunaia Monzogabbro (595 ± 2 Ma) stock and the Feinan-Humrat granites (ca. 600-586) and associated dykes took place during this deep burial phase. This small stock-like intrusive activity has a similar intrusive setting to the post-Murdama 'stitching' granitoids dated ca. 650–565 Ma in the Murdama Basin (Johnson et al., 2011).

The second Ediacaran sub-cycle followed uplift of the Safi Group and emplacement of the Qunaia intrusion (Figure 5). This sub-cycle is more similar in tectono-stratigraphical style to the mixed-terrestrial and shallow-marine setting of the Jibalah basins in Saudi Arabia (Johnson et al., 2013). Renewed rifting and half-graben formation in an extensional-transtensional regime resulted in a second phase of basaltic/rhyolitic volcanism (Aheimir effusives and lavas) and closely associated syn-tectonic agglomerates and conglomerates (e.g. Mufaraqad conglomerates). Crustal relaxation was followed by further movement on bounding faults with oligomict conglomerates and alluvial siliciclastics filling the accommodation space (Umm Ghaddah Formation) (Amireh et al., 2008). A crucial distinction between the first and second Araba sub-cycles is the presence of ANS granitoid clasts found only in the basal Saramuj Formation. Their presence indicates rapid uplift and weathering of the ANS, which in the absence of organic soils, provided a ready source of clasts from the weathered regolith. This erosional phase initiated the peneplanation of the ANS Aqaba Complex so that subsequent braided alluvial siliciclastics ('sand-sea') deposited during the early Cambrian by-passed this relatively mature peneplain (Powell et al., 2014). In contrast, the second sub-cycle of volcanic-volcaniclastic-alluvial rocks is devoid of ANS basement clasts, their component pebbles and cobbles being derived only locally from adjacent volcanic rocks in the hanging-walls of the rifted basins. This lends weight to the hypothesis, above, that the ANS in the hinterland Levant region had been reduced to a virtual peneplain during Saramuj times, and therefore did not supply voluminous sediments to the subsequent rifted Araba/Jibalah basins. Only in the early Cambrian was the ANS again uplifted (Figure 5) to the south, which subsequently provided the necessary high geomorphic gradient, deep weathering of the granitoid regolith and humid climate (?) capable of supplying voluminous and extensive fluvial braidplain siliciclastics to the rapidly subsiding basins across much of the Arabian Platform (e.g. Cambrian Ram Group in Jordan; Siq and Saq formations in Saudi Arabia) (Powell et al., 2014).

Although borehole data is sparse, the identification of fine-grained carbonate-cemented siliciclastics and associated calcitic anhydrite in the Al Inab Member of JF-1 Well suggests a possible marine connection between the Jafr Formation in Jafr Basin of central-east Jordan and similar rifted basins such as the Antaq and Jifn basins that preserve the Jibalah Group (Al-Husseini, 2011, 2014; Nettle et al., 2014; Vickers-Rich et al., 2013; Johnson et al., 2013). The Jibalah Group basins lie within transpressional NW-trending faults that define the Najd Fault System located in the north of the

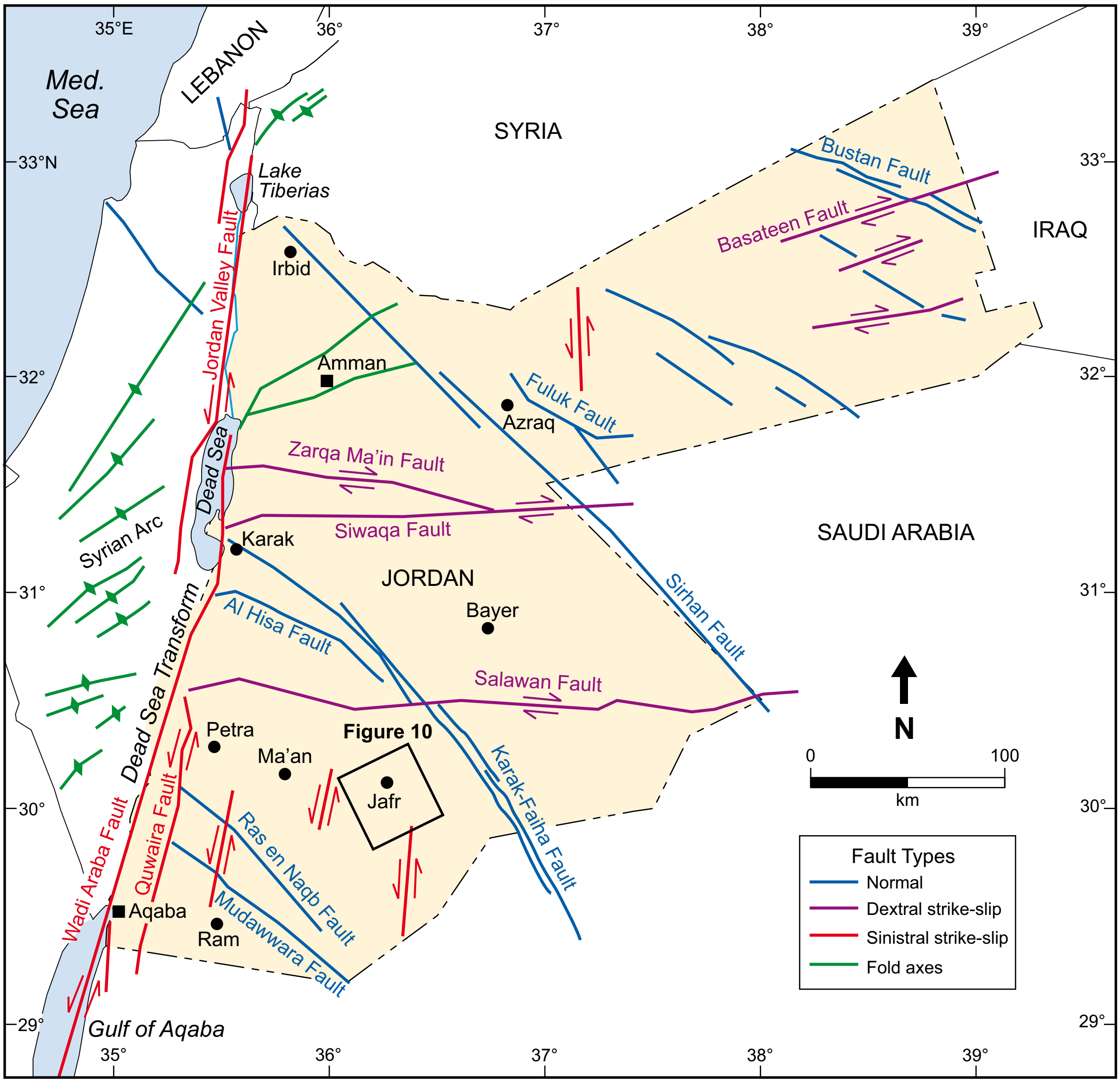


Figure 14: Regional faults and structures in Jordan (modified after Diabat and Masri, 2002). Note the Jafr faults are based on seismic interpretation of 'top basement', i.e. pre-Ram Unconformity.

Arabian Shield. A similar structural grain is present in the Wadi Sirhan and Karak-Wadi Faiha faults in Jordan (Figure 14) which displace Mesozoic and Neogene strata along transtensional and extensional rifts; these probably represent reactivation of deeper-seated Ediacaran Najd Faults. Another distinctive N-S-trending fault system, orthogonal to the NW Najd trend was proven in the Jafr Basin on the Jordan Hunt Oil Company seismic line (Figures 9 and 10). These extensional graben and half-graben structures were active in late Ediacaran time since they only displace the Araba Complex and earlier basement rocks, prior to the early Cambrian Ram Unconformity. We interpret these Jafr Basin extensional faults as orthogonal (possibly pull-apart) structures oblique to the Najd Fault trend. If the N-S Ediacaran trend as seen in the Jafr Basin is more widespread in the basement, the N-S-trending Neogene DST might also represent a reactivated N-S Ediacaran suture. Thick sequences of Saramuj conglomerates and alluvial lithofacies seen at outcrop along the Dead Sea Transform margins and at depth in north Jordan (AJ-1 and NH-1) and the Golan Heights, may represent a north-south orientated, rapidly subsiding rift basin that developed as a structural 'flower-structure' above an ANS suture. It is notable that first sub-cycle (Safi Group) rocks are not present to the east (e.g. Jafr Basin), that is, outside the earlier active rift. It seems likely, therefore, that the Jafr Basin had a similar mid- to late Ediacaran history as the Jibalah/Najd basins of Saudi Arabia.

There is some debate as to whether the Jibalah Group (and by analogy the Ma'an/Jafr formations of the Jafr Basin) were interconnected or if the marine successions developed in isolated rifts, but the presence of Ediacaran fossils in the Jibalah Group, thought to be marine, indicates a possible connection to the Mozambique Ocean (Collins and Pisarevsky, 2005; Cox et al., 2012). The absence of marine strata in the outcropping Araba Complex adjacent to Wadi Araba may indicate that these locations were either higher up the geomorphic gradient (terrestrial settings) or that they developed under different extensional-transtensional regimes. Because these rocks are only exposed in fault-bounded slithers constrained by Neogene faults related to the north-northeast trending DST, it is difficult to determine if they also developed within an earlier north-northeast Ediacaran structural grain that was reactivated during the Neogene spreading of the Red Sea, or if true NW-trending Nadj faults were the bounding faults of the Ediacaran rifts in Jordan (Figure 14).

CONCLUSIONS

The Ediacaran Araba Complex in Jordan is defined and described for the first time in lexicon style, with an emphasis on the sedimentary, volcanic and volcaniclastic units at outcrop adjacent to Wadi Araba, and from seismic and deep exploration well data. The Araba Complex ranges in age from ca. 605 to 550 Ma and comprises a major cycle of sedimentary, volcanic and volcaniclastic, and igneous rocks emplaced in an overall extensional tectonic regime that followed intrusion and amalgamation of the granitoid and metamorphic Aqaba Complex, a part of the Gondwanan Arabian-Nubian Shield (ca. 900 to 605 Ma).

The Araba Complex is bounded by two major erosional unconformities, the newly defined Ediacaran Araba Unconformity (ca. 605 Ma) at its base, underlain by the Aqaba Complex, and the post-extensional, regional lower Cambrian Ram Unconformity (ca. 530 Ma) that marked by the widespread deposition of thick alluvial and marginal-marine siliciclastics (Ram Group).

Two sub-cycles can be recognised in the Araba Complex. The earliest (Safi Group) followed suturing and extensional rifting of the Aqaba Complex that resulted in rapid basinal subsidence and the deposition of coarse-grained, polymict conglomerates (Saramuj Formation) in predominantly proximal, but evolving to more distal, alluvial fan settings. The early extensional basin appears to have been orientated approximately north-south (with westward subsidence) and can be traced from north Sinai to the Lebanon, approximately parallel to the present-day Dead Sea Transform. Rounded clasts, up to boulder-size, include a variety of local to regionally derived basement lithologies, including granites, diorites, metamorphic rocks and doleritic dyke rocks. Rapid isostatic uplift and weathering of the granitoid basement resulted in high sediment flux that kept pace with rapid basin subsidence; this, in turn, led to erosion and partial peneplanation of the hinterland Arabian-Nubian Shield. Regional detrital zircon ages from the conglomerate clasts and matrix indicate age ranges from ca. 600 to 650 Ma with a minor cluster between 700 to 750 Ma, indicating mostly a local or, at least, near-field provenance. A cluster of youngest detrital zircons indicate a maximum age of ca 615 Ma. Subsequent to this early, rapid basin-fill, continued crustal extension resulted in tapping of rhyolitic and basaltic effusive volcanics and volcaniclastics (Haiyala Volcaniclastics and Museimir Effusives, ca. 598–595 Ma), including flow-banded rhyolitic lavas and air-fall tuffs, the latter deposited in a lacustrine or shallow-water environments.

The early part of the second Araba sub-cycle (595–586 Ma) is characterised by renewed basinal subsidence, very low burial metamorphism (chlorite-epidote grade) to about 6 km depth, and associated stock-like intrusion of the Qunaia Monzogabbro (595 ± 2 Ma) that resulted in thermal contact metamorphism of the Saramuj conglomerate, as well as granite plutons (e.g. Feinan-Humrat intrusions) and dolerite dykes. As with the first sub-cycle in the in the present-day DST areas, the second cycle is characterised by renewed extension, rifting and the deposition of volcanic rocks, agglomerates (Aheimir Volcanics) and, in contrast to the polymict, basement-derived clasts in the first Saramuj subcycle, monomict conglomerates (Umm Ghaddah Formation) that were sourced, locally, from volcanic rocks on the rift shoulders.

To the east, in south-central Jordan, the early Safi sub-cycle is absent. Deep exploration wells and seismic data in the Jafr area demonstrate that the Araba Complex comprises terrestrial lavas (Ma'an Formation) with weathered soil horizons, unconformably overlying weathered Aqaba Complex granitic basement (Araba Unconformity). Seismic data for the Jafr region reveals the eruption of lavas in north-south trending graben and half-graben settings, and possible northwest-trending bounding faults similar to the Ediacaran Najd/Jibalah Group basins in Saudi Arabia. Again, in contrast to the outcrop areas to the west, the upper part of the Araba Complex, hereabouts, consists of fine-grained, in part carbonate-cemented sandstone and claystone, together with anhydrite (Jafr Formation) suggesting a shallow-marine or coastal sabkha setting. These characteristics indicate a possible link to volcanic to shallow-marine extensional basin-fills that developed widely within NW-trending Najd basins across the ANS in Saudi Arabia (e.g. Jibalah and Antaq basins). It is not clear whether these Najd basin successions developed more or less coevally in isolated rifts, or if they were interconnected during the transgressive events.

To date, no Ediacaran biotas have been described from the Araba Complex, but the Jafr Formation, which post-dates the appearance of soft-bodied faunas around 579 Ma and which was probably deposited in marginal-marine environments, is a potential candidate for these enigmatic fossils.

Subsequent to the final Araba extensional rifting phase, renewed regional uplift, far to the south, of the ANS hinterland during the early Cambrian, led to widespread deposition of alluvial and shallow-marine siliciclastics as a progradational 'sand-sea' (Ram Group) that blanketed the now peneplained Aqaba Complex in south Jordan and surrounding countries (Ram Unconformity). However, the younger Ediacaran Araba Complex outcrops (e.g. Aheimir Volcanics) adjacent to Wadi Araba remained, in places, as a relatively immature palaeotopography against which the lower Cambrian sandstones rest with marked unconformity. It was not until early mid-Cambrian times (ca. 509 Ma), during the Burj marine transgression that this late Ediacaran palaeotopography was finally buried.

The Araba Complex in Jordan with its multi-cycle development provides an insight to the regional development of Ediacaran extensional basins in the Arabian-Nubian Shield, an important phase in the evolution and transition from Neoproterozoic to Phanerozoic crustal tectonics and associated basin-fill.

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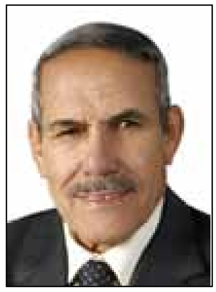

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