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Cambrian stratigraphy of Jordan

John H. Powell, Abdulkader M. Abed and Yves-Michel Le Nindre

ABSTRACT

The lower and middle Cambrian succession (Ram Group) in Jordan is described in lexicon-style format to document an important phase of Earth history following the uplift and erosion of the Arabian-Nubian Shield (Aqaba Complex) during the late Neoproterozoic, and younger, but more localised, intrusive and volcanic/volcaniclastic activity that formed the Araba Complex. The early Cambrian Ram Unconformity (ca. 530 Ma) marks the base of a predominantly fluvial siliciclastic succession derived from rapidly eroding Neoproterozoic (including Ediacaran) basement rocks, but includes a brief, but biostratigraphically significant, sequence of marine siliciclastics and carbonates, the early mid-Cambrian Burj Formation.

Rapid uplift and erosion of the granitoid basement (Arabian-Nubian Shield or ANS) resulted in a peneplanation of the Aqaba Complex over millions of years duration (latest Neoproterozoic to Cambrian) in the Southern Desert of Jordan. Early Cambrian pebbly sandstones and locally derived conglomerates (Salib Formation) were deposited on an alluvial plain by high velocity-high discharge, northward flowing (NNE to NNW) braided rivers, characterised by trough cross-bedding and erosive tabular sets. Brief, and rare, marine influence is represented, locally, by thin *Skolithos*-burrowed sandstones.

A regional sea-level rise in the early mid-Cambrian marks a major marine transgressive-regressive cycle and southward thinning carbonate-siliciclastic wedge (Burj Formation) widely present in the subsurface across the Arabian Platform. During deposition of this transgressive marine sequence the palaeoshoreline was oriented WNW-ESE in southern Jordan. The transgressive phase (TST) is represented by tidal-dominated siltstones and fine-grained sandstones (Tayan Member) containing a diverse *Cruziana/Rusophycus* ichnofaunal assemblage. The overlying carbonate unit (Numayri Member) represents the highstand (HST) and maximum marine flooding surface (MFS), and comprises a carbonate ramp sequence of shelly wackestone, packstone and grainstone with ooids and oncolites, and a diverse shelly fauna including trilobites, brachiopods and hyolithids. A return to regressive tidal-influenced sandstone and siltstone (along with thin carbonates in central Jordan) (Hanneh Member) represents a regressive wedge (RST) deposited in response to renewed uplift of the ANS. Trilobites, represented by the *Kingaspis campbelli* and *Redlichops* faunules, suggest a biostratigraphical age of early mid-Cambrian for the carbonate MFS, which equates approximately to the base of the Cambrian Series 3 (Stage 5). This event probably represents the Cambrian marine flooding surface Cm20 (approximate geochronological age of 509 to 505 Ma). South of Feinan, in the Wadi Araba, the carbonates pass laterally to marine sandstone (Abu Khusheiba Sandstone) with extensive *Skolithos* burrows and *Cruziana/Rusophycus* traces. Traced southwards (palaeohinterland) the marine influence diminishes, so that the Burj/Abu Khusheiba units are absent in the Southern Desert.

Ediacaran intrusives, together with extrusive volcanic and volcaniclastic rocks (Araba Complex) are associated with rifting and half-graben formation in the Feinan-Petra area. This later tectonic activity produced a younger (Ediacaran to early Cambrian), immature palaeotopography, in marked contrast to the Neoproterozoic Aqaba Complex peneplain in the Southern Desert. Consequently, early and mid-Cambrian fluvial and shallow-marine siliciclastics (Salib and Abu

Khusheiba formations) onlap progressively onto this immature palaeotopography that was subsequently buried by mid-Cambrian time. Increased basinal subsidence to the north of the Araba Complex 'high' provided increased accommodation space that resulted in the deposition of a thick sandstone succession in north Jordan. The Feinan-Petra region seems to have acted as an east-west hinge-line with greater subsidence of the Arabian Platform to the north; similar thickness trends are seen in the Burj and Umm Ishrin formations.

Renewed uplift and erosion of the ANS to the south led to deposition of a thick succession of fluvial-dominated sands, again deposited by large-scale braided rivers (Umm Ishrin Formation). Fluvial sedimentation continued through mid to late Cambrian times and also the Ordovician (Disi and Umm Sahm formations), but episodic shallow-marine or estuarine flooding of the low-gradient alluvial plain resulted in colonisation, locally, by arthropods and annelid worms that produced a diverse and abundant *Cruziana*/*Rusophycus*/*Planolites* assemblage of tentative Floian (Arenig) age (upper Disi Formation).

Overall the Cambrian to Ordovician Ram Group siliciclastics (Salib-Umm Ishrin-Disi-Umm Sahm formations) show an upward increase in sand maturity from arkose (Salib) to orthoquartzite (Disi); heavy-mineral signatures (ZTR), specifically datable zircons, indicate provenance from a predominantly distant Neoproterozoic granitoid source rock area located to the south (ANS) that was undergoing intensive weathering. However, a small zircon component was derived from older pre-Neoproterozoic rocks, consistent with the general trend in the Levant.

The highly permeable Cambrian siliciclastics of Jordan and surrounding countries provide an important regional aquifer, the Ram (formerly Disi) Aquifer. In a suitable setting these reservoir rocks might have potential for hydrocarbon exploration where source rocks of Neoproterozoic, Silurian or Permian age are faulted and in proximity, at depth, in the central Arabian Platform.

INTRODUCTION

This paper focuses on the lower to middle Cambrian succession of Jordan that comprises the lower part of the Ram Sandstone Group, up to the top of lower middle Cambrian Burj Formation (ca. 509 Ma; base Series 3, Stage 5; Table 1). This corresponds to the Asfar Sequence of Al-Husseini (2010, 2014). Here, the emphasis is on the major phases of sedimentation and the relationship of the Ram Unconformity to the Neoproterozoic Aqaba and Araba complexes that form part of the Arabian-Nubian Shield (ANS), the source of the bulk of the Ram Group siliciclastic sediments. The Ram Group represents an important sandstone aquifer in south Jordan and Saudi Arabia, and might be prospective for hydrocarbons where favourable tectonic/stratigraphical settings are present; for instance where these reservoir rocks are faulted against organic-rich Silurian source rocks in the subsurface of the Arabian Plate (Alsharhan and Nairn, 1997; Strijker et al., 2012; Naylor et al., 2013).

The lower to middle Cambrian lithostratigraphical units are described here in lexicon format, updated from Heimbach (1976) and based largely on the Natural Resources Authority of Jordan (NRA) bulletins of Powell (1989) and Andrews (1991), and incorporating more recent research on this succession. However, because the Ram Group includes three middle Cambrian to Ordovician formations above the Burj Formation (in upward sequence: Umm Ishrin, Disi and Umm Sahm formations), these units are also described briefly below and are summarised in Table 1. Further details of these formations can be found in several papers (Selley, 1970, 1972; Bender, 1974; Powell, 1989; Andrews, 1991; Amireh, 1991; Amireh et al., 1994; Makhlouf and Abed, 1991; Makhlouf, 2003).

Nomenclatural Note: It was customary during the systematic 1:50,000-scale geological surveys carried out by the NRA to define formations using a dominant lithological epithet; for example, Abu

Table 1: Summary of Ram Group depositional history and major tectonics events, and relationship of this group with the underlying Araba and Aqaba complexes.

Age	**Geochronological Age**	**Lithostratigraphical/ Lithodemic Units**		**Events**
		Group/ Complex	**Formation/ Lithodeme**	
Ordovician (?Floian [Arenig]-Darriwilian [Llanvirn])	Not available	Ram Group	Umm Sahm	Increasing marine/tidal influence from north; interbedded marine siliciclastics (*Cruziana* and *Harlania* trace fossil assemblages) with linguoid ripples, interbedded with fluvial braided channel sandstone (convolute and overturned foresets, and pebble lags).
'late' Cambrian to Ordovician	Not available		Disi	Continued high sediment flux, on predominantly fluvial braidplain; larger rivers and change to mature (2nd cycle) quartz sand; periodical brief marine/estuarine incursions along coastal margins/embayments manifested in fine-grained sandstone with abundant *Cruziana* assemblage; convolute and overturned foresets and pebble lags.
'mid to late' Cambrian (?Stage 5 to Stage 10)	Not available		Umm Ishrin	Progradation of high velocity-high discharge fluvial braided river siliciclastics northwards; high sediment flux; common convolute and overturned foresets; tidal influence in north Jordan in rapidly subsiding foreland basin.
'early mid' Cambrian (?Stage 4 to Stage 5*)	~ 511- 509 Ma* *Based on *Kingaspis campbelli* and *Redlichops* faunules = *Ovatoryctocara granulata* FAD at base Stage 5		Burj/ Abu Khusheiba	Tilting of ANS foreland; eustatic sea-level rise; transgressive tidal siliciclastics followed by carbonate ramp = maximum flooding event; shelly fauna (trilobites; brachiopods; hyolithids; sponges; echinoids) regressive prograding siliciclastics with carbonate lenses in north; *Skolithos* and *Cruziana* trace fossil assemblages.
'early' Cambrian (?Fortunian to Stage 4)	~ 540 Ma? (or younger) to ~511 Ma		Salib	Uplift of ANS granitoids; high sediment flux and northward progradation of alluvial braided river lithofacies; brief marine incursion on coastal plain with *Skolithos* burrows; erosion of ANS to south; high velocity-high discharge pebbly sandstone and quartz conglomerate in lower part; sparse convolute and overturned foresets; further development of sub-Ram peneplain on Aqaba Complex; gradual burial of immature Araba Complex palaeotopography.
Ram Unconformity (~530 Ma to 598.2 ± 3.8 Ma# based on U/Pb for Museimir Effusives)				
Ediacaran	598.2 ± 3.8 Ma# 601 ± 12 Ma#	Araba Complex	Aheimir Volcanic	Rifting and half-graben formation in Feinan-Petra-Dana area; volcanic centre with lavas, effusives, volcaniclastics and tuffs, interbedded with fragmentrary rocks and oligomict alluvial conglomerates. Intruded at various levels by alkaline and peralkaline granites, monzodiorite and at least two dyke events (these do not intrude the overlying Ram Group). Safi Group, at base, includes Saramuj Conglomerate, a proximal alluvial fan sequence containing well-rounded pebbles and cobbles of Aqaba Complex granitoids and older volcanic rocks; deposited in extensional half-grabens associated with volcaniclastic rocks. Early development of Aqaba Complex peneplain.
	586.2 ± 5 Ma# 603.6 ± 2.6 Ma#		Feinan-Humrat-Mubarak Granitic	
	598 ± 5 Ma#		Araba Mafic	
			Safi Group	
Araba Unconformity (~610-600 Ma)				
Cryogenian to Ediacaran	Calc-Alkaline Granitoids (~ 630-610 Ma)# and Calc-Alkaline Gabbros (~ 640-605 Ma)#	Aqaba Complex		Intrusion of calc-alkaline gabbros and calc-alkaline granitoids.
Cryogenian	Metamorphic Rocks (~900-620 Ma)#			Metamorphism of Arabian-Nubian Shield protolith.

Notes: Arrow indicates the Ram Group formations of Cambrian age, the focus of this paper. #U/Pb geochronological age dates based on Jarrar et al. (2003, 2008, and Jarrar personal communication). The age of the Burj transgression is based on Rushton and Powell (1998) and Elicki and Geyer (2013) and tentative correlation of the *Kingaspis campbelli* and *Redlichops* faunules of the latter authors with the *Ovatoryctocara granulata* FAD at the base Stage 5 (509 Ma) (Peng et al., 2012).

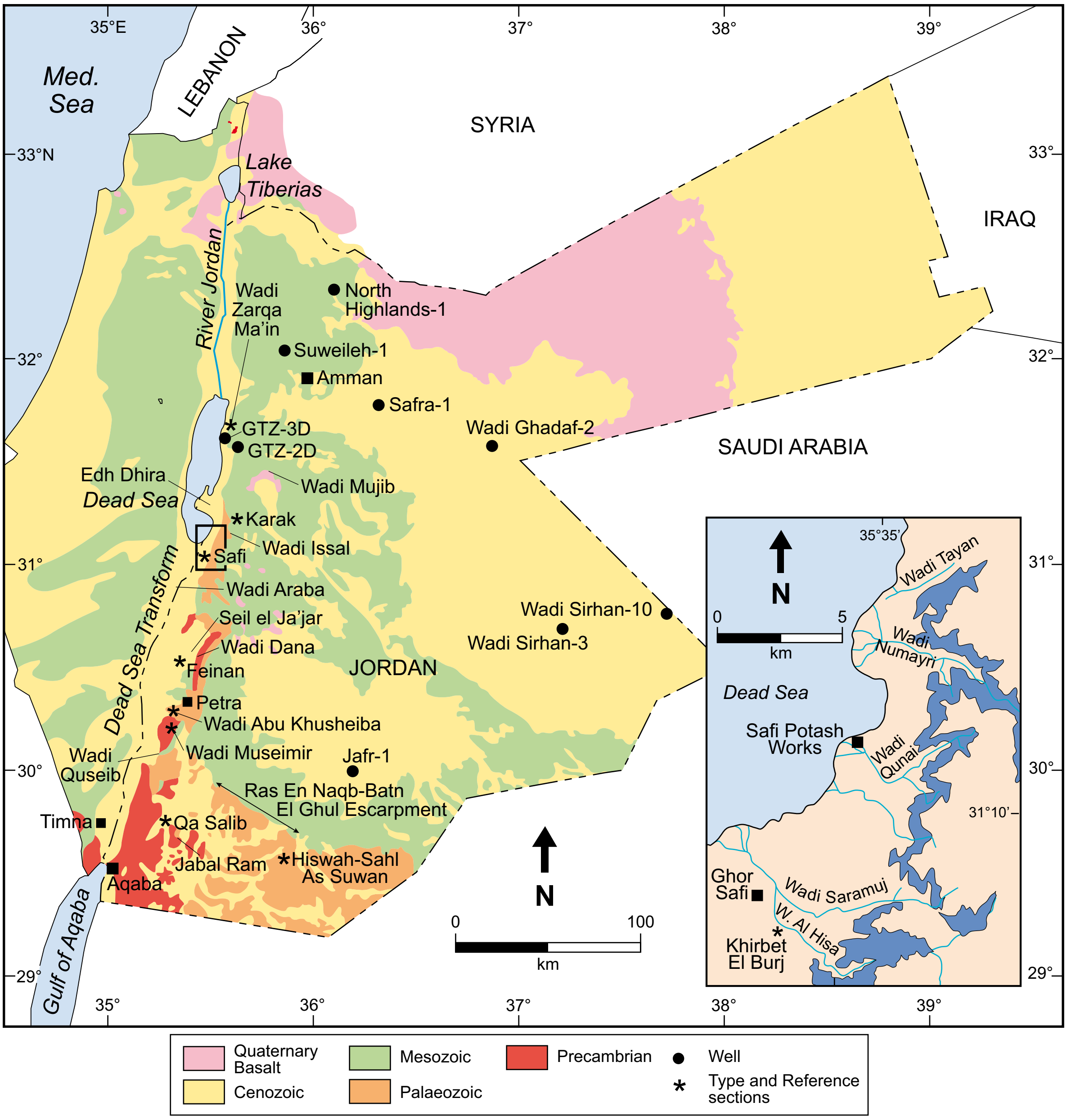


Figure 1: Type localities and reference sections for the Ram Group. Inset map: Type and reference sections of the Burj Formation (blue) and the Salib Formation in the Safi area (after Rushton and Powell, 1998).

Khusheiba Sandstone Formation, to provide non-specialists (such as petroleum engineers and civil engineers) with an initial impression of the lithology of the unit (Rawson et al., 2002). This practice is followed in this lexicon paper for the first use of the stratigraphical name but, for conciseness, the lithological description is subsequently omitted (e.g. Abu Khusheiba Formation). Any formerly defined lithological epithet has been dropped for units with heterolithic lithologies (e.g. Burj Dolomite-Shale Formation is now termed the Burj Formation).

GEOLOGICAL SETTING OF THE RAM SANDSTONE GROUP

Lower Palaeozoic rocks in Jordan crop out in the Southern Desert and along the Rift margins (Wadi Araba) as far north as Wadi Zarqa Ma'in area (Figure 1) (see Powell, 1989 for overview). In the north and east of the Hashemite Kingdom the Lower Palaeozoic rocks are known from deep exploration wells, including the western margin of the Tabuk Basin, which extends at depth, into Saudi Arabia, where upper Palaeozoic strata of Devonian and Carboniferous age are present (Powers et al., 1966; Al-Laboun, 1986; Andrews, 1991; Alsharhan and Nairn, 1997; Naylor et al., 2013). In Jordan, post-Llandovery strata are known only from boreholes in the northeast, and the lower Palaeozoic rocks are cut out (overstepped) progressively westwards and southwards as a result of three major phases of tilting, uplift and erosion, which occurred in Carboniferous, early Permian and late Jurassic to early-Cretaceous times. The 'Hercynian' erosional phase is also known from overstep of the Permian Unayzah Formation, at depth, in Saudi Arabia (Al-Laboun, 1986). At outcrop in Jordan, the lower Palaeozoic strata are overlain unconformably by the Lower Cretaceous Kurnub Sandstone in south and central Jordan, and by the Permian Umm Irna Formation in north Jordan (Bandel and Khoury, 1981; Makhlouf et al., 1991; Stephenson and Powell, 2013).

Sedimentation throughout the early Palaeozoic, and also during the Mesozoic, was largely controlled by global (eustatic) and regional sea-level fluctuations and the relative isostatic movements of the cratonic ANS that lay to the south (Husseini, 1989, 1990; Johnson et al., 2011), which in Jordan comprises mostly calc-alkaline granitoids of the Aqaba Complex (Bender, 1974; McCourt and Ibrahim, 1990; Stern, 1994; Ibrahim and McCourt, 1995; Jarrar et al., 2013). Uplift and continental erosion of the ANS resulted in the establishment of a mature geomorphic palaeo-peneplain during a sequence of erosional phases in late Neoproterozoic (Ediacaran) to early Cambrian time (i.e. syn-Saramuj Conglomerate, syn-Ram Group, respectively). The ANS supplied large volumes of sub-mature to mature sand and gravel during the Cambrian to Ordovician (Ram Group); sand and gravel was deposited in a predominantly alluvial environment in a semi-arid to humid climatic regime on a gently subsiding foreland basin, with unimodal palaeocurrent flow to the north or north-northeast (Selley, 1972; Powell, 1989; Amireh et al., 1994). In mid to late Ediacaran time (Narbonne et al., 2012) a phase of extensional tectonics, granitic intrusion and extrusive volcanics/volcaniclastics and proximal alluvial fan deposits (Araba Complex) occurred in the Feinan-Dana area (Powell, 1988; McCourt and Ibrahim, 1990; Jarrar et al., 1991; Amireh et al., 2008). These rocks formed a local palaeohigh (half-grabens bounded by extensional faults) (Barjous, 1988), which was not completely buried by the initial Cambrian phase of continental/marine sedimentation until the early mid-Cambrian (Stage 4/5) (Figure 2). However, north of the Feinan-Dana area, higher rates of basin subsidence resulted in the accumulation of a thicker sequence of sub-mature siliciclastics.

During the early Cambrian (Salib Formation time) the coastline was situated north of Jordan, but increased subsidence and/or a eustatic sea-level rise resulted in deposition of shallow-water marine carbonates and siliciclastics (Burj Formation) in north and north-central Jordan during the early mid-Cambrian (ca. 509 Ma). The Burj Formation is a strong seismic reflector that separates contrasting, structurally controlled basin-fill, below, and more uniform siliciclastic sedimentation, above (Figure 2). Continued uplift and erosion of the ANS resulted in a renewed influx of fluvial and shallow-marine siliciclastics and thin carbonates along the coastal margins, as the sea regressed northwards (Figure 3). In post-Burj times, renewed basin subsidence allowed rivers draining from the ANS to prograde northwards over the coastal plain, depositing mostly mature fluvial siliciclastics over the whole country during the late Cambrian (and Early Ordovician). At some horizons, tidal bedforms and *Skolithos*/*Cruziana* ichnofossil assemblages indicate brief tidal and shallow-marine sedimentation along the palaeo-coastal plain.

During the Floian (Arenig), marine influence became more pronounced upwards with deposition of intercalated marine and fluvial siliciclastic sediments. The top of the Ram Group is marked by a major change in sedimentation that took place during the early Darriwilian (early Llanvirn), when a major marine transgression advanced from the east and northeast depositing mature graptolite-bearing siliciclastics (Khreim Group) in an epeiric shelf-sea characterised by fluctuating water-depth during the remaining Ordovician and Silurian (Powell, 1989). The Hirnantian (late Ordovician) glaciation created incised palaeovalleys subsequently filled by fluvio-glacial and glacio-marine sediments, and overlain by early Silurian organic-rich 'hot shales' in Jordan (Abed et al., 1993; Powell et al., 1994; Amireh et al., 2001). This event can be traced eastwards, at depth, to the Tabuk Basin, Saudi Arabia (Vaslet, 1990; Armstrong et al., 2005) where the organic-rich mudrocks represent an important hydrocarbons source rock (Alsharhan and Nairn, 1997; Naylor et al., 2013).

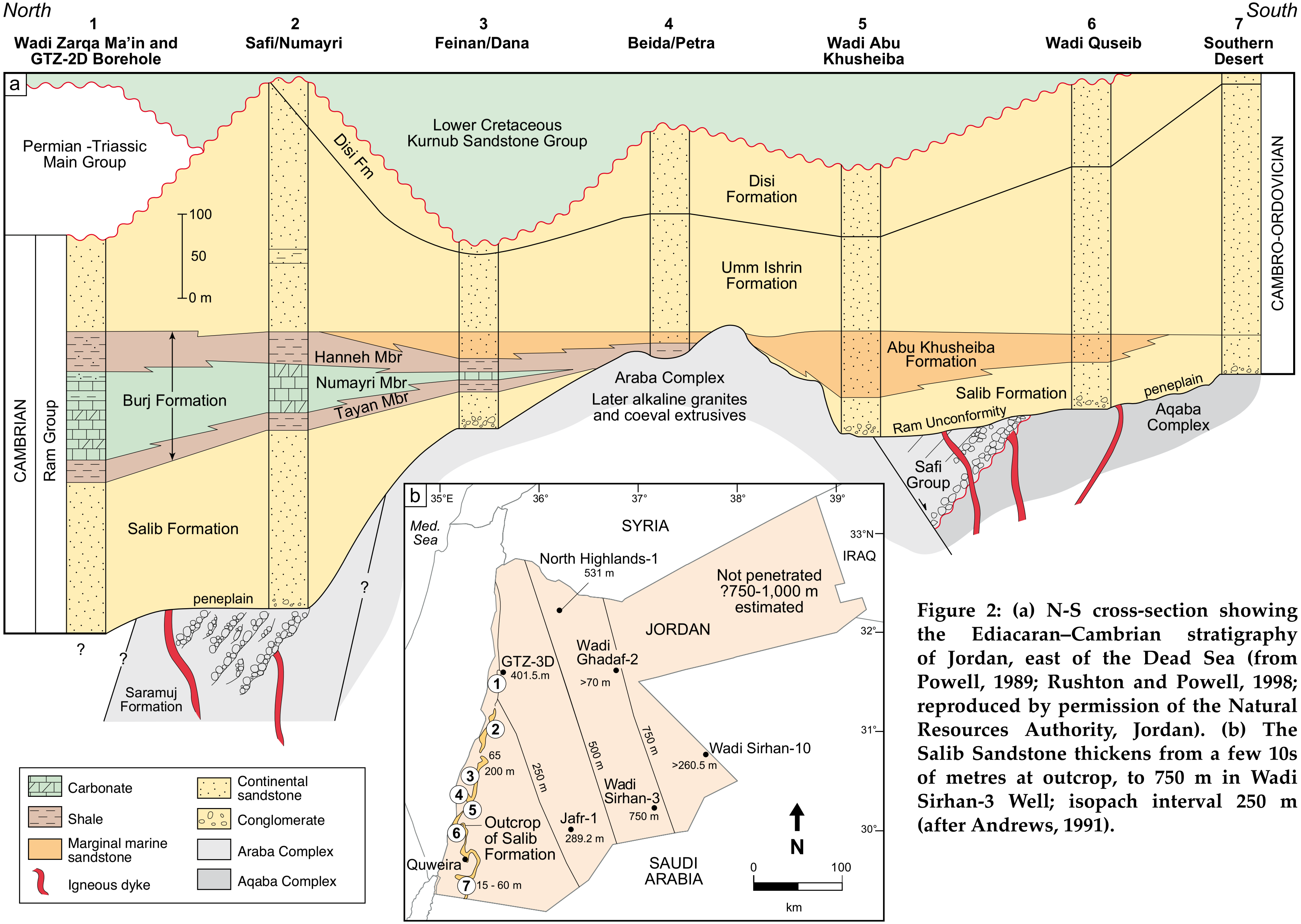


Figure 2: (a) N-S cross-section showing the Ediacaran–Cambrian stratigraphy of Jordan, east of the Dead Sea (from Powell, 1989; Rushton and Powell, 1998; reproduced by permission of the Natural Resources Authority, Jordan). (b) The Salib Sandstone thickens from a few 10s of metres at outcrop, to 750 m in Wadi Sirhan-3 Well; isopach interval 250 m (after Andrews, 1991).

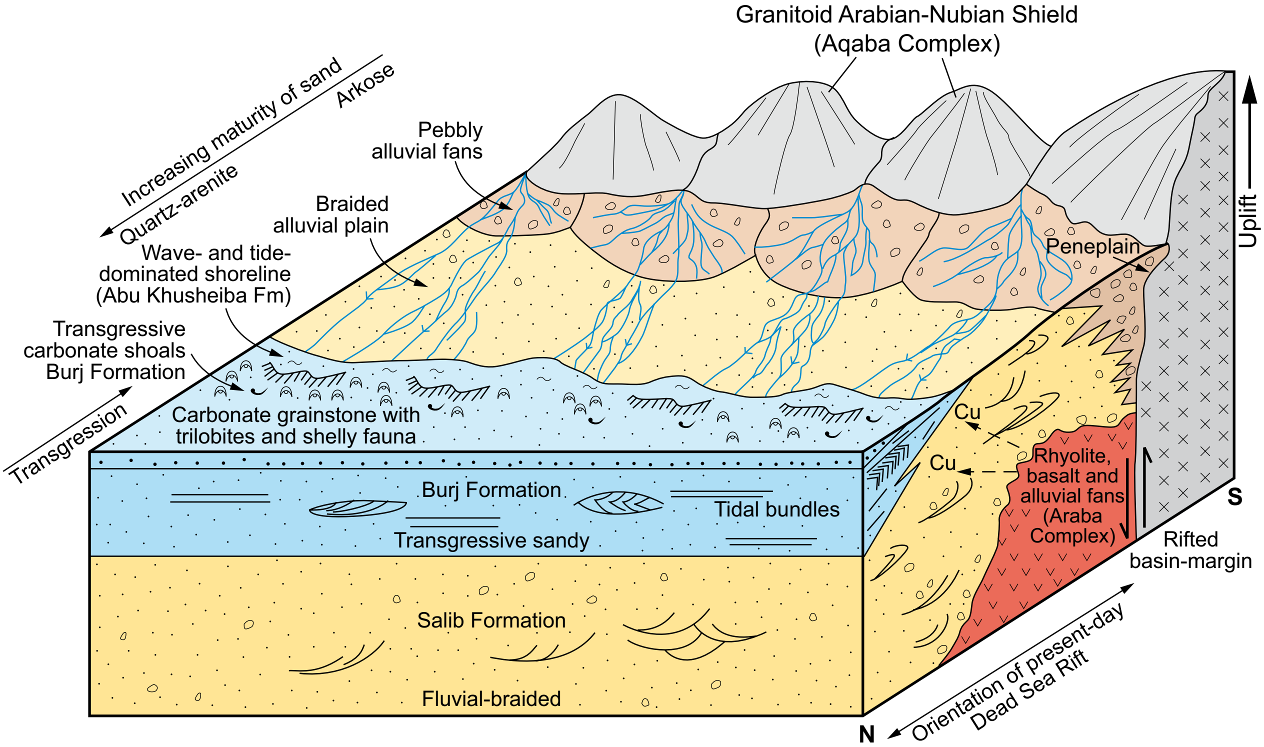


Figure 3: Depositional setting and palaeo-environments during Burj marine transgression (early mid-Cambrian), and the overall tectonic setting for the Ram Group. Cu indicates the post-depositional migration of mineralising copper brines (see Plate 23).

RAM GROUP

Introduction

The Ram Group, first defined by Powell (1988, 1989), includes all the predominantly siliciclastic formations and the marine carbonate/siliciclastic wedge, unconformably overlying the Neoproterozoic 'basement' terrain (Aqaba Complex and Araba Complex); the base of the group thus marks the Ram Unconformity, defined here. The upper group boundary is defined at the base of the marine, graptolite-bearing Hiswah Sandstone Formation (early Llanvirn) of the Khreim Group (Lloyd, 1969). The Ram Group ranges in age from early Cambrian to Ordovician (Floian [Arenig] to Darriwilian [Llanvirn]) and incorporates the following formations, from base to top: Salib Sandstone, Burj Formation, Umm Ishrin Sandstone, Disi Sandstone and Umm Sahm Sandstone (Lloyd, 1969; Selley, 1970, 1972; Powell, 1988, 1989). The Abu Khusheiba Sandstone is coeval with the upper part of the Burj Formation (Bender, 1974; Powell, 1989; Amireh et al., 1994).

The group forms a coherent unit of predominantly fluvial medium- to coarse-grained sandstones and siltstones, and includes a marine carbonate/fine-grained sandstone unit (Burj Formation), which wedges out to the south of the Feinan-Dana area (Figure 2) and passes laterally into the broadly coeval Abu Khusheiba Formation. The Ram Group forms a spectacular topography of rugged, steep-faced cliffs and mesas, separated by sand-filled wadis in the Southern Desert area, and a rugged topography of steep cliffs cut by narrow gorges (siqs) along the Dead Sea Rift margins.

The full succession is preserved only in the Southern Desert (Figure 1) below the overstepping Lower Cretaceous Kurnub Sandstone. Traced westward along the Ras En Naqb Escarpment, the uppermost unit (Umm Sahm Formation) and the underlying Disi Formation are overstepped. North of Ras En Naqb the base Kurnub unconformity gradually cuts down through the Ram Group, although the lower part of the Disi Formation is still present at Petra. Farther north (Safi and Karak areas) only the underlying Umm Ishrin Formation is present below the unconformity (Figure 2). Between Wadi Mujib and Wadi Zarqa Ma'in the upper part of the Burj Formation and overlying Umm Ishrin Formation crop out in an up-faulted block; north of where the Umm Ishrin Formation is overlain unconformably by the Middle Permian Umm Irna Formation (Bandel and Khoury, 1981; Makhlouf et al., 1991; Stephenson and Powell, 2013).

Type Area and Reference Sections

The type area (Figure 1) is the Southern Desert where the lithostratigraphical and chronostratigraphical relationships were first established in composite sections (Bender, 1968, 1974; Lloyd, 1969; Selley, 1972; Powell, 1989). The most complete succession is present at Jabal Ram (also spelt 'Rum' or 'Rumm') (29°34'19.66"N; 35°23'58.25"E), but here the higher parts are mostly inaccessible (Plates 1 to 4). However, the component, eastward younging formations are readily accessible, downdip, between Qa Salib in the west (Plate 5), to Sahl As Suwwan in the east (Abdelhamid, 1988). The type area for the Burj Formation is between Safi and Wadi Numayri (Wadi Araba), in composite sections (Figure 1). The Abu Khusheiba Sandstone Formation is well exposed in the eponymous wadi (Bender, 1968, figure 134; Amireh et al., 1994).

Subsurface Reference Section

The Ram Group is best represented in the subsurface by Wadi Sirhan-3 Well (WS-3, Figures 1 and 4), but was also penetrated by other wells with representative geophysical logs in North Highland-1 (NH-1) and Al Jafr (JF-1) (Andrews, 1991). In WS-3, the lowermost formation (Salib) consists of arkosic sandstone with micaceous, sandy claystone laminae, overlain by red-brown micaceous

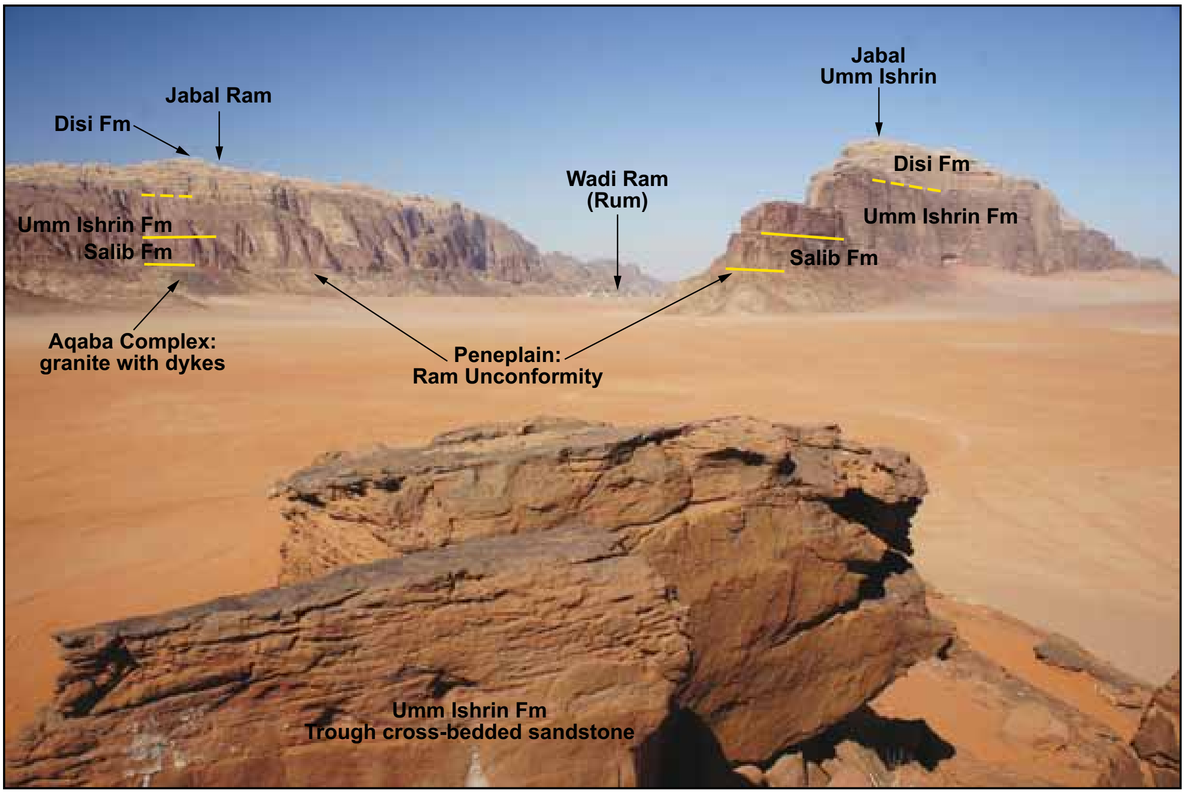


Plate 1: Neoproterozoic Aqaba Complex, Ram Unconformity and Cambrian formations (Ram Group) in Wadi Ram type area. View northwards from Khazali. Desert elevation, 950 m above sea level; Jabal Umm Ishrin, 1,733 m, above sea level. Photo by J.H. Powell.

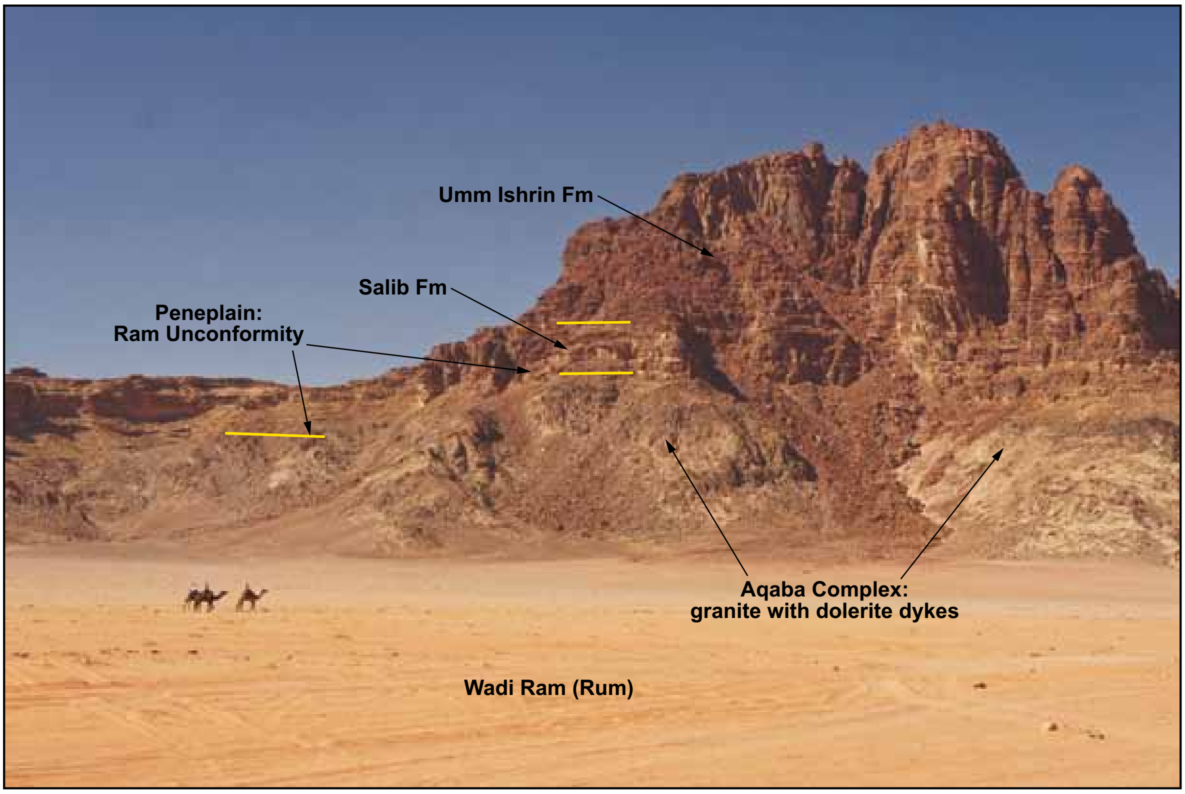


Plate 2: Neoproterozoic Aqaba Complex, Ram Unconformity and Cambrian formations (Ram Group) southwest of Wadi Ram. View westwards. Photo by J.H. Powell.

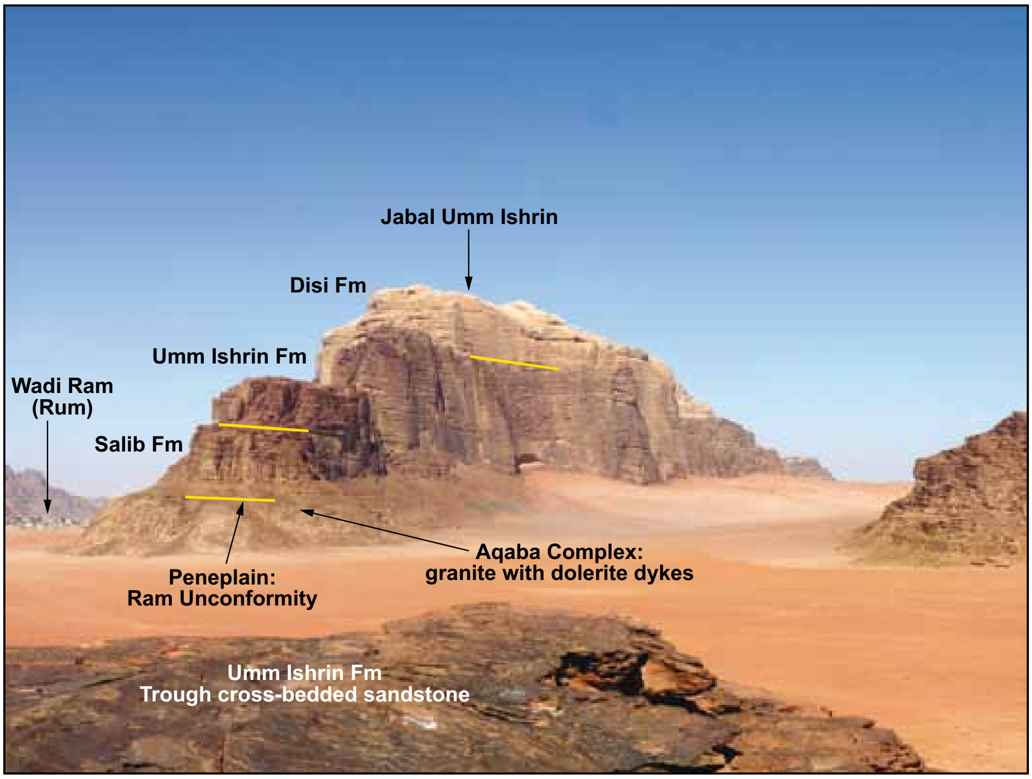


Plate 3: Neoproterozoic Aqaba Complex, Ram Unconformity and Cambrian formations (Ram Group) at Jabal Umm Ishrin. View northwards from Khazali. Desert elevation, 950 m above sea level; Jabal Umm Ishrin, 1,733 m above sea level. Photo by J.H. Powell.

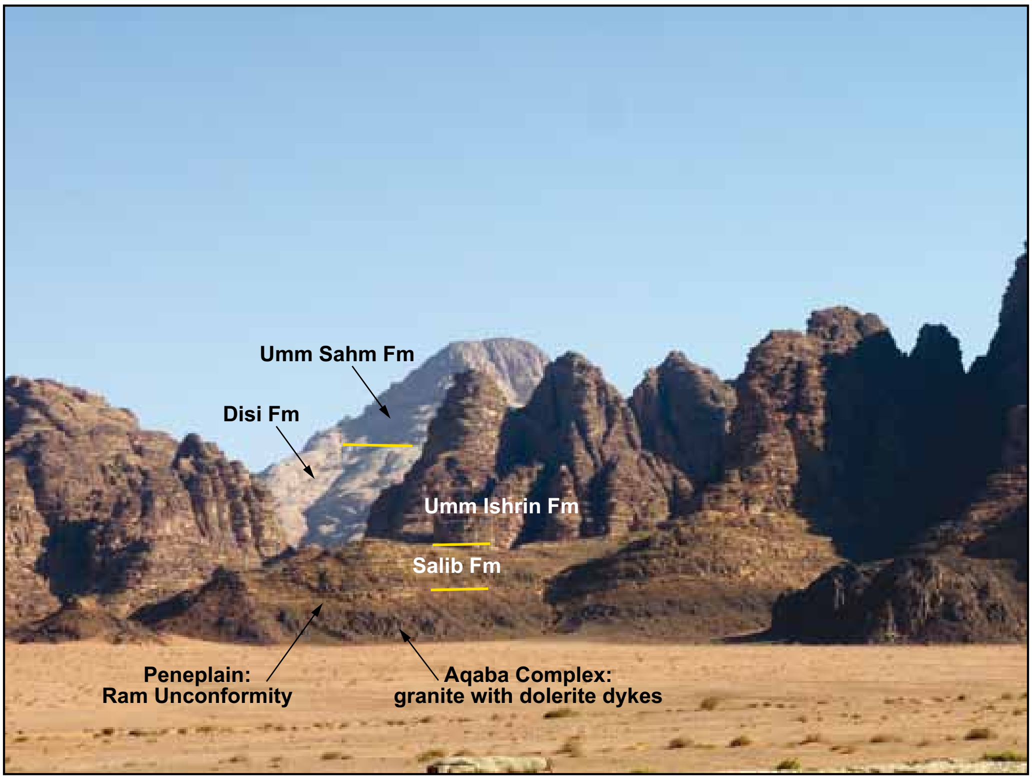


Plate 4: Cambrian to Ordovician stratigraphy (Ram Group) east of Wadi Ram village. View eastwards at Seven Pillars; note Disi and Umm Sahm formations are down-dip in the distance. Photo by J.H. Powell.

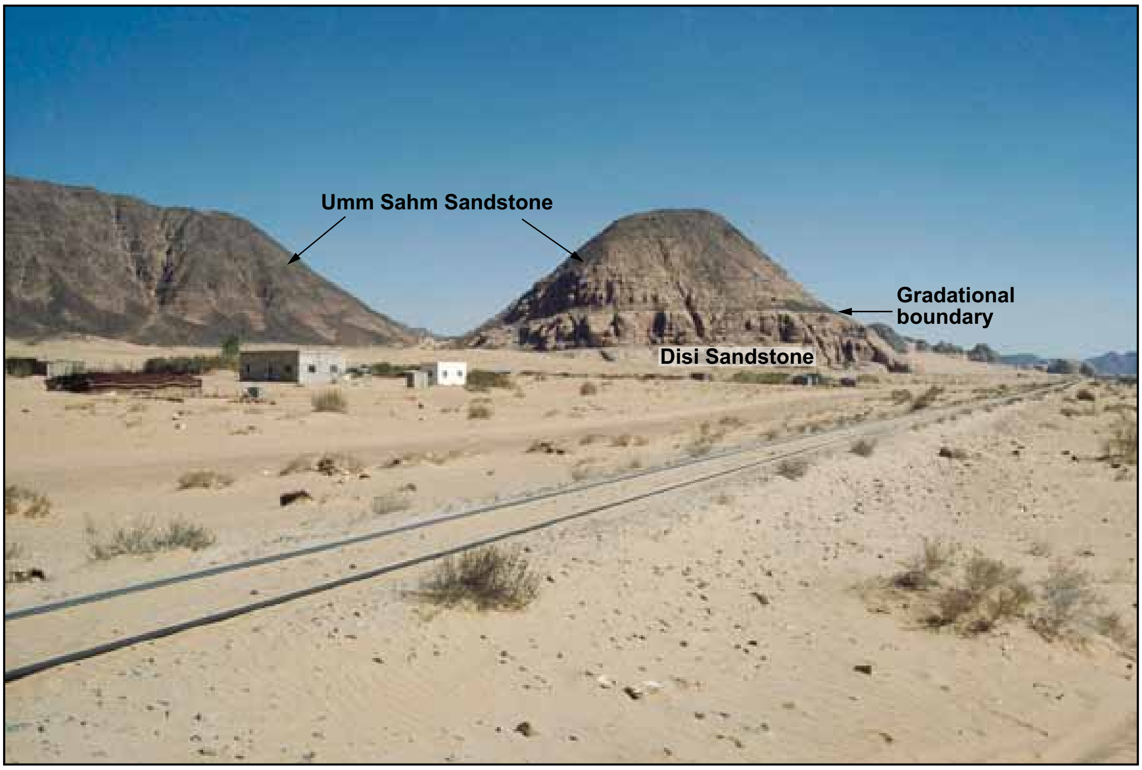
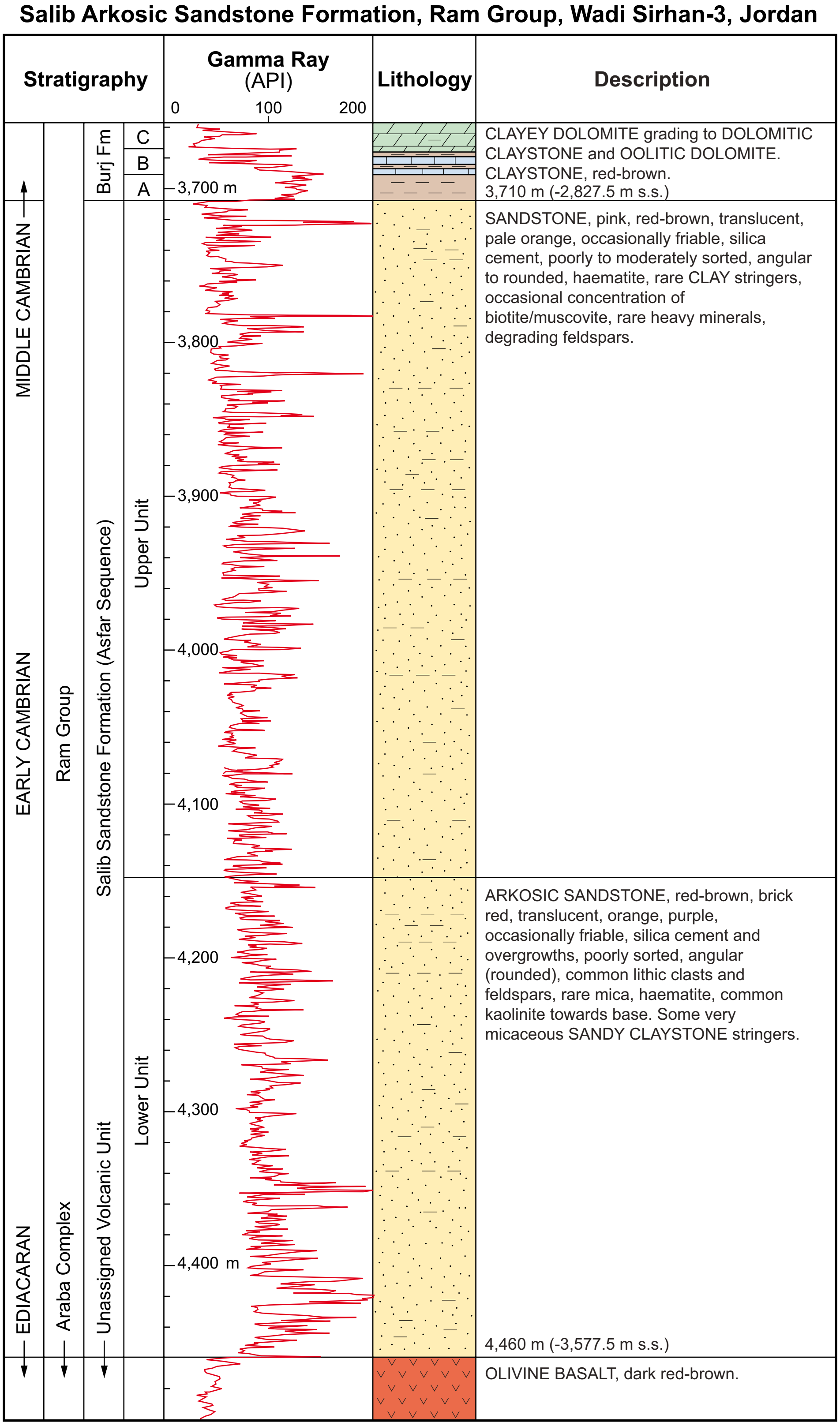


Plate 5: Gradational boundary between the Disi Sandstone Formation and the Umm Sahm Sandstone Formation, adjacent to Aqaba railway, east of Qa Disi. Note the distinctive bedforms, weathering and colour in the two formations. Conical hill is about 80 m high. Photo by J.H. Powell.



Salib Arkosic Sandstone Formation, Ram Group, Wadi Sirhan-3, Jordan

CLAYEY DOLOMITE grading to DOLOMITIC CLAYSTONE and OOLITIC DOLOMITE. CLAYSTONE, red-brown.
3,710 m (-2,827.5 m s.s.)

SANDSTONE, pink, red-brown, translucent, pale orange, occasionally friable, silica cement, poorly to moderately sorted, angular to rounded, haematite, rare CLAY stringers, occasional concentration of biotite/muscovite, rare heavy minerals, degrading feldspars.

ARKOSIC SANDSTONE, red-brown, brick red, translucent, orange, purple, occasionally friable, silica cement and overgrowths, poorly sorted, angular (rounded), common lithic clasts and feldspars, rare mica, haematite, common kaolinite towards base. Some very micaceous SANDY CLAYSTONE stringers.

4,460 m (-3,577.5 m s.s.)

OLIVINE BASALT, dark red-brown.

Figure 4: Reference section of Salib Formation in Wadi Sirhan-3 Well (WS-3) (after Andrews, 1991, reproduced by the permission of the Natural Resources Authority, Jordan). The ‘Unassigned Volcanic Unit’ is probably equivalent to the Aheimir Volcanic Suite.

sandstone. The mixed carbonate-siliciclastic Burj Formation is also well represented in this well, as are the overlying siliciclastics equivalent to the Umm Ishrin, Disi and Umm Sahm formations referred by Andrews (1991) to the Ajram (= Umm Ishrin) and Amud (= Disi and Umm Sahm, undivided) formations. Elsewhere in central-south Jordan the Salib Formation is represented in the subsurface by quartz conglomerate, up to 6 m thick and poorly sorted pebbly feldspathic sandstone (JF-1); in north Jordan (NH-1) the lowermost beds include laminae rich in mica and detrital heavy minerals, giving a high gamma-ray log response. The quartz pebble-rich, pebbly arkosic sandstone proved in the subsurface is similar to the basal lithologies seen at outcrop in the Feinan-Safi area and the Southern Desert (Plates 6 to 8).

Distribution

The Ram Group is present either at outcrop or in the subsurface throughout most of Jordan; the exception is the southern part of the Southern Desert where it has been eroded exposing the Aqaba Complex. It is equivalent to the Siq, Burj and Saq formations of Saudi Arabia (Tabuk Basin) (Powers, 1966; Al-Husseini, 2011); west of the Dead Sea Transform (DST) the lower part (up to the stratigraphical level of the Umm Ishrin Formation) is correlative with the Yam Suf Group (Weissbrod, 1970; Weissbrod and Sneh, 2002). Comparison of the lithostratigraphical nomenclature in the region is shown in Table 2.

Plate 6: Salib Formation, lower reaches of Wadi Dana, showing the two main lithofacies: granule-pebble conglomerate and trough cross-bedded pebbly sandstone. Pen 0.13 m for scale. Photo by A.M. Abed.

Plate 7: Conglomerate (C) and arkosic sandstone (S) lithologies in basal Salib Formation resting unconformably on Aqaba Complex granite, Wadi Rum; arrows mark Ram Unconformity surface. Lens cap (left centre) 42 mm diameter. Photo by J.H. Powell.

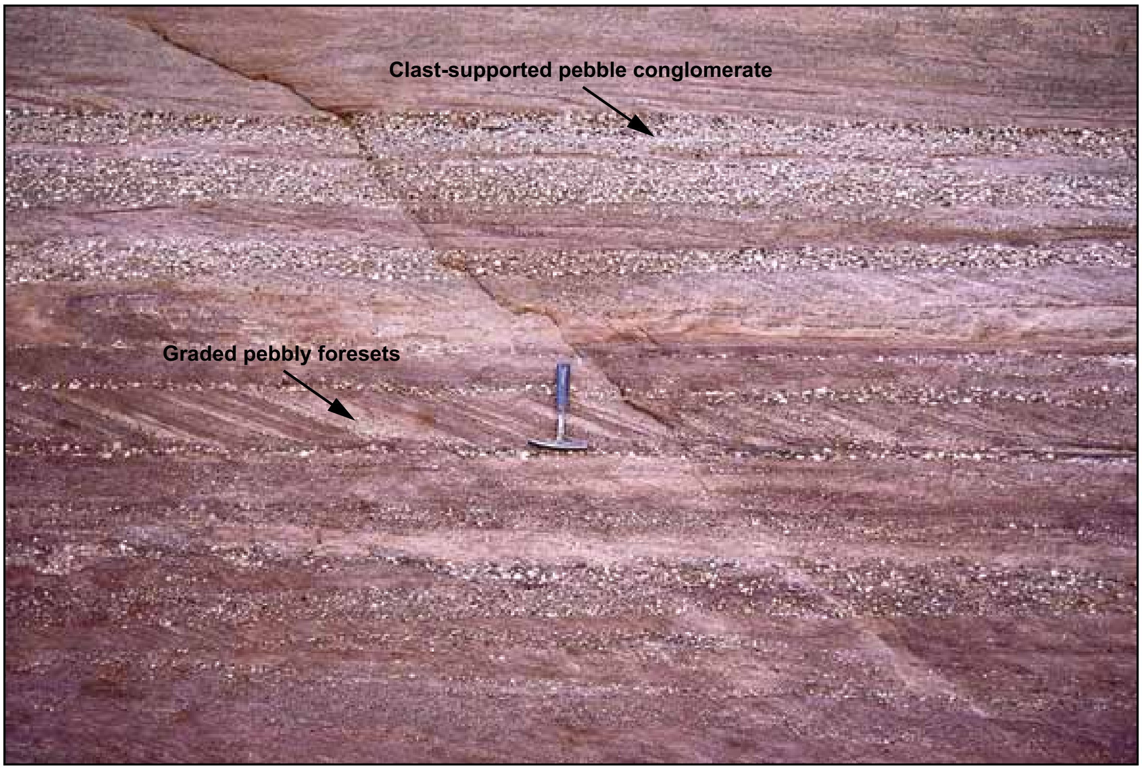
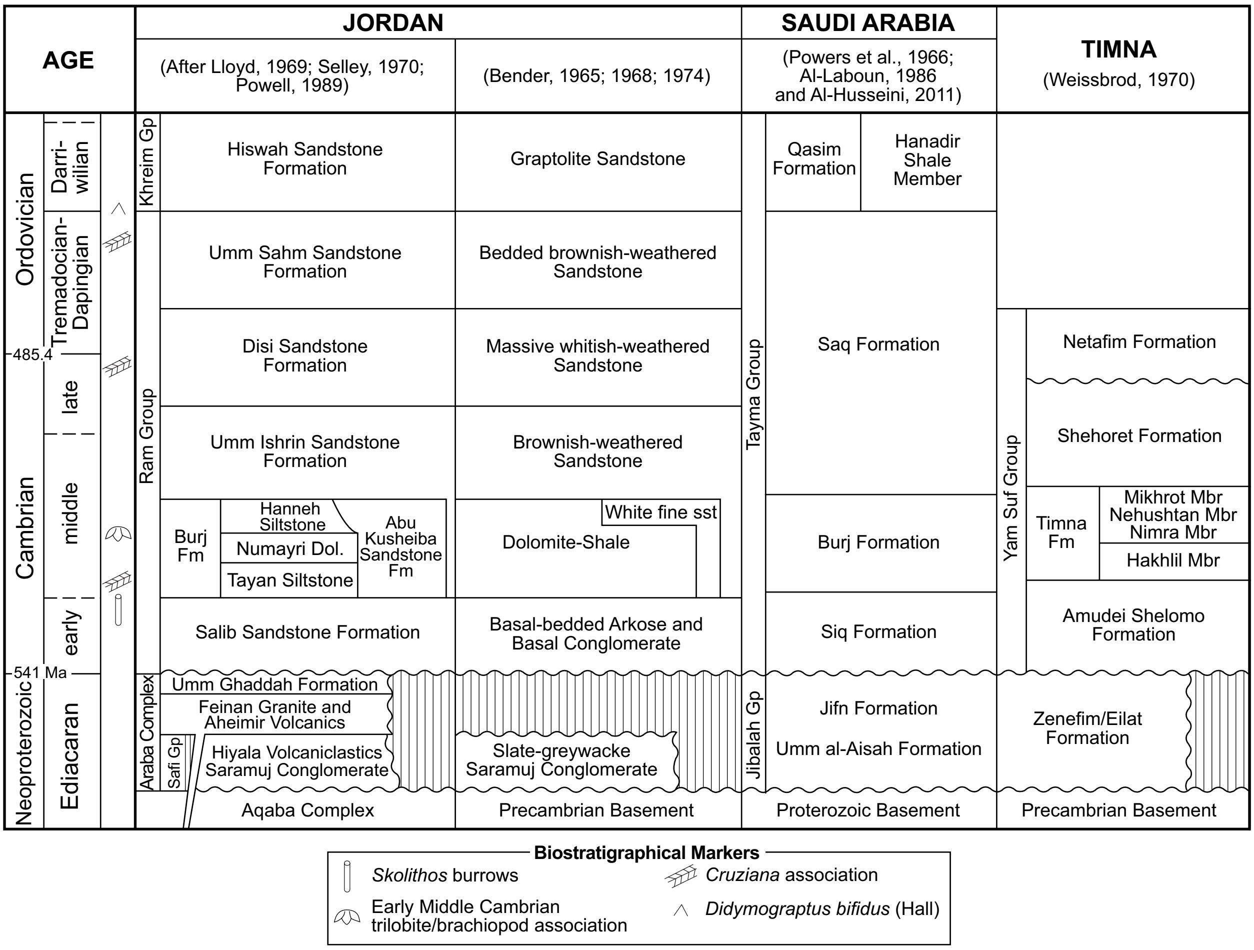


Plate 8: Salib Formation illustrating pebble conglomerate and trough cross-bedded pebbly arkosic sandstone lithofacies. Note the graded pebbly foresets and pebble-lined cross sets indicating a high energy flow regime (palaeoflow to right, north). Wadi Numayri. Hammer length 0.33 m. Photo by J.H. Powell.

Table 2: Lithostratigraphical nomenclature and correlation of the Cambrian in Jordan and adjacent countries.



AGE		JORDAN			SAUDI ARABIA		TIMNA	
			(After Lloyd, 1969; Selley, 1970; Powell, 1989)	(Bender, 1965; 1968; 1974)		(Powers et al., 1966; Al-Laboun, 1986 and Al-Husseini, 2011)		(Weissbrod, 1970)
Ordovician	Darriwilian	Khreim Gp	Hiswah Sandstone Formation	Graptolite Sandstone	Tayma Group	Qasim Formation Hanadir Shale Member		
	Tremadocian-Dapingian	Ram Group	Umm Sahm Sandstone Formation	Bedded brownish-weathered Sandstone		Saq Formation		
Cambrian (485.4)	late		Disi Sandstone Formation	Massive whitish-weathered Sandstone			Yam Suf Group	Netafim Formation
	middle		Umm Ishrin Sandstone Formation	Brownish-weathered Sandstone				Shehoret Formation
			Burj Fm: Hanneh Siltstone Numayri Dol. Tayan Siltstone Abu Kusheiba Sandstone Fm	Dolomite-Shale White fine sst		Burj Formation		Timna Fm: Mikhrot Mbr Nehushtan Mbr Nimra Mbr Hakhlil Mbr
	early		Salib Sandstone Formation	Basal-bedded Arkose and Basal Conglomerate		Siq Formation		Amudei Shelomo Formation
Neoproterozoic (541 Ma)	Ediacaran	Araba Complex	Umm Ghaddah Formation Feinan Granite and Aheimir Volcanics Safi Gp: Hiyala Volcaniclastics Saramuj Conglomerate	Slate-greywacke Saramuj Conglomerate	Jibalah Gp	Jifn Formation Umm al-Aisah Formation		Zenefim/Eilat Formation
			Aqaba Complex	Precambrian Basement		Proterozoic Basement		Precambrian Basement

Biostratigraphical Markers

Skolithos burrows

Cruziana association

Early Middle Cambrian trilobite/brachiopod association

Didymograptus bifidus (Hall)

Authors and Nomenclature

The name was first assigned (Powell, 1988) to the formations established by Bender (1968, 1974) and Lloyd (1969) in the Southern Desert, and derives from Wadi/Jabal Ram. It was referred to as the Disi Group by Lloyd (1969) but this name has been abandoned because it is used for one of the component formations (see NACSN, 1983). The term 'Nubian Sandstone' (Russeggar, 1847) was formerly used as a 'catch-all' term for fluvial siliciclastics of Cambrian to Cretaceous age in Egypt and the Levant, but the term has mostly been abandoned now that the lithostratigraphy and chronostratigraphy of the rock units (Bender, 1974; Powell, 1989) have been clearly demonstrated (Table 1). 'Nubian sandstone' is still occasionally used as a vague term to indicate fluvial siliciclastics lithofacies in north Africa and the Levant region (Schneider et al., 1984; Weissbrod and Nachmias, 1986), but should be abandoned.

Lithology and Bedforms

These are described in more detail in the descriptions of the early Cambrian formations up to the stratigraphical level of the Burj Formation. The Ram Group consists predominantly of medium- to coarse-grained, well-rounded, pebbly and non-pebbly sandstone (quartz-arenite, sub-arkose and arkose, in decreasing order of abundance), with subsidiary pebble conglomerate (in the lower part), micaceous fine-grained sandstone and siltstone.

Pebble- to cobble-grade conglomerates are uncommon and are mostly restricted to the basal Salib Sandstone, infilling shallow erosional depressions in the generally peneplaned Aqaba Complex 'basement' terrain (Plates 6 to 8). Pebble clasts include quartz pebbles and feldspar granules derived from Aqaba Complex granitoids and dyke rocks and, near Safi, include lithic-arkose clasts (Saramuj Conglomerate). Where the Ediacaran Araba Complex underlies the Ram Group adjacent to the Wadi Araba, locally derived volcanic and coarse-grained siliciclastic clasts are common in the basal beds. Siltstone laminae, often containing heavy mineral concentrations, are present in the lower part of the group. Cements consist of carbonate, kaolinite, haematite/limonite or illite/quartz overgrowths. Porosities are variable, but can reach 12–13% in the lowermost unit.

Along the Wadi Araba, north of Wadi Abu Khusheiba, a wedge of northward thickening marine carbonates (partly dolomitised wackestone, packstone, grainstone and micrite, in decreasing order of abundance) and fine- to medium-grained marine siliciclastics are present (Burj Formation; Figure 2). This unit has also been proven in boreholes to the east, near Wadi Sirhan (WS-3 and WS-10) and in North Jordan (NH-1) (Figure 1; Andrews, 1991). Macrofauna is absent in the fluvial sandstone lithologies, but trace fossil horizons are occasionally present (Selley, 1970; Seilacher, 1970; Powell, 1989; Amireh et al., 1994; Hofmann et al., 2012); the carbonates of the Burj Formation, however, are rich in bioclastic shell debris, including brachiopods, trilobites, hyolithids and sponge spicules as well as algal oncolites.

In the general absence of sharp lithological boundaries (except for the Burj Formation), the Ram Group formations can be distinguished in the field principally by changes in colour and bedform, which combined with variations in cements, produces distinctive weathering morphologies, at outcrop (Plates 1 to 5). In boreholes the formation boundaries are less distinct and are mostly taken at marked changes in geophysical log response.

Fluvial bedforms comprise three major types: (a) trough cross-bedding is most common, particularly in the Salib, Umm Ishrin and Disi formations. They are usually large-scale sub-aqueous dune forms,

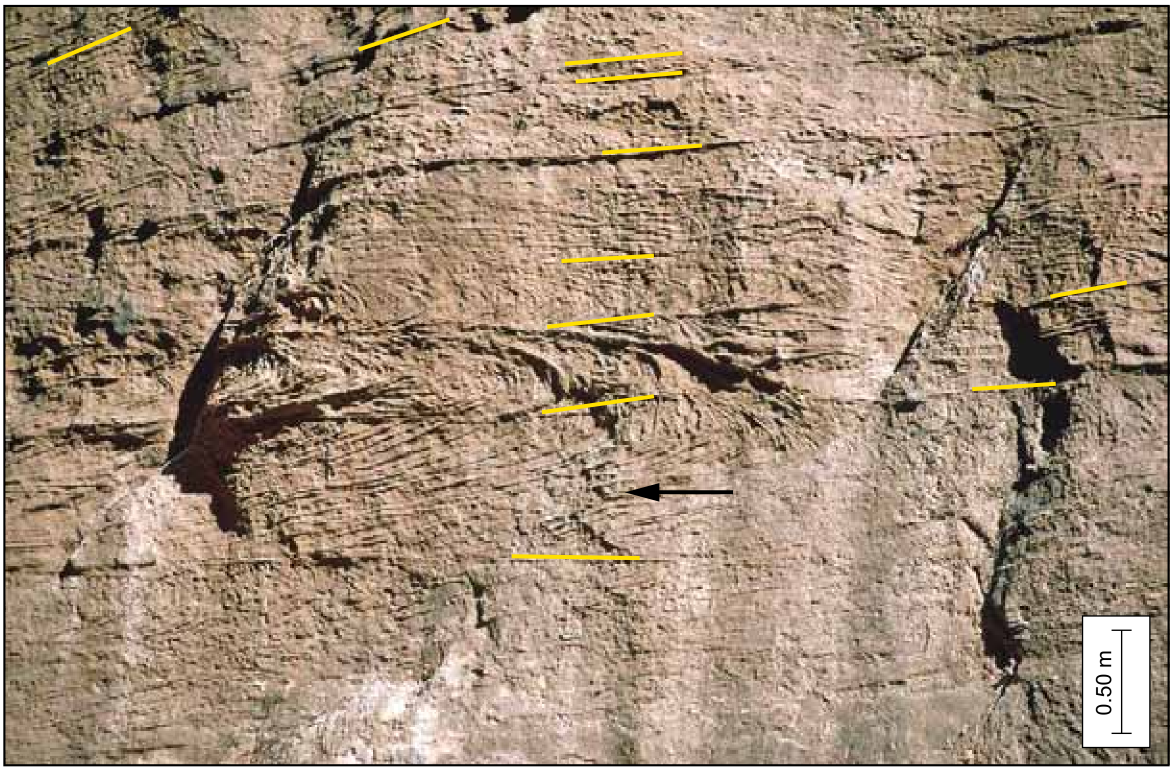


Plate 9: Stacked sets of overturned cross-bedding in the Umm Ishrin Sandstone near Petra. Individual cross-set boundaries are marked by yellow lines. Note unimodal (down-current to NNE) direction of overturned foresets (black arrow) and marked erosional bounding surfaces. Scale bar is 0.50 m. Photo by J.H. Powell.

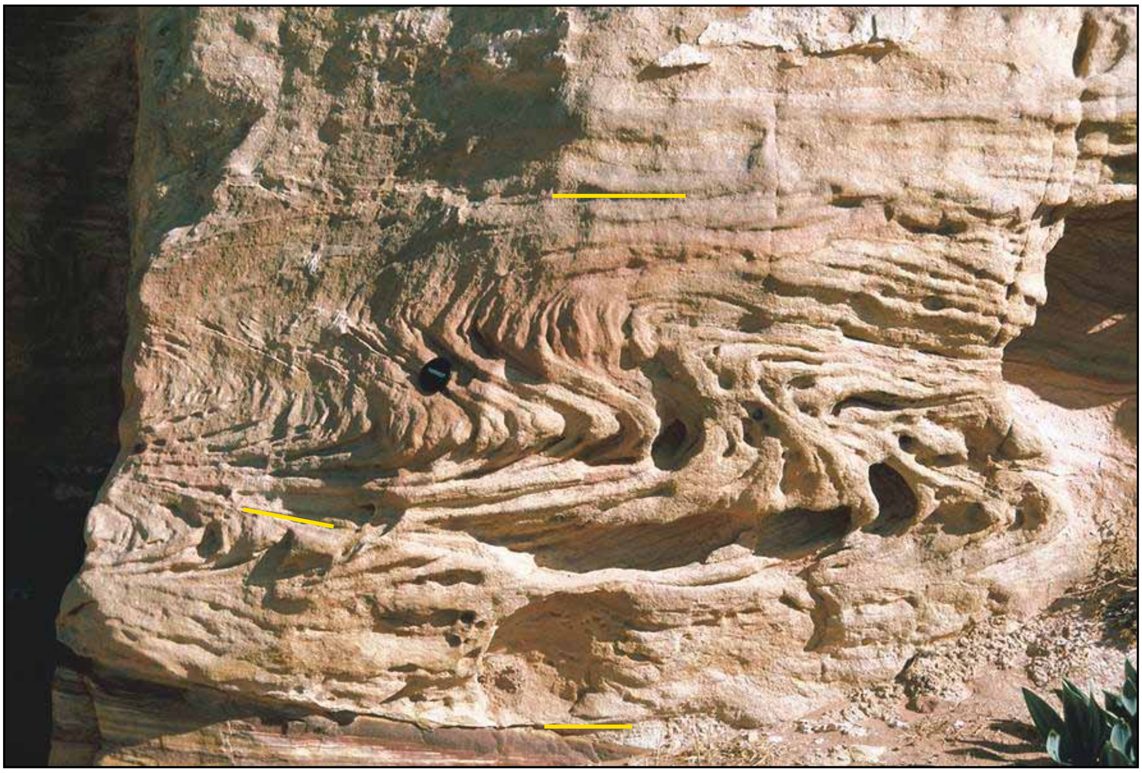


Plate 10: Overturned, sigmoidal trough cross-bedding in the Disi Sandstone near Petra. Note the sigmoidal deformed foresets (down-current to N) in the upper set. Cross-set boundaries marked by yellow lines. Lens cap 42 mm diameter. Photo by J.H. Powell.

Plate 11: Overturned trough cross-bedding, Umm Ishrin Formation, Anfasheh area, southeast of Wadi Ram. Dashed lines mark co-set boundaries. Height of geologist 1.80 m. Photo by J.H. Powell.

in sets up to 2 m in height with pebbly basal lags and graded foresets (Plate 7); the latter are frequently overturned (and locally convoluted) (Plates 9 to 11); (b) Planar cross-bedding in tabular sets (2–3 m height), is found in the Salib particularly in the Safi area (Dead Sea) (Plate 8) and near the base of this unit in the Southern Desert. It is also common below, and within, the *Cruziana* trace-fossil horizons of the Disi Formation and as medium-scale sets in the Umm Sahm Sandstone; (c) planar (or parallel) lamination is common in the fine-grained sandstones and siltstones within the trace fossil horizons (mostly Disi and Umm Sahm formations) and in the fine- to medium-grained siliciclastics of the Burj Formation where it is associated with ripple cross-lamination and tidal bundles. Parting lineation can also be observed on some bedding planes. Planar bedding also occurs as top-set units to some of cross-bedded sets. Palaeocurrent measurements for the group (Selley, 1972; Powell, 1989; Amireh et al., 1994) indicate general unimodal sediment dispersal towards the north-northwest, north and north-northeast.

Studies of heavy-mineral assemblages in the region (Powers et al., 1966; Weissbrod and Nachmias, 1986; Weissbrod and Sneh, 2002; Avigad et al., 2003; Kolodner et al., 2006; Knox et al., 2011) indicate an assemblage comprising zircon, tourmaline, rutile (ZTR) with detrital apatite, and locally with authigenic barite and authigenic apatite. This mature, stable assemblage indicates a distant granitic source area and deep weathering of the Proterozoic Arabian-Nubian Shield basement rocks (Weissbrod and Nachmias, 1986; Weissbrod and Sneh, 2002; Avigad et al., 2005; Kolodner et al., 2006; Knox et al., 2007, 2011). The overall cumulative-detrital age signal (U-Pb zircons) derived from Ram Group sandstones equivalent in the southern Levant show a concentration of geochronological age dates between 530 Ma and 1,100 Ma, with smaller peaks from pre-Neoproterozoic units at about 1,800 Ma and 2,600 Ma (Kolodner et al., 2006). These trends suggest derivation of the zircons and associated siliciclastics from the erosion of distant Pan-African orogens for the older zircon suites, and predominantly the near-field Neoproterozoic Arabian-Nubian Shield for the more abundant, younger-age zircon suite.

Boundaries

The base of the group is marked, in the south, by the erosional Ram Unconformity (Plates 1 to 4) between the Salib Sandstone Formation and the underlying granitoid Aqaba Complex (Bender, 1974; McCourt and Ibrahim, 1990; Rashdan, 1988; Powell, 1988, 1989), and in the Feinan-Wadi Abu Khusheiba region, in central Wadi Araba (Figure 1), between the Salib, Burj or Umm Ishrin formations and the Araba Complex and/or Aqaba Complex (Barjous, 1988) depending on the level of erosion. In the Southern Desert the top of the underlying Aqaba Complex is a peneplain with local erosional depressions and highs of low palaeo-relief. However, in the central Wadi Araba the granites (Feidan Suite) and extrusives (Aheimir Suite) of the younger (Ediacaran) Araba Complex form a faulted block that had considerable palaeo-relief (up to 200 m high). To the north of the Feinan area, the Salib, Burj and Umm Ishrin formations onlap southwards; to the south of the block the Salib Sandstone, Abu Khusheiba Sandstone and Umm Ishrin Sandstone onlap northwards (Figure 2).

The top is seemingly conformable in the western part of the Southern Desert (Hiswah-Sahl as Suwwan area), where the Umm Sahm Sandstone of presumed Floian (Arenig) age is overlain by the Hiswah Sandstone of Darriwilian (Llanvirn) age. Elsewhere, the group is unconformably overstepped by the Kurnub Sandstone (Cretaceous) or, north of Wadi Mujib, by the Permian–Triassic Umm Irna Formation (Bandel and Khoury, 1981; Powell and Moh'd, 1993). Along the margins of the Wadi Araba, the angular discordance between the Ram Group and the basal Kurnub Sandstone or the Umm Irna sandstone is very slight, or almost parallel. However, the angular unconformity along the Ras En Naqb-Batn El Ghul Escarpment is higher (ca. 2 degrees dip) due to the eastward tilt of the Lower Palaeozoic, pre-Kurnub strata. The tilting and erosional phases occurred in the late Palaeozoic (post-Devonian to pre-Carboniferous) (Al-Laboun, 1986; Powell and Moh'd, 1993) and also in early Permian times (Stephenson and Powell, 2013). A further period of extensional faulting and erosion took place in central and north Jordan in Late Jurassic to Early Cretaceous times, prior to deposition of the Cretaceous Kurnub Sandstone (Bender, 1974; Bandel and Khoury, 1981; Powell and Moh'd, 1993).

Thickness

The most complete succession is present in the Southern Desert, where the Ram Group ranges in thickness from 850–1,010 m. Evidence from boreholes indicate that the unit thickens towards the east (Lloyd, 1969; Andrews, 1991); in WS-3 it is reported as 2,360 m thick, underlain by volcanic rocks equivalent to the Araba Complex (Figure 2), and overlain by the marine Khreim Group. In the Tabuk Basin (Saudi Arabia) up to 928 m were encountered in the Ri Al-Fuheh well without reaching 'basement' rocks (Al-Laboun, 1986). From south to north Jordan, the data illustrate interesting thickness trends in the Salib, Burj and Umm Ishrin formations. The former maintains a slight decrease in thickness towards the Dana-Feinan block, i.e. away from the Arabian-Nubian craton. It thins over this block due to ca. 200 m palaeo-relief, and shows a rapid increase in thickness northwards (Wadi Numayri/Suweileh-1 well) suggesting a rapidly subsiding basin to the north. Increased subsidence of this basin compared to the Southern Desert is also demonstrated by basinward-thickening of the marine carbonates of the Burj Formation north of the Dana-Feinan block, and their absence to the south where coeval Abu Khusheiba siliciclastics are present (Figure 2). Thickness trends in the Umm Ishrin Formation are more difficult to establish because of Late Palaeozoic and Mesozoic erosional levels. However, data from Wadi Numayri (Karak area) and Suweileh-1 well indicate a slightly thicker succession with intercalations of a marginal marine facies (tidal lithofacies) to the north (Wadi Zarqa Ma'in area). This pattern suggests more uniform subsidence over the whole region with slight tilting towards the north and northeast during late Cambrian times.

Age and Fauna

The group ranges in age from early Cambrian to Ordovician (Floian [Arenig]). Geochronologically, the Salib Formation is younger than 561 ± 31 Ma (Brook et al., 1988; Ibrahim and McCourt, 1995) because it on-laps against the Feinan Granite/Aheimir Extrusive Suite (Araba Complex) in the Feinan-Dana block; these igneous rocks give a combined Rb/Sr isochron noted above. However, more precise U/Pb zircon determinations (Jarrar, 2001; Jarrar et al., 2003, 2008) give an older (and narrower) age range for these Araba Complex igneous rocks (586.2 ± 5 Ma, for the Museimir Effusives) that underlie the Ram Group unconformably. The Salib Formation contains *Skolithos* burrows near the top of the unit in the Southern Desert and south Wadi Araba, and the Abu Khusheiba Formation has yielded both *Skolithos* and *Cruziana* assemblage burrows. These ichnofossil assemblages indicate the presence of burrowing (infaunal) and grazing (epifaunal) animals that disturbed the sandy sediment, and thus indicate at least an early Cambrian age (i.e. post 541 Ma base of the Cambrian; [Peng et al., 2012]).

Age-diagnostic fossils such as trilobites, brachiopods, and hyolithids (Parnes, 1971; Cooper, 1976; Rushton, 1988; Rushton and Powell, 1998; Elicki and Geyer, 2013) indicate an 'early mid-Cambrian' age for the Burj Formation in the Safi (and Timna) areas, and a slightly later age for the Wadi Zarqa Ma'in area. Elicki and Geyer (2013) tentatively equated the trilobite assemblage (faunula) in the Safi area to latest Series 2/Age 4, and that of the Zarqa Ma'in area to the early part of Series 3/Age 5, thus spanning the first appearance datum (FAD) of the trilobite *Ovatoryctocara granulata;* the top of this zone marks the boundary between Age 4 and Age 5 of Peng et al. (2012) with a numerical age of 509 Ma. However, trilobite faunal provinces during the Cambrian are markedly endemic, including the Redlichiid Province of Gondwana typical of the Burj carbonates. Consequently, it is difficult to correlate from one faunal realm to another. In addition, Keegan et al. (1990) described 'early Middle Cambrian' microfauna of acritarchs in the subsurface Burj Formation (NH-1; WS-3). In summary, the geochronological age of the Burj Formation is taken here, tentatively, at about 511 to 509 Ma.

The overlying Umm Ishrin Sandstone is faunally barren at outcrop, but sparse *Cruziana* traces are present (Plate 12). However, diverse *Cruziana/Rusophycus* trace fossil assemblages (Plates 13 and 14) from the upper part of the Disi Formation indicate a probable Floian (Arenig) age (Selley, 1970), so the Cambrian/Ordovician boundary must lie somewhere within these two formations. A similar suite of trace fossils (Selley, 1970) and Floian (Arenig) acritarchs (Basha, 1978) have been reported from the Umm Sahm Sandstone. The upper age boundary for the group is determined by late Floian to early Darriwilian graptolites (*Didymograptus* cf. *bifidus* (Hall); *Didymograpellus* sp. in the basal ripple marked sandstones of the Khreim Group (Huckriede in Bender, 1974; Rushton, 1988; Powell, 1989).

Plate 12: *Cruziana* trace on oscillation-rippled surface, lower Umm Ishrin Formation, Wadi Rumman. Arrow marks track direction. Lens cap 42 mm diameter. Photo by J.H. Powell.

Plate 13: Large-scale trough cross-bedding in the Disi Formation, overlain by a thin, planar bedded fine-grained sandstone with rippled surfaces and abundant *Cruziana* and *Rusophycus* traces marking a brief estuarine to brackish-marine incursion. See Plate 14 for trace assemblage. Location, east of Quweira. Hammer length 0.45 m. Photo by J.H. Powell.

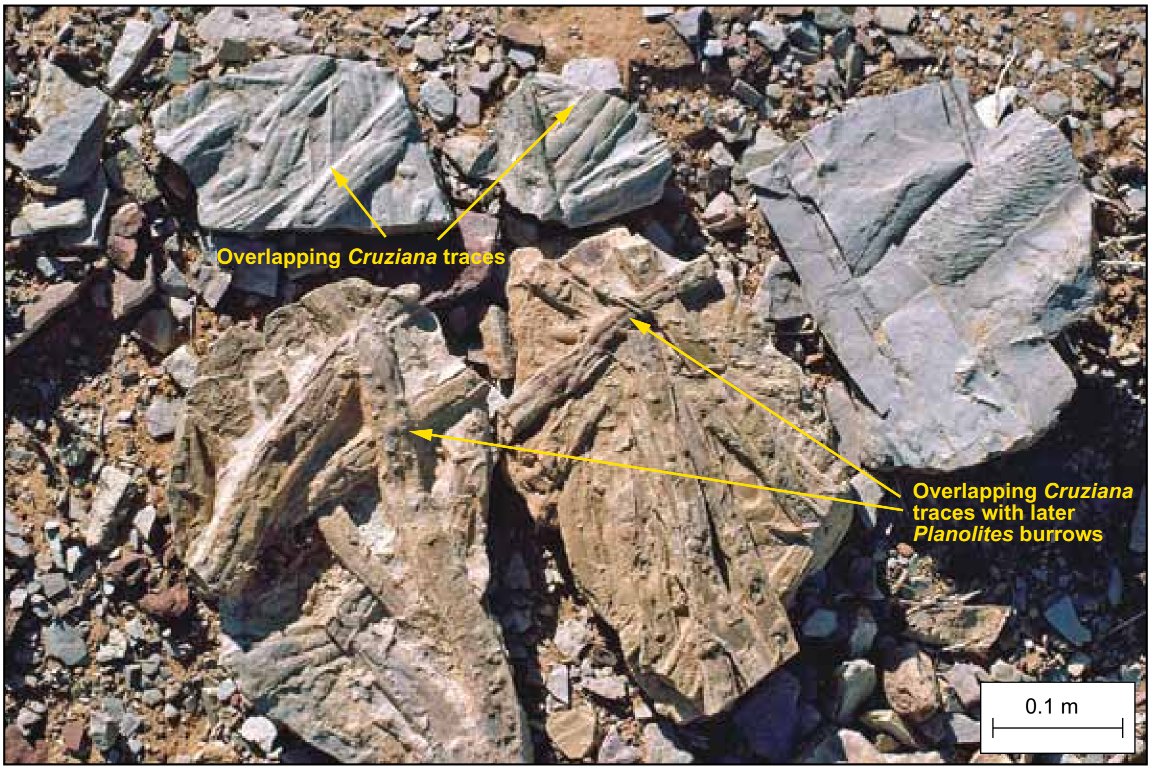


Plate 14: Random selection (not *in situ*) of arthropod traces collected from the planar sandstone in Plate 13 (Disi Formation). Note the abundant and diverse traces with overlapping tier structure showing multiple grazing and burrowing events. Location, east of Quweira. Photo by J.H. Powell.

Environment of Deposition and Tectono-stratigraphical Events

The lithology, bedforms and fauna indicate that the Ram Group was deposited in a predominantly alluvial fan and fluvial braided-stream environment with large river systems dispersing sediment northwards to a low-lying alluvial plain (Figure 3). Sediment was derived from the isostatically buoyant, granitoid ANS, part of north Gondwana, located to the south (Selley, 1970, 1972; Powell, 1989; Makhlouf and Abed, 1991; Amireh et al., 1994; Stern, 1994).

Initial sedimentation during development of the peneplain in the Southern Desert is characterised by thin pebbly, coarse-grained, proximal siliciclastics that 'buried' any remaining low topographical expression of the Aqaba Complex (Plates 1 to 4). By contrast, the Araba Complex in the Feinan to Wadi Abu Khusheiba area, remained as prominent relief until its final burial in late Burj or early Umm Ishrin times (middle Cambrian) (Figure 3). Here, the boundary between the Araba Complex rhyolites/quartz porphyries and the Ram Group was considered to be intrusive (Bender, 1974), but field relationships in the Beida and Wadi Museimir areas show that the Ram Group onlaps unconformably against an immature palaeo-topography of igneous rocks (Bigot, 1981; Barjous, 1988; Ibrahim and Rashdan, 1988) (Figure 2; Plates 15 to 17). Since the upper surface of the Saramuj Conglomerate (which contains rounded-pebble clasts of granitoids derived from the Aqaba Complex), is also a peneplain in the Safi area, north of this block, it suggests that the peneplain in the Southern Desert developed over many tens of millions of years and may be the result of a series of erosional events (i.e. during both Saramuj and early Ram sedimentation) spanning late Neoproterozoic (Ediacaran) to early Cambrian times.

Basin subsidence was greater in north Jordan where a thick sequence of very coarse- to coarse-grained siliciclastics was deposited on an alluvial plain by braided streams and/or sheet-flood gravels. Sedimentation, here, was rapid, and kept pace with subsidence until the late early- to early mid-Cambrian times (late Stage 4 to early Stage 5 of Peng et al., 2012) when sea-level rise across north

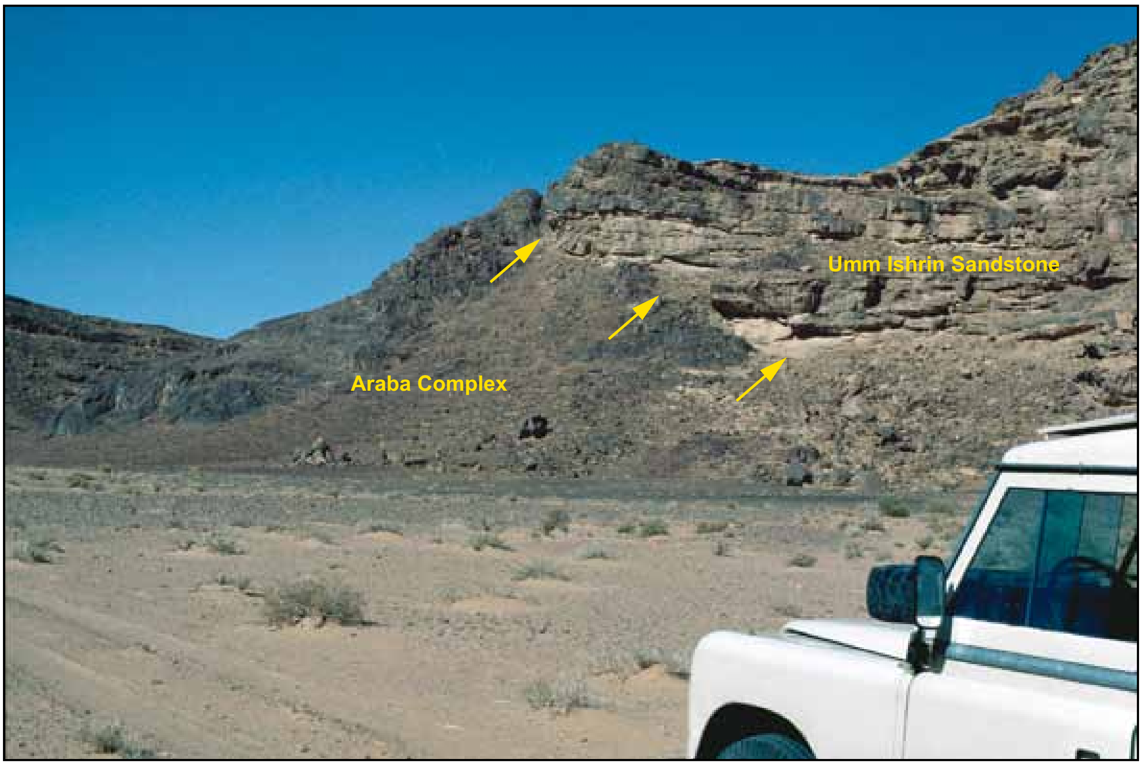


Plate 15: Channelised Umm Ishrin Formation sandstone resting unconformably on immature palaeotopography of the Araba Complex; Wadi Ghuweir. Arrows mark Ram Unconformity surface. Height of face approximately 20 m. Photo by J.H. Powell.

Plate 16: Ram Unconformity in the Petra area viewed from Petra ridge looking west towards the Wadi Araba. Umm Ishrin and Abu Khusheiba formations rest unconformably, with marked palaeorelief, on the Aheimir Volcanics (Araba Complex). Photo by J.H. Powell.

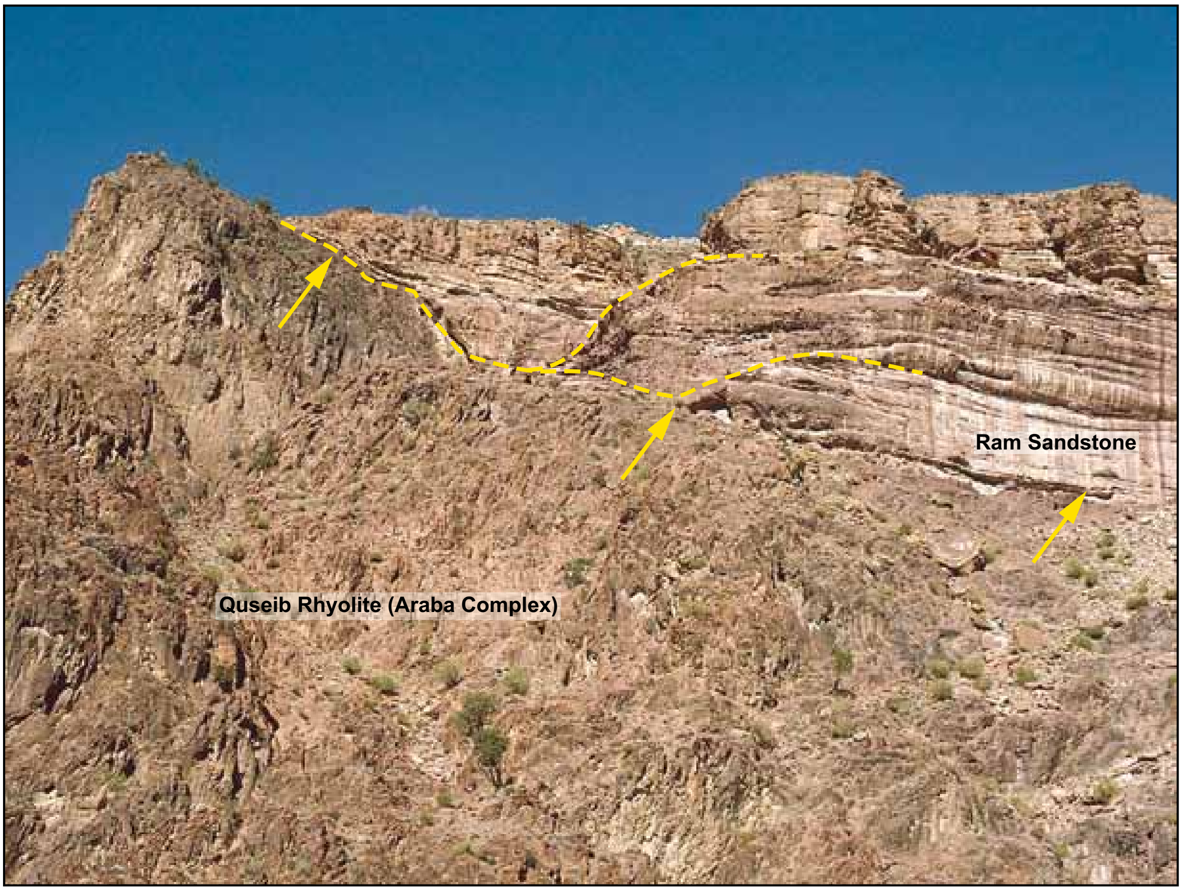


Plate 17: Ram Unconformity (yellow arrows) in Wadi Museimir showing channelised Ram Sandstone resting with marked palaeorelief on the Quseib Rhyolite (Araba Complex). Note the stacking of incised fluvial channels (yellow dashed); channel flow is into the photograph. Height of face approximately 250 m. Photo by J.H. Powell.

Gondwana resulted in transgression southwards to the Feinan-Dana area and, farther east, in the present-day Wadi Sirhan area. The initial Burj transgression deposited near-shore tidal siliciclastics over central-southern Jordan, but a subsequent sea-level rise (maximum flooding) and/or decrease in the influx of siliciclastics from the alluvial hinterland (ANS) led to the establishment of a shallow-water carbonate ramp (Powell, 1989; Rushton and Powell, 1998). Bioclastic and algal limestones were deposited in warm, shallow subtidal or intertidal lagoons (Shinaq and Bandel, 1992). The palaeo-shoreline in Jordan ran between Dana and Wadi Quseib, extending east-southeast (Jafr-1 and Wadi Sirhan-3). A diverse marine ichnofossil assemblage in the fine-grained siliciclastics (including *Skolithos* burrows and *Cruziana* traces) in the Southern Desert at the level of the Burj transgression suggest that marginal marine environments briefly advanced this far south during Burj times (maximum flooding).

North and northwestward thickening of the carbonates from Jordan to Syria (Best et al., 1993) and Iraq/Iran (Stöcklin and Setudehnia, 1972) and their absence south of Feinan, suggests that the Burj marine transgression may have been in response to northward tilting and subsidence of this part of the Arabian-Nubian Shield, which, combined with a gradual global eustatic sea-level rise at around the boundary of Series 2, Stage 4 and Series 3, Stage 5 (ca. 509 Ma) (Peng et al., 2012, figure 19.3), resulted in maximum southward flooding of the coastal plain. The axis of tilting may have coincided with an approximate ENE-WSW line from the Dana/Petra area to Jafr-1 borehole (Figure 5), that is, sub-parallel to the Burj lithofacies belts. This trend may be related to renewed movement on the dominant Najd Fault System that cuts the ANS in Saudi Arabia (Stern, 1994).

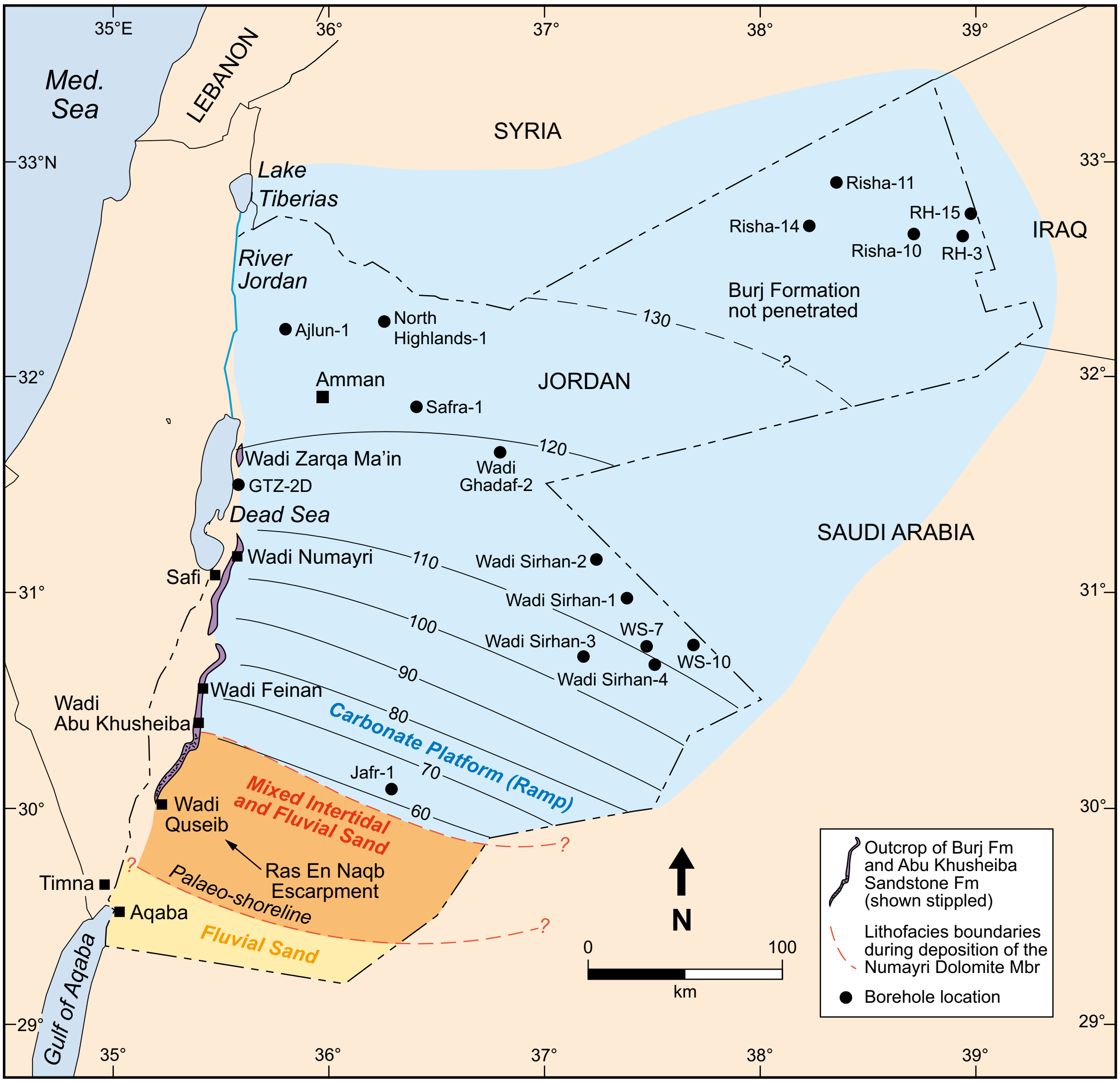


Figure 5: Lithofacies belts and thickness of the Burj Formation in Jordan. Isopach interval is 10 m. Based on Andrews (1991) and Rushton and Powell (1998).

Regression of the coastline to north Jordan/Syria in late Burj time was probably due to renewed uplift of the ANS that resulted in progradation of intertidal marine siliciclastics deposited near the palaeo-shoreline in central Jordan. However, lenses of marine carbonates are intercalated with marine siliciclastics lithofacies in the subsurface north of Karak, indicating periodic transgression and regression of the sea in this area (Wadi Zarqa Ma'in area and Suweileh-1 well) (Figure 5). Similar mixed fully marine/intertidal facies were also developed in the Wadi Sirhan area. A return to predominantly fluvial and subsidiary marginal marine sedimentation (Umm Ishrin) was probably a result of renewed isostatic uplift of the granitoid ANS, located to the south, which supplied voluminous sand and gravel to the northward flowing rivers in a humid climatic regime.

Subsequently, fluvial siliciclastics of braided-channel lithofacies spread over much of southern Jordan in Umm Ishrin and Disi formation time (mid-Cambrian to Ordovician). A change in provenance (Kolodner et al., 2006) or perhaps reworking of the fluvial sand (2nd erosional cycle) is indicated by the change in both colour and lithological maturity (from arkosic to orthoquartzite) during Umm Ishrin to Disi sedimentation, although palaeocurrent flow (north-northeast to north-northwest) was similar for both formations (Powell, 1989; Amireh et al., 1994). Locally, the base of the Disi Formation is marked by a quartz- pebble conglomerate, suggesting a change in sedimentation style, possibly due to hinterland tectonics (uplift). Brief incursions along broad estuarine or low-gradient alluvial plains are indicated by thin planar-bedded horizons of fine-grained siliciclastics with an abundant and diverse *Cruziana/Rusophycus* trace-fossil assemblage (Selley, 1970) near the top of the Disi Sandstone (Plates 13 and 14). The overlying Umm Sahm Sandstone records a transition from braided-stream alluvial sedimentation of pebbly trough cross-bedded sandstone (Disi type), intercalated with both tabular sheet sandstone with planar cross-bedding and rippled, cross-laminated fine-grained sandstone with *Cruziana, Skolithos, Harlania* trace fossil assemblages (Umm Sahm type) (Powell, 1989). Repetition of these lithofacies types throughout the formation suggests deposition in a coastal alluvial plain with prograding rivers depositing longitudinal sand bars, which were inundated periodically during high sea-level stands. Sheet sandstones were deposited during these high-level stands as both nearshore sand-waves and bars; the cycle was capped by quiet water sedimentation in a shallow subtidal zone (*Cruziana* assemblage). Shelly macrofossils have not be found in the interval between the top of the Burj carbonates and the base of the ripple marked and graptolite-bearing Hiswah Sandstone Formation (Khreim Group) where *Didymograptus bifidus* indicates an early Darriwilian (Llanvirn) age (Selley, 1970; Bender, 1974; Powell, 1989). The sea advanced westward during late Floian/Darriwilian times to cover much of the alluvial plain and heralded almost continuous shallow-marine siliciclastic sedimentation on a broad epeiric shelf throughout the deposition of the overlying Khreim Group.

Palaeomagnetic studies (Scotese, 2001; Stampfli and Borel, 2002) indicate that Jordan formed part of the Gondwana continent (Arabian-Nubian Shield) and lay about 30° south of the equator during the Cambrian. The climate is interpreted as globally warm, greenhouse conditions (Peng et al., 2012). This is supported by the presence of marine blue-green algae (*Girvanella*) in the lagoonal Burj carbonates indicating a warm ocean. Furthermore, the enormous volume of fluvial siliciclastics deposits predominantly by large, high-flux braided rivers indicates a wet (humid) climate in the ANS hinterland resulting in a deeply weathered regolith, the source of an abundant supply of bedload sediment to the northward flowing rivers and coastal plain. Land plants did not evolve until Devonian time, so no baffling/binding soils developed and, consequently, rock slopes and their regolith were easily eroded and transported by high flux-high discharge rivers (Powell, 1989; Davies and Gibling, 2010; Gibling and Davies, 2012).

SALIB SANDSTONE FORMATION

Type and Reference Sections

The type section of the Salib Sandstone Formation is at Qa Salib adjacent to the Desert Highway-Wadi Ram road in the Southern Desert of Jordan, where the formation is between 40 and 60 m thick (Figure 1) (Selley, 1972). Reference sections are the Safi-Wadi Numayri area at the southern end of the Dead Sea, south and north of the Safi Potash Works, respectively (Powell, 1989), and in central Wadi Araba at Wadi Abu Khusheiba and Wadi Dana (Figure 1; Bender, 1974; figure 134; Powell, 1989, figure 3; Amireh et al., 1994, figure 2).

Subsurface Reference Section

The Salib Formation was recognised on geophysical log signatures in several deep boreholes in Jordan (Andrews, 1991). Only three boreholes intersected the whole of the unit; they are: North Highlands-1 (NH-1); Wadi Sirhan-3 (WS-3) and Jafr-1 (JF-1) (Figure 1). The most representative borehole is WS-3 (Figure 4) in southeast Jordan where the Salib Formation consists of 750 m of sandstone and arkosic sandstone (Andrews, 1991).

Distribution

The formation crops out (Figure 1) in the Dead Sea basin-Wadi Araba area from Wadi Numayri southwards to Wadi Quseib (Powell, 1988, 1989; Amireh et al., 1994). In the Southern Desert it crops out above the Aqaba Complex basement rocks in the type area of Qa Salib, east of Quweira, and in the Wadi Ram area. In the subsurface it has been proven in boreholes over most of Jordan eastwards from the Dead Sea Rift and north of the Aqaba Complex outcrops in the Southern Desert (Andrews, 1991, figure 2b).

The Salib Formation is correlated with the Siq Sandstone of northwest Saudi Arabia (Powers, 1966; Al-Husseini, 2011), with the Amin Formation in Oman, and with the Lalun Formation in Iran (Al-Husseini, 2011, 2014, Enclosure). West of the Dead Sea Rift in the Timna area it is equivalent to the Amudei Shelomo Sandstone Formation (Weissbrod, 1970, figure 3); this unit is offset from the coeval strata in the Safi area of Jordan by about 110 km left-lateral (southerly) shear on the Dead Sea Transform (Freund et al., 1970). To the southwest in Wadi Nasib, Sinai, it is equivalent to the Sarabit El Khadim Member (Araba Formation) (El-Shahat and Kora, 1986; Knox et al., 2011).

Authors and Nomenclature

The name was established by Lloyd (1969) and Selley (1972) and is derived from Qa Salib, near Quweira village, where the type section is exposed. It is synonymous, in Jordan, with the Basal Conglomerate and Basal Bedded Arkose (Bender, 1968; 1974), the Lower Quwayra Series (Quennell, 1951; Burdon, 1959), and the Quwayra Sandstone (Wetzel and Morton, 1959). The name Quwayra (or Quweira) was abandoned (Powell, 1989) because, (1) the formation does not outcrop there, and (2) to avoid confusion with the 'upper' and 'lower' Quwayra units described by Quennell (1951) and Burdon (1959). The earlier name Salib Arkosic Sandstone Formation (Powell, 1989) has been amended, here, to Salib Sandstone Formation.

Lithology and Bedforms

The Salib Formation consists predominantly of yellow-brown, red, and purple medium- to very coarse-grained, pebbly cross-bedded arkosic and sub-arkosic sandstone; pebble- to cobble-conglomerates are locally present, and thin beds of planar to ripple cross-laminated, fine-grained micaceous sandstone are present in the Safi area (Powell, 1989; Amireh et al., 1994). Figure 6 shows the lithostratigraphical/sedimentological section through the Salib Formation in Wadi Rum. Trough cross-bedding within medium- to large-scale tabular sets (about 1.5 m high) with pebbly basal lags and graded foresets is the most common bedform (Plates 6 to 8), although planar cross-bedding in small-scale tabular sets is also present. Trough cross-bedded foresets are occasionally overturned or convoluted (de-watered) (Figure 6).

In the Southern Desert type area, the lithology and bedforms produce a distinctive step-like, well-bedded weathering morphology above the 'basement' Aqaba Complex peneplain (Plates 1 to 4). Depressions in the peneplain are locally infilled with pebble- to boulder-grade, clast-supported, granite-rich conglomerates, which pass up into a series of fining-upward units of pebbly sandstone. Over most of the Southern Desert peneplain area, however, the granitoid basement rocks are weathered to a depth of 0.5 to 1.5 m and are overlain by pebbly sandstone with conglomeratic lenses. Parallel-bedded, fine-grained, micaceous sandstones near the top of the unit display surface burrows and *Cruziana* feeding traces; at some localities these are commonly associated with long *Skolithos* burrows, penetrating and destroying the primary lamination in cross-bedded, non-pebbly sandstone. Near Qa Salib, load structures ('ball and pillow') are developed in heterogeneous sandstone/siltstone lithologies. In the area east of Qa Disi, the Salib Formation consists of two lithofacies alternating throughout the thickness of the formation: they are, arkosic sandstone and pebbly sandstone.

Between Wadi Quseib and Wadi Dana on the eastern flank of Wadi Araba, the basal sediments are highly conglomeratic. They consist of clast- to matrix-supported, sub-angular conglomerates composed of local basement rocks (Aqaba and Araba complexes) passing sequentially upwards to sandstones, interbedded throughout with pebbly sandstone containing rounded quartz pebbles (Plate 8), and conglomeratic lenses. At about 65 m above the base, *Skolithos*-burrowed sandstones are about 17 m thick and contain sparse *Cruziana* sp. (Powell, 1989; Amireh et al., 1994). Rounded pebbles of 'milky' quartz derived from the Proterozoic basement rocks are common throughout the lower part of the formation in the Wadi Numayri area (Powell, 1988).

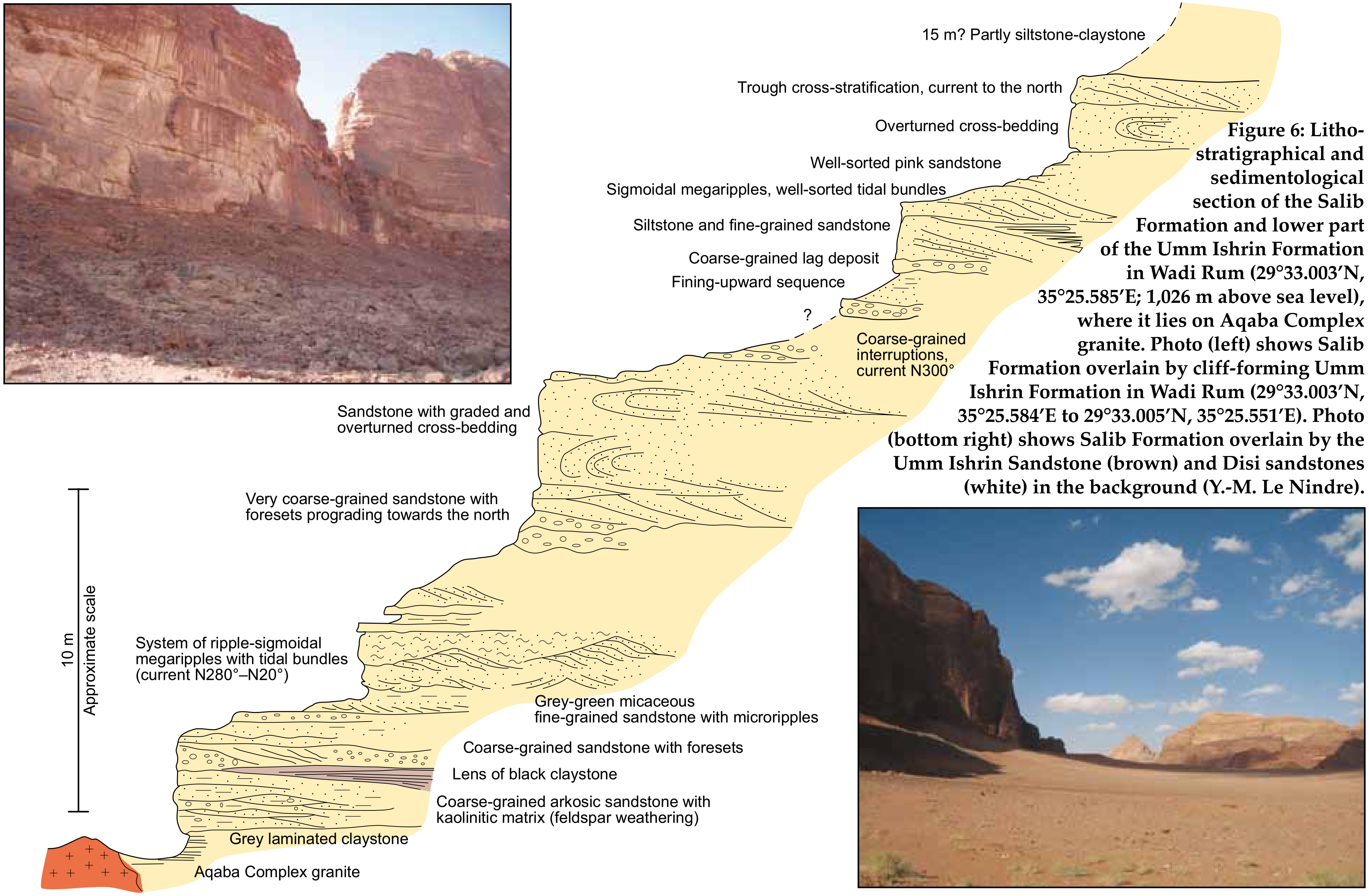


Figure 6: Litho-stratigraphical and sedimentological section of the Salib Formation and lower part of the Umm Ishrin Formation in Wadi Rum (29°33.003′N, 35°25.585′E; 1,026 m above sea level), where it lies on Aqaba Complex granite. Photo (left) shows Salib Formation overlain by cliff-forming Umm Ishrin Formation in Wadi Rum (29°33.003′N, 35°25.584′E to 29°33.005′N, 35°25.551′E). Photo (bottom right) shows Salib Formation overlain by the Umm Ishrin Sandstone (brown) and Disi sandstones (white) in the background (Y.-M. Le Nindre).

Northwards from Feinan, the formation thickens to become over 200 m in the Safi area (Figure 2b). Here, it consists of three informal subdivisions (Powell, 1988) that, from base to top are: (a) pebbly, trough cross-bedded medium- to coarse-grained sandstone with a basal conglomerate (0.3–2.0 m thick) infilling a palaeorelief of up to 3 m, intercalated with non-pebbly, planar cross-bedded micaceous fine- to medium-grained sandstone (total thickness 60 to 70 m); (b) planar cross-bedded sandstone in small- to medium-scale tabular sets intercalated with thin beds (up to 60 cm thick) of well-rounded pebble-grade quartz gravel (58–70 m thick); (c) pebbly, large-scale trough cross-bedded medium-grained sandstone similar to the basal unit. Laterally accreted cross-bedding in medium-scale channels has been observed at the top of this unit in the Safi area (Powell, 1988).

Petrographically, the sandstones range from arkose near the base to sub-arkose above. This upward trend of increasing maturity is paralleled, in the Southern Desert, by an overall decrease in grain-size culminating in the fine-grained micaceous sandstones with surface traces, and associated *Skolithos*-burrowed sandstones. The trend is different in the Safi area where the middle gravelly unit (b, above) marks a distinct change in provenance and depositional energy. Palaeocurrent measurements in the Southern Desert indicate dispersal towards the north and northwest; a similar-trend is noted for the upper and lower units in the Safi area, but the middle gravelly unit records dispersal to the west and northwest (Selley, 1972; Powell, 1989; Amireh et al., 1994).

The heavy mineral assemblage is dominated by zircon, tourmaline, rutile (ZTR) and detrital apatite, locally with authigenic barite and authigenic apatite. This mature, stable assemblage indicates a distant granitic source area and deep weathering of the Proterozoic granitoid basement rocks (Weissbrod and Nachmias, 1986; Weissbrod and Sneh, 2002; Avigad et al., 2003, 2005; Kolodner et al., 2006; Knox et al., 2011). The overall cumulative-detrital age signal (U-Pb zircons) derived from early Cambrian sandstones equivalent to the Salib Formation across the southern Levant show a concentration of zircon dates between 500 Ma and 1,100 Ma, with smaller peaks from pre-Neoproterozoic units at about 1,800 Ma and 2,600 Ma (Kolodner et al., 2006). These trends suggest derivation of the zircons and associated siliciclastics from the erosion of distant Pan-African orogens for the older zircon suites and from predominantly near-field Neoproterozoic Arabian-Nubian Shield for the younger zircon suite. Similar studies in the Wadi Nasib area (Sinai) by Knox et al. (2011) showed that cross-plots of RZi (Rutile-Zircon index) and MZi (Monazite-Zircon index) in sandstones of the Sarabit El Khadim Formation equivalent to the Salib Formation indicate a lack of homogenisation. This suggests a short transport distance from the Arabian-Nubian Shield and a first-cycle origin (Avigad et al., 2005).

Boundaries

The base of the formation is taken at the erosional unconformity above the Neoproterozoic Aqaba or Araba complexes. This major unconformity is here named the Ram Unconformity (see Section on Unconformities). The erosional surface is generally a peneplain with local, low palaeo-relief in the Southern Desert and Safi areas, and is marked by pebbly, coarse-grained sandstone or conglomerate overlying a weathered zone (0.3–1.5) of granitoids, volcanics or lithic-arkose. The formation is also cut by rare Tertiary dykes in southern Jordan, and by Late Jurassic dykes in the Wadi Zarqa Ma'in area.

In the Safi-Wadi Numayri area adjacent to Wadi Araba (Figure 7), the unconformable base of the Salib Formation rests on the peneplaned surface of the steeply dipping late Neoproterozoic Saramuj Conglomerate Formation (Safi Group) (Powell, 1988; Jarrar et al., 1991) and locally on the Ediacaran Umm Ghaddah Formation (Amireh et al., 2008). At exposures near Jabal Samrat Qunai, the basal sandstone contains mostly pebbles of quartz derived from the granitoid Aqaba Complex, together with clasts of the Saramuj Conglomerate and Neoproterozoic dyke rocks (Powell, 1988). Farther south along Wadi Araba, the Salib Formation rests either with locally high palaeorelief on the Araba Complex (Plates 15 to 17) (Barjous, 2003), or on the ?Ediacaran to lower Cambrian alluvial-fan deposits of the Umm Ghaddah Formation (Amireh et al., 2008).

On seismic sections, the Ram Unconformity is imaged as a major erosional surface that truncates the older, fault-bounded Safi Group and/or basement rocks (Andrews, 1991). In the reference well Wadi Sirhan-3 (Figure 4), it rests unconformably on olivine basalt of probable late Neoproterozoic age.

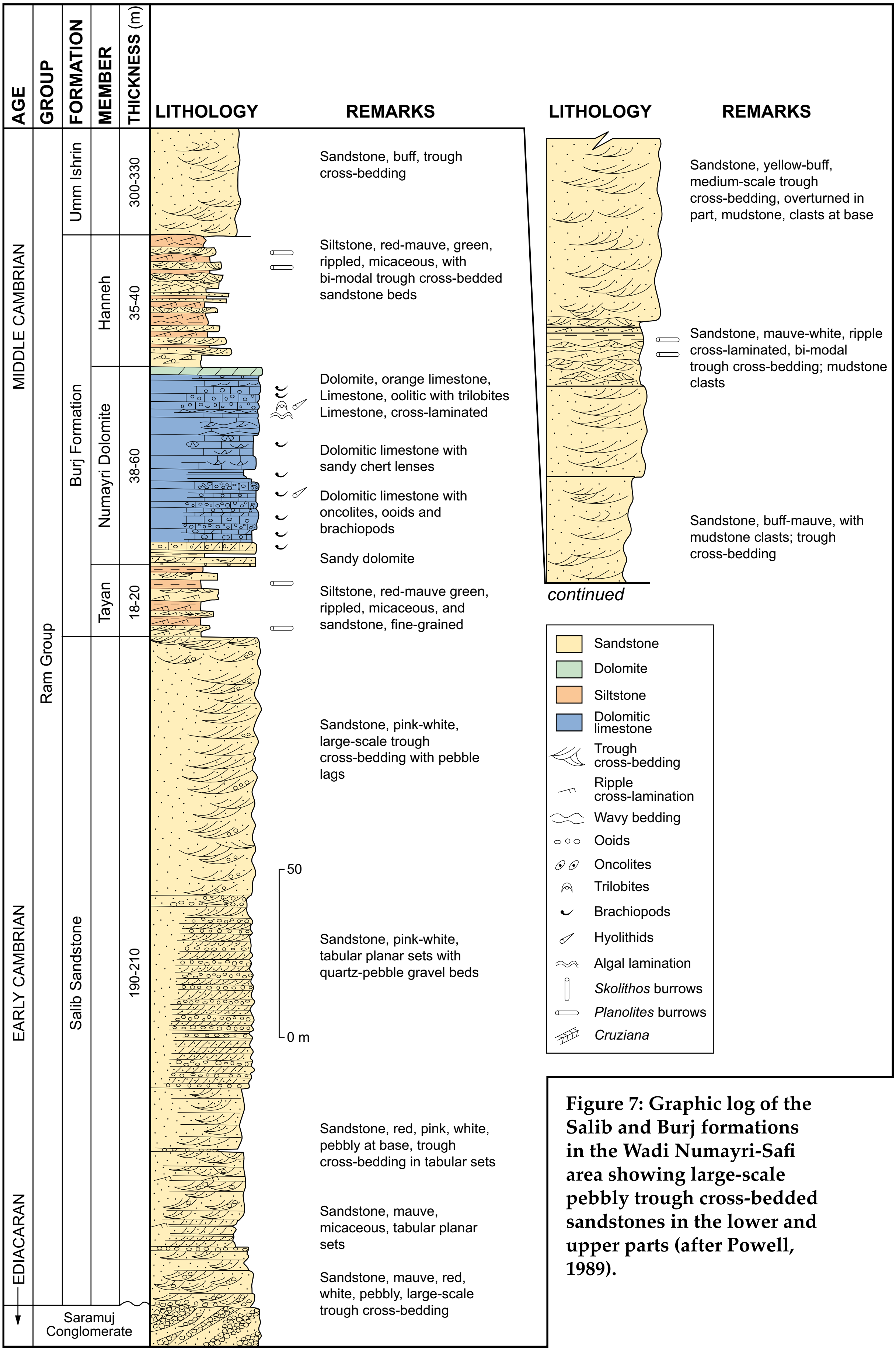


Figure 7: Graphic log of the Salib and Burj formations in the Wadi Numayri-Safi area showing large-scale pebbly trough cross-bedded sandstones in the lower and upper parts (after Powell, 1989).

The top of the formation is defined in the Southern Desert and southern Wadi Araba at the base of the Umm Ishrin Sandstone Formation, where the Burj and Abu Khusheiba formations are absent (Plates 1 to 4). Farther north along Wadi Araba, it is taken at the base of the Abu Khusheiba Sandstone Formation or at the base of the Burj Formation (Powell, 1988, 1989). In the subsurface the latter boundary is sharp and is marked by an upward increase in gamma-ray logs characteristic of the Burj mudstones, siltstones and carbonates (Figure 4); it can be traced in seismic sections in the subsurface over most of Jordan and the surrounding countries.

Thickness

The formation ranges in thickness (Table 3) from 15 to 60 m in the Southern Desert type area. Traced northwards along Wadi Araba it thickens from 80 m in the Feinan-Wadi Abu Khusheiba area to 220 m in the Safi area (Figure 2b). Boreholes indicate a general increase in thickness from 289 m in JF-1 in the south, to 531 m in NH-1 in the north, and to 750 m in Wadi Sirhan (WS-3) in the east of Jordan; an interpreted thickness of 930 m in Suweileh-1 northwest of Amman is uncertain (Andrews, 1991).

Age and Fauna

No age-indicative macrofossils have been found to date in the Salib Formation, but *Skolithos* and *Cruziana* trace-fossils assemblages are indicative of an early Palaeozoic, probably early to mid-Cambrian age (Selley, 1970; Powell, 1989; Amireh et al., 1994; Hofmann et al., 2012). The presence of early mid-Cambrian trilobites, brachiopods and hyolithids in the overlying Burj Formation (Parnes, 1971; Cooper, 1976; Rushton and Powell, 1998; Elicki and Geyer, 2013) limits the upper age. The Salib Formation onlaps against the Feinan Granite Suite and/or the Aheimir Volcanic Suite (both of the Araba Complex) in the Dana-Feinan area. These underlying igneous rocks gave Rb-Sr isochron ages of 561 ± 31 Ma (Brook et al., 1988; Ibrahim and McCourt, 1995) indicating an approximate early Cambrian age (base ca. 541 Ma; Peng et al., 2012) for the lower part of the Salib Formation. However,

Table 3: Salib Thickness.

Borehole	**Top**	**Base**	**Thickness** (m)
GTZ-3D	698.5	1,100.0	401.5
JF-1	3,336.4	3,625.6	289.2
NH-1	2,394.0	2,965.0	531.0*
SA-1	2,015.0	2,130.0	115.0
SW-1	1,398.0	2,329.0	931.0
WG-2	3,670.0	3,740.0	70.0+
WS-3	3,710.0	4,460.0	750.0
WS-10	4,032.5	4,293.0	260.5+
Outcrop			**Thickness** (m)
Southern Desert (type area)			15-60
Petra			80
Wadi Dana			65
Wadi Numayri/Safi			220
Timna area (west of Dead Sea Transform Fault)			90

Note: * Does not include 40 m of intrusive dolerite.

more recent zircon ages (Jarrar et al., 2013) indicate that these igneous rocks are considerably older (about 600–585 Ma) and are overlain unconformably by Ediacaran to early Cambrian age (?) alluvial fan deposits of the Umm Ghaddah Formation preserved locally in half-grabens (Amireh et al., 2008). These in turn are overlain unconformably by the Salib Formation in the Wadi Abu Khusheiba and Safi areas adjacent to Wadi Araba. Consequently, there is probably a considerable time gap between the Araba Complex rocks and the base of the Salib Formation.

Trace fossils in the Southern Desert consist of *Skolithos* burrows about 3 to 5 mm in diameter and up to 300 mm long that penetrate cross-bedded medium-grained sandstone; burrows commonly disappear laterally when traced along individual beds. Surface traces on fine-grained laminated sandstones consist of sinuous circular, horizontal burrows about 2 to 3 mm in diameter. In the Wadi Museimir area, about 65 m above the base of the unit *Skolithos* burrows are up to 75 cm in length and are associated with small *Cruziana* sp. traces that include *Cruziana aegyptica* (Seilacher) (Powell, 1989; Seilacher, 1990; Amireh et al., 1994).

Environment of Deposition

Lithological characteristics such as the immature lithology (mostly conglomeratic and pebbly trough cross-bedded sandstone), a unimodal palaeocurrent flow to the north and north-northeast in the Southern Desert (Ram area) to north-northwest in the Dana-Safi area (Wadi Araba), and the absence of shelly macrofossils, suggest that the formation was deposited in a predominantly braided-stream alluvial environment (Selley, 1970, 1972; Powell, 1988, 1989; Amireh et al., 1994). Less common proximal alluvial fans lithofacies are preserved adjacent to areas of basement palaeorelief, and the alluvial braid-plain lithofacies pass basinwards (northwards) into siliciclastic tidal flats (Figure 3). Tabular, erosive trough cross-bedded sets suggest high-energy, high-discharge rivers with medium- to large-scale sub-aqueous dunes and longitudinal bars. Overturned cross-bedding, locally with de-watered convolute bedding indicates slumping of sub-aqueous dune foresets during phases of high-flow regime. Depressions below the Ram Unconformity were locally filled by granite-rich conglomerates deposited by traction currents (Plates 6 and 7). Stacked, tabular sets of pebble conglomerate fining upwards to medium-grained sandstone with graded foresets indicate fluctuating high-discharge river flood to waning-flow conditions.

The stable ZTR heavy mineral assemblage (Weissbrod and Nachmias, 1986; Avigad et al., 2003; Kolodner et al., 2006; Knox et al., 2011) with rounded detrital apatite suggests a distant source area and intensive weathering during transport. Although the basal sandstones contain sub-angular granitoid conglomeratic layers (Plate 7), the wide extent of the underlying basement peneplain and paucity of local granitoid bedrock types in these basal beds suggests that the peneplain was largely formed during the phase of erosion and sedimentation that produced the Ediacaran Saramuj Conglomerate. The latter, in contrast, is rich in Aqaba Complex well-rounded granitoid pebbles as well as volcanic rocks that are more abundant in the small pebble/granule fraction. The latter fraction may have been sourced from basement volcanic rocks not currently exposed in the Wadi Araba outcrops, or perhaps from distant outcrops in the Arabian-Nubian Shield (Jarrar et al., in preparation/press). This implies that the granitoids immediately below the Ram peneplain did not contribute greatly to the immediately overlying siliciclastics and, furthermore, that the Salib pebbly sands, which contain abundant rounded to well-rounded quartz pebbles were mostly derived from a distant provenance of the Arabian-Nubian Shield located to the south of the Aqaba complex outcrops.

Large channels, up to 4 m deep, infilled with large-scale pebbly trough cross-bedded sandstones in the lower and upper parts of the sequence in the Safi area (Wadi Museimir) (Figure 8), indicate, in this area, the migration of bar-forms in large river systems. In contrast to the Southern Desert area, the Salib Formation in the Safi area contains angular and sub-angular fragments of locally derived Arab Complex rhyolite (Figure 8). The middle planar-cross-bedded, gravelly unit of the sequence indicates a change of environment and this is supported by a more northwesterly palaeocurrent flow. Well-rounded, well-sorted quartz gravel is intercalated with planar cross-bedded sandstone in tabular sets that are interpreted as the product of high-velocity sheet floods deposited in proximal areas of the Arabian-Nubian granitoid basement, located to the east or southeast that was undergoing renewed

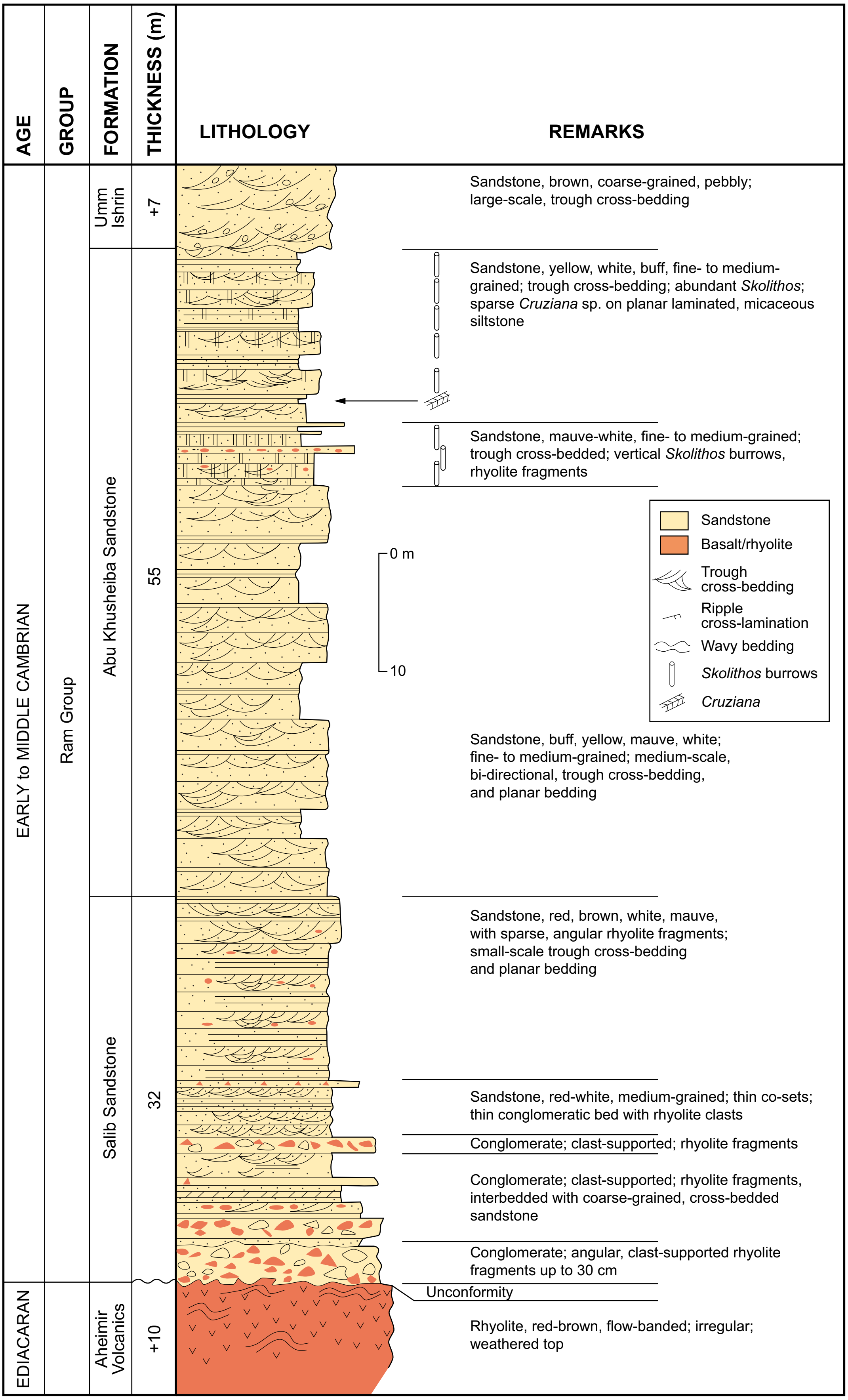


Figure 8: Graphic log of the lithological section at Wadi Museimir (after Powell, 1989).

uplift. Subsidence rates were much greater in the Safi area than in either the Southern Desert area or on the Feinan-Wadi Abu Khusheiba palaeohigh.

Furthermore, the exceptional thickness (about 931 m) of the formation in the Suweileh-1 (SW-1) borehole northwest of Amman and to the southeast in Saudi Arabia where the coeval Siq Sandstone is about 1,000 m thick (Al-Husseini, 2011), shows that alluvial sedimentation kept pace with rapid basin subsidence until the widespread marine Burj transgression in the early mid-Cambrian at about 509 Ma. Since the carbonate ramp lithofacies (maximum flooding surface) of this transgression did not advance far south of the Feinan-Dana block, it suggests that this area acted as a hinge line between the more stable cratonic area to the south and the more rapidly subsiding Palaeo-Tethys foreland basin to the north. This pattern of sedimentation is supported by the broadly WNW-trending lithofacies and thickness trends in Jordan (Figure 5) (Andrews, 1991).

Brief marine incursions across the low-gradient alluvial plain are indicated by the trace-fossil horizons near the top of the Salib Formation in Wadi Museimir, and locally in the Southern Desert (Powell, 1989; Amireh et al., 1994). Although the fully marine Burj Formation is absent at these localities, the southwards advance of marginal marine facies is clearly indicated. Local, laterally intermittent preservation of the *Skolithos* and *Cruziana* trace-fossil assemblages in the Southern Desert (Quweira area) suggest that the sea encroached across broad, low-gradient embayments during late Salib to early Burj time. Small, shallow-water lakes or marginal coastal lagoons with indeterminate surface burrows (c.f. *Planolites*) are indicated by rare, laterally intermittent laminated mudstone/siltstone beds containing 'ball and pillow' structures that penetrate from the overlying sandstone beds in the Qa Salib type area.

BURJ FORMATION

Type and Reference Sections

The type section in the Safi area is Khirbet El Burj, Locality 1 of Blanckenhorn (1912; 'Chirbet el-Burdich' in Richter and Richter, 1941). The full sequence is not well exposed at this locality so reference sections are proposed in the same area (Figure 1; Rushton and Powell, 1998) in Wadi Saramuj [Palestine National Grid 198:047] (Powell, 1988, 1989; Rushton and Powell, 1998) and east of Safi Potash Works [PNG 201:055] (Figure 7). The Wadi Zarqa Ma'in section (Figure 9) provides a useful reference section for the north-central area, but this outcrop may be stratigraphically slightly younger than the type area (Rushton and Powell, 1998; Elicki and Geyer, 2013) (see Section Age and Fauna, below).

Subsurface Reference Sections

The Burj Formation was proven in a number of boreholes in central and south Jordan (Andrews, 1991). The most representative boreholes (Figure 5) are Wadi Sirham-3 (WS-3), Wadi Sirhan-10 (WS-10), Al Jafr-1 (JF-1) in the south and southeast Jordan, GTZ-3D and

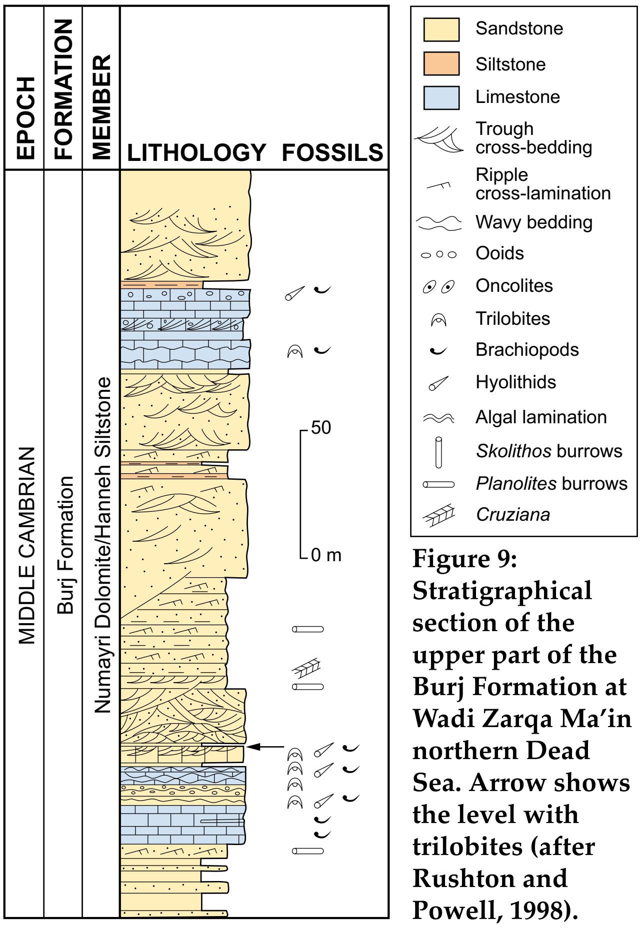
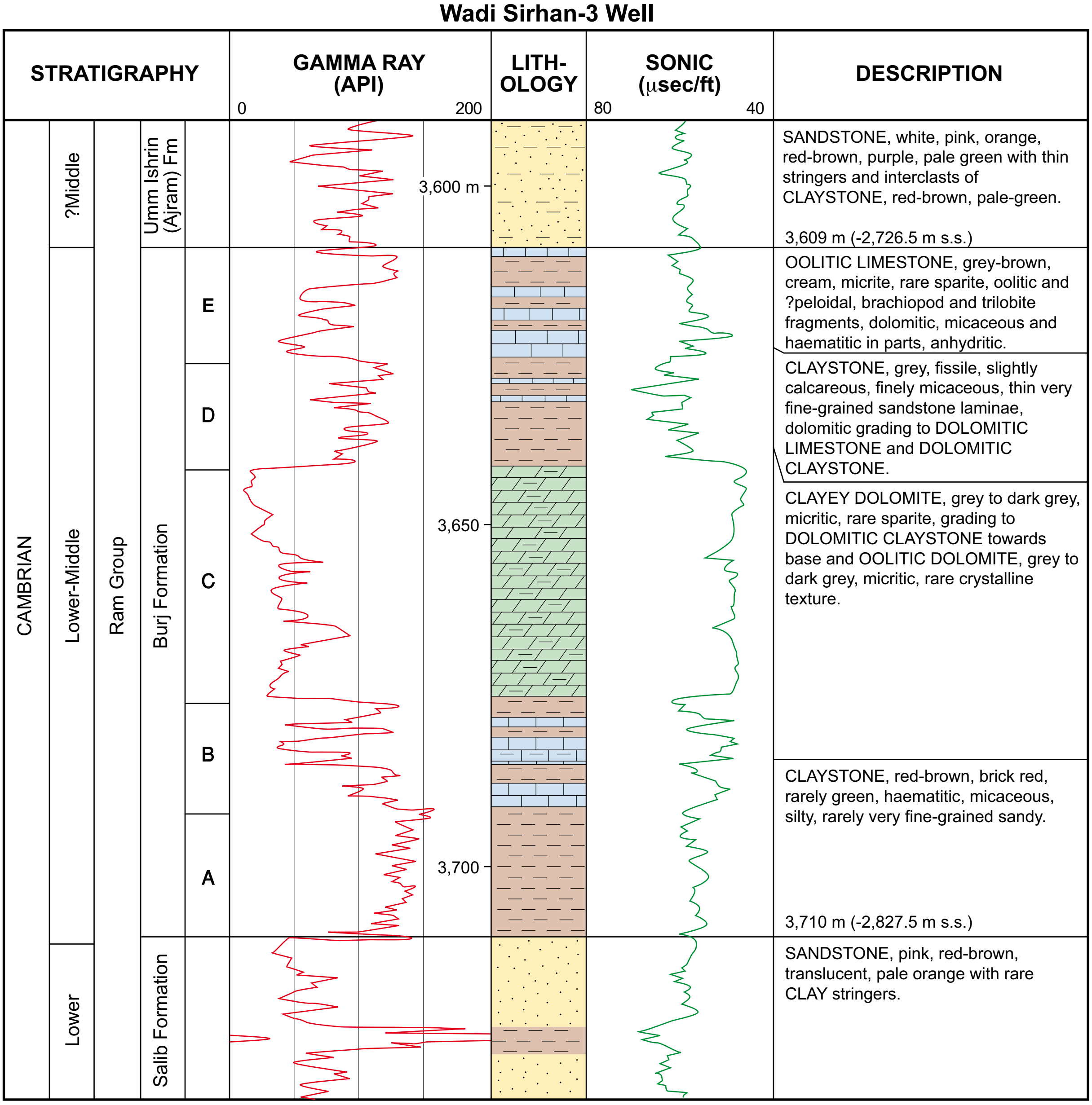


Figure 9: Stratigraphical section of the upper part of the Burj Formation at Wadi Zarqa Ma'in northern Dead Sea. Arrow shows the level with trilobites (after Rushton and Powell, 1998).


Wadi Sirhan-3 Well

SANDSTONE, white, pink, orange, red-brown, purple, pale green with thin stringers and interclasts of CLAYSTONE, red-brown, pale-green.

3,609 m (-2,726.5 m s.s.)

OOLITIC LIMESTONE, grey-brown, cream, micrite, rare sparite, oolitic and ?peloidal, brachiopod and trilobite fragments, dolomitic, micaceous and haematitic in parts, anhydritic.

CLAYSTONE, grey, fissile, slightly calcareous, finely micaceous, thin very fine-grained sandstone laminae, dolomitic grading to DOLOMITIC LIMESTONE and DOLOMITIC CLAYSTONE.

CLAYEY DOLOMITE, grey to dark grey, micritic, rare sparite, grading to DOLOMITIC CLAYSTONE towards base and OOLITIC DOLOMITE, grey to dark grey, micritic, rare crystalline texture.

CLAYSTONE, red-brown, brick red, rarely green, haematitic, micaceous, silty, rarely very fine-grained sandy.

3,710 m (-2,827.5 m s.s.)

SANDSTONE, pink, red-brown, translucent, pale orange with rare CLAY stringers.

Figure 10: Reference section of the Burj Formation in Wadi Sirhan-3 well (after Andrews, 1991, reproduced by the permission of the Natural Resources Authority, Jordan).

Wadi Ghadaf-2 (WG-2) in central Jordan and North Highlands-1 (NH-1) in north Jordan. The most representative well is Wadi Sirhan-3 (Figure 10). In this well, Andrews (1991) divided the formation into five informal units (A–E) from 3,710 m to 3,614 m depth, but these are considered here to represent the three formal members at outcrop, so that A = Tayan Member; B and C = Numayri Dolomite Member; and D, E = Hanneh Siltstone Member.

Distribution

At outcrop the formation forms a prominent cliff between the Salib and Umm Ishrin formations in areas adjacent to the Dead Sea Rift, southward from Wadi Isal (Edh Dhira) to the Feinan-Dana area (Figure 2). It also crops out a few kilometres north of Wadi Zarqa Ma'in where only the uppermost part of the carbonate sequence is exposed (Figure 9). Between the Feinan-Dana area and Wadi Quseib the formation is represented by coeval marine siliciclastics in the Abu Khusheiba Formation (Bender, 1974; Powell, 1989; Amireh et al., 1994) but is absent south of the latter locality and in the Southern Desert where the Umm Ishrin Sandstone directly overlies the Salib Formation (Figure 2; Plates 1 to 4). The formation has been penetrated in deep boreholes northwest of Amman (Suweileh-1), in the southern Wadi Sirhan, and 250 km north of Amman in the Khanaser-1 Well in northern Syria (Best et al., 1993).

Hydrocarbon exploration wells and seismic reflection profiles (Andrews, 1991) have shown that the Burj Formation is present throughout most of Jordan and that it extends north and east into neighbouring countries (Saudi Arabia and Syria) and also into Iran. Only in the extreme southwest of Jordan is it absent where it passes laterally to coeval marginal marine and alluvial siliciclastics that overlie granitoid basement rocks (Ibrahim and McCourt, 1995). Coeval beds (Timna Formation) outcrop at Timna, near Eilat (Weissbrod, 1970; Parnes, 1971); these beds are offset from the Burj Formation outcrops by about 110 km left-lateral movement on the Dead Sea Transform (Freund et al., 1970). The four formations of the review by Parnes (1971) are here considered to be members of the Timna Formation. Coeval marginal marine siliciclastics present south of the Dana area are defined as the Abu Khusheiba (Sandstone) Formation (see below).

Authors and Nomenclature

The formation was defined by Quennell (1951) as the ‘Burj Series’, a name not accepted by the International Commission of Stratigraphic Nomenclature. The name is taken from the ruins of El Burj (Arabic for ‘the tower’) in the lower course of Wadi Hisa (also ‘Hasa’). The dolomite-limestone unit (‘Wadi Nasb Limestone’) was first recorded by Hull (1886) in this area, and Blanckenhorn (1914) described a more complete succession consisting of 30 m of red and green micaceous shales and ‘marls’ (‘Hasa Shales’ of Wetzel and Morton, 1959) overlain by 30 m of limestone and dolomite. This definition was followed by Burdon (1959) who, with Quennell (1951), assigned to it group status. Bender (1974) termed it the ‘dolomite-limestone-shale formation’ and followed the definition of Blanckenhorn (1914). However, in lithological sections and maps, Bender (1968) included about 30 m of overlying shales and sandstone (the “cb 2+1” map unit of Bender) within the same formation. The latter definition is adopted here following Powell (1988, 1989) at outcrop; namely, from the base upward, about 20 m of siltstone and fine-grained sandstone (Tayan Siltstone), 30 to 60 m of limestone and dolomite (Numayri Dolomite) and about 30 m of siltstone and fine-grained sandstone (Hanneh Siltstone). The formation is equivalent to the Timna Formation on the west side of Wadi Araba, near Eilat (Weissbrod, 1970). In the subsurface, Andrews (1991) defined the Burj Formation on gamma-ray and sonic wireline logs signature and limited core data (Figure 10).

Lithology and Bedforms

The Burj Formation, at outcrop, consists of two siliciclastic members (Tayan and Hanneh) separated by a carbonate member (Numayri) (Figures 7 to 9). These members can also be broadly recognised in the subsurface (Figure 9). The siliciclastic members are composed of red-brown, mauve, green and buff micaceous siltstone and sandstone with ripple cross-lamination, ripple marks and sparse burrows; thin beds of buff-brown sandstone with bimodal trough cross-bedding are also present (Plates 18 and 19). Diverse ichnofossils (see below) are present (Powell, 1989; Amireh et al., 1994; Hofmann et al., 2012). The carbonates are yellow-brown or grey, dolomitic limestone, dolomite and sandy dolomite with chert sandstone lenses; cross-lamination is common in the siliciclastic lenses; oncolites, ooids, peloids and bioclasts are present in the purer carbonates (Plate 20). The limestones and dolostones consist of packstones, grainstones and floatstones-rudstones with shelly bioclasts such as brachiopods, trilobites, echinoids and hyolithids; ooids and pisoliths are common in some beds, together with *Girvanella*-coated oncoids. Near Safi, the upper part of the carbonate unit contains algal stromatolites and thin beds of siltstone with shelly fossils and glauconite peloids. Microfacies and diagenesis of the carbonates were described by Shinaq and Bandel (1992). Siliciclastic beds above the carbonate member show mega-ripples (Plate 18) and bimodal cross-bedding, including tidal bundles (Plate 19). The lithology of the three members is described below and summarised in Figures 8 to 10.

Plate 18: **Burj Formation, Wadi Zarqa Ma'in (see also, lower part of Figure 9). Thin-bedded limestone and calcareous siltstone (Numayri Member) overlain by bi-directional tidal sandstone (Hanneh Member); dashed line marks boundary. Note tidal bundles in Hanneh Member. Hammer (top left) length 0.33 m. Photo by J.H. Powell.**

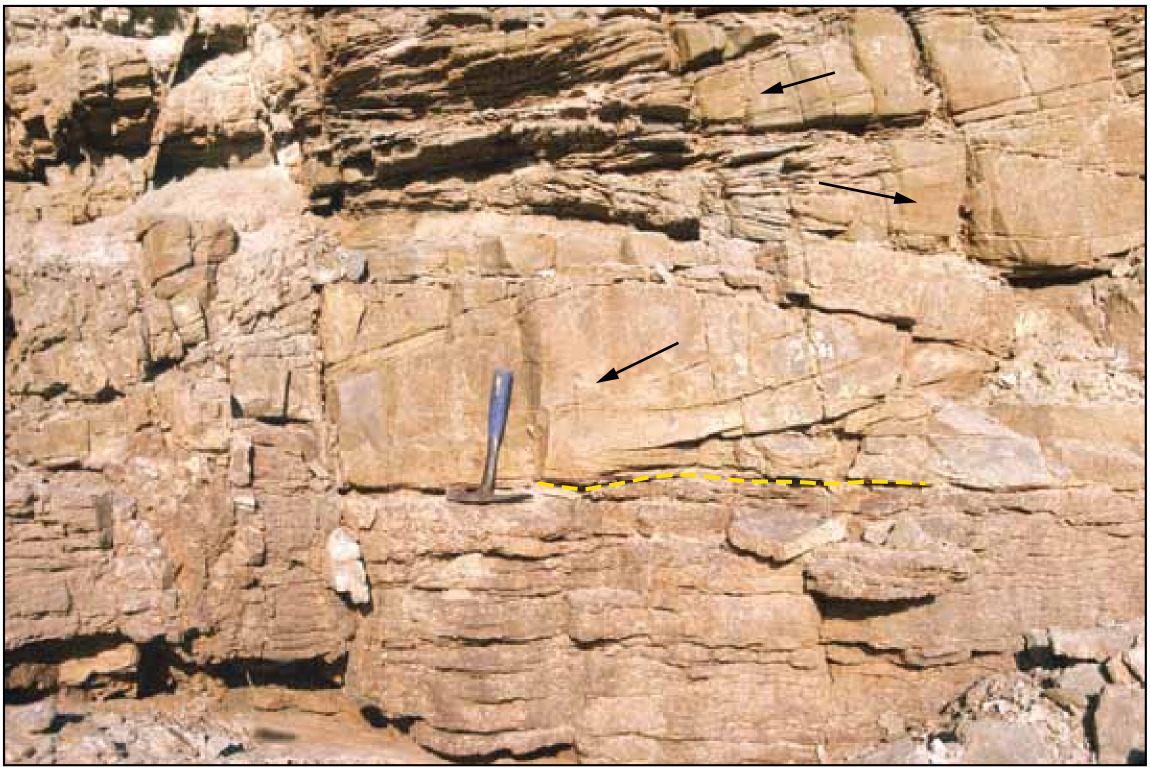


Plate 19: Burj Formation (Numayri Member); grainstone with abundant shell fragments including trilobites, brachiopods and hyolithids overlain by fine- to medium-grained sandstone with bi-directional dune form sets (tidal bundles, black arrows); hammer head and dashed line marks the boundary. Wadi Zarq'a Main, road section. Hammer length 0.30 m. Photo by J.H. Powell.

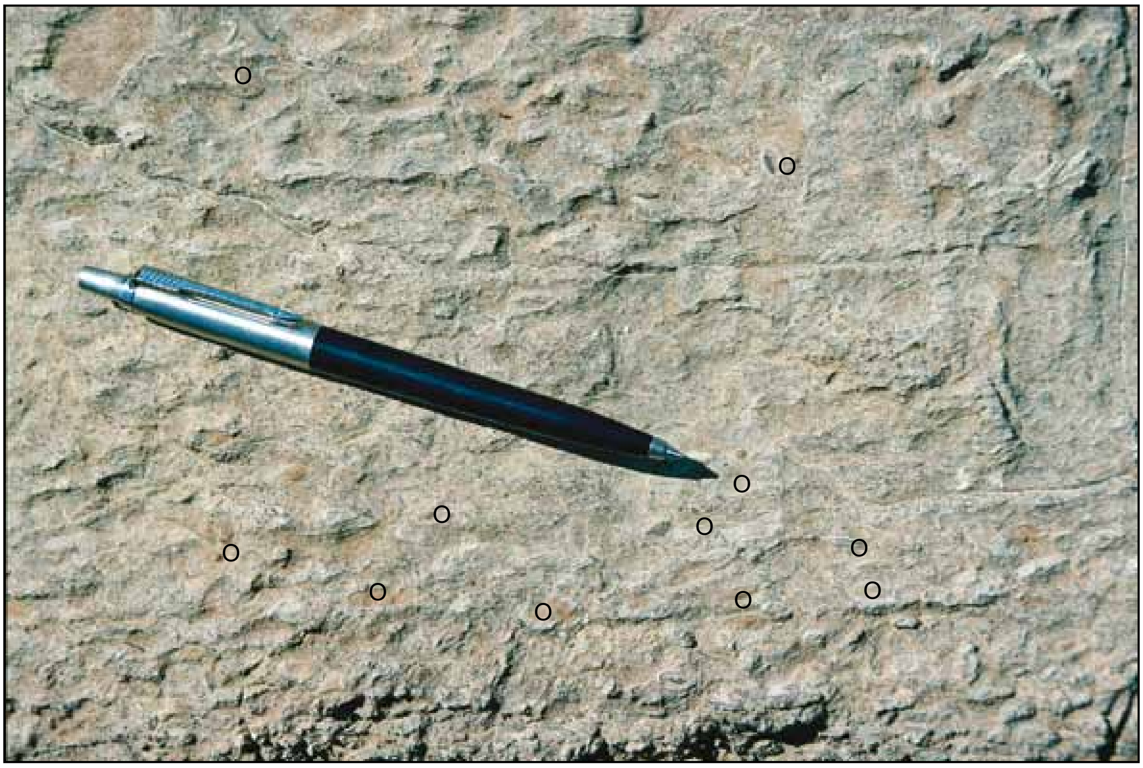


Plate 20: Burj Formation (Numayri Member); packstone with abundant shell fragments including trilobites, brachiopods, hyolithids and ovoid *Girvanella* oncolites, indicated (O). Pen length 135 mm. Wadi Al Hisa, Safi. Photo by J.H. Powell.

Boundaries

The lower boundary, at outcrop, is defined at the base of mauve-red, micaceous siltstone and fine-grained sandstone that overlies yellow-brown medium-grained, trough cross-bedded sandstone of the Salib Sandstone Formation (Figure 7). The top is clearly marked by the overlying buff and red-brown, medium- to coarse-grained sandstone with large-scale trough cross-bedding of the Umm Ishrin Formation (Figures 7 and 11; Plate 21) (Powell, 1988, 1989).

In the subsurface, the lower boundary is taken at the sharp gamma-ray inflection at the base of the claystone of the Tayan Member (3,710 m depth in WS-3; (Figure 4); the top is taken at the gamma-ray inflection at the base of claystone overlying interbedded claystones and thin limestones of the Hanneh Member (top of unit E of Andrews, 1991) at 3,609 m depth (Figure 10).

In reviews of the Neoproterozoic–Cambrian chronostratigraphy of the Arabian Platform, Al-Husseini (2010, 2014) defined the top of the Asfar Sequence (continental, quartz-rich arkosic sandstone and siltstone) the top of which is marked by the base of the Burj Formation; the top of the overlying Burj Sequence was taken at the base of the Umm Ishrin Sandstone Formation in Jordan (Figure 11; Plate 21), and at the base of the correlative Saq Sandstone in Saudi Arabia.

Thickness

The formation ranges in thickness (Table 4 and Figure 5) from zero in the Southern Desert of Jordan to 120 m in the Safi area, and to 124 m and 135 m in boreholes Suweileh-1 and Safra-1, near Amman (Bender, 1974). In the Zarqa Ma'in area near the Dead Sea (wells GTZ-2D; GTZ-3D) the Burj Formation is 120.5 m thick and consists of several carbonate units intercalated with marine siliciclastics; similar lithofacies were reported from deep boreholes in the southern Wadi Sirhan area (WS-3; WS-10) where the formation is 96.0 and 113.5 m thick, respectively (Andrews, 1991). It thickens toward the north

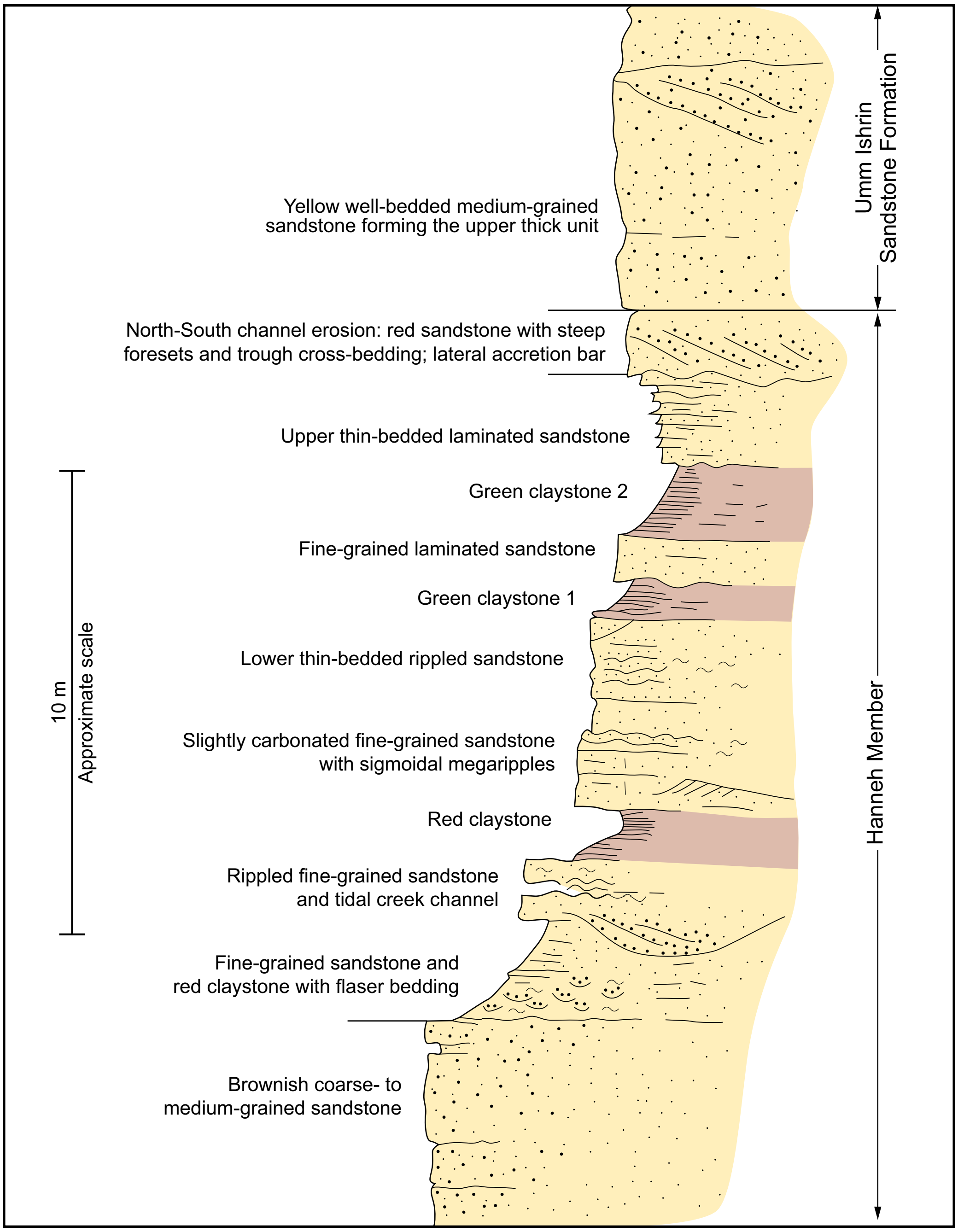


Figure 11: Lithostratigraphical and sedimentological section of the Hanneh Member (Burj Formation) and the overlying Umm Ishrin Formation, near Wadi Issal, Dead Sea (31°10.387′N; 35°32.262′E, at 340 m below sea level). The Hanneh Member represents the Regressive Systems Tract (RST) of the Burj Sequence. See also Plate 21.

and northeast (Figure 5) and, although not penetrated in cored boreholes in the Risha area close to the Iraq border, the seismic response suggests that it is more than 135 m thick hereabouts (Andrews, 1991). Indeed, to the north in Syria, about 250 m were proved in the Khanaser-1 Well (Best et al., 1993).

Subdivisions

The Burj Formation is formally subdivided into three members, from base to top, the Tayan Siltstone, Numayri Dolomite and Hanneh Siltstone (Powell, 1988, 1989). These are described in more detail as follows.

Plate 21: Umm Ishrin Sandstone overlying the red and green claystone/siltstone/fine-grained sandstone of the uppermost unit (Hanneh Member) of the Burj Formation. Safi area, Dead Sea Basin. Photo by Y.-M. Le Nindre.

Tayan Siltstone Member

The member ranges in thickness from 18 to 20 m, and consists of finely laminated green, mauve and red or buff, micaceous, fine-grained sandstone and siltstone. The name is taken from Wadi Tayan (PNG 201.5:061.5) and Jabal Tayan where the member is well exposed. Straight-crested, oscillation (wave) ripples, ripple cross-lamination, and parallel lamination are common. The thicker sandstone beds have small-scale, bimodal trough cross-bedding with mudstone intraclasts. Thin dolomite lenses are present near the middle of the member and surface burrows including *Cruziana* and *Rusophycus* are common on some bedding planes. The lower boundary is defined by the base of the formation. The upper junction with the Numayri Dolomite is taken at the base of the first thick bed of limestone or dolomitic limestone (Figure 7).

Numayri Dolomite Member

The member forms a prominent, brown-weathering cliff. The name derives from Wadi Numayri (PNG 203:059) where it is well exposed and ranges in thickness from 38 to 60 m. The carbonate varies from limestone to dolomitic limestone and dolomite with wackestone and packstone textures; clasts include ooliths and bioclasts (brachiopods, hyolithids and trilobites). The vertical sequence of microfacies varies throughout the outcrop, but the following generalised sequence is common to most exposures in the Safi-Wadi Numayri areas.

The basal carbonate unit (5 m thick) has a high proportion of fine-grained quartz sand with ripple cross-lamination, low-angle scours, and sandstone intraclasts. This unit passes up into a massive, grey (brown-weathering) dolomite and dolomitic limestone (microcrystalline, wackestone and

Table 4: Burj and Abu Khusheiba thickness.

Borehole	**Top**	**Base**	**Thickness** (m)
GTZ-2D	999.5	1,120.0	120.5
GTZ-3D	579.5	698.5	119.0
JF-1	3,275.4	3,336.4	61.0**
NH-1	2,193.5	2,394.0	122.5*
SA-1	1,880.0	2,015.0	135.0
SW-1	1,274.0	1,398.0	124.0
WG-2	3,551.5	3,670.0	118.5
WS-3	3,614.0	3,710.0	96.0
WS-10	3,919.0	4,032.5	113.5
Outcrop			**Thickness** (m)
Safi			120
Wadi Zarqa Ma'in		Lower part not exposed	82

Notes: ** This figure (Andrews, 1991) includes lithofacies attributed here,in part, to the Abu Khusheiba Formation siliciclastics. *Does not include 78 m of intrusive dolerite.

packstone textures), 20 to 30 m thick, with glauconite peloids, cross-laminated and parallel-laminated oolites, and oncolites (algal-coated grains); lenses of disarticulated brachiopods and rare trilobite fragments are also present. Irregular lenses of orange-brown dolomite are intercalated with the clast-rich carbonates. There is an increase in quartz sand above, with alternating sand-rich and sand-poor lenses; the sand-rich lenses are cross laminated, with shallow scours and they weather as prominent dark brown chert-like bands, 2 to 3 m thick. Beds of oolitic, oncolitic or brachiopod shell-rich dolomicrite limestone are locally present at the top of the member in the south.

Near Safi (Figure 7), the member is thicker (58 m) and the upper part includes beds of cross-laminated oolitic limestone, algal stromatolites, and thin (40 cm thick) beds of green calcareous siltstone with abundant trilobite fragments, hyolithids and glauconite peloids. Here, the sequence is capped by a distinctive orange-weathering dolomite. The textures and fine details of the carbonates are often obscured at outcrop by ubiquitous brown staining. The contact with the green, red or grey micaceous siltstone or fine-grained sandstone of the overlying Hanneh Siltstone Member is sharp.

An outcrop about 1 km north of Wadi Zarqa Ma'in exposes only the topmost part of the carbonate sequence (Figure 9; Plate 18). Grey finely laminated, fine-grained quartz-arenite with burrows and ripple cross-lamination (3 m thick) is overlain by intercalated green-grey cross-laminated siltstone, fine-grained sandstone and shelly grainstone, passing up to oolitic packstone and cross-bedded trilobite-bearing grainstone (4 m). This is overlain with an erosive base by marine siliciclastics with bimodal cross-bedding, trilobite traces and *Harlania* burrows (24.5 m). A second carbonate unit (3 m) consisting of trilobite-, brachiopod- and hyolithid-bearing grainstone, oolitic and cross-bedded in part, follows and is overlain by about 50 m of marine siliciclastics equivalent to the Hanneh Siltstone Member of the Safi area.

Hanneh Siltstone Member

The name is taken from Jabal Tabaq Hanneh (PNG 201.5:060.0), on the north side of Wadi Numayri. The lithology of this member is similar to the Tayan Siltstone, but there is a higher proportion of silt-grade siliciclastics over sand in the type area, although this unit is sand-dominated in the Wadi Zarqa Ma'in outcrop. Colours are red, green and buff-brown, and the unit is readily distinguished in the field and on aerial photographs. It was not previously included in the Burj Formation, except on maps and lithological sections in Bender (1968).

It is 30 m thick in the Wadi Saramuj area and 35 m thick in the cliffs below Jabal Tayan. The base is sharp (Plate 18), and is taken where red-grey, or green parallel-laminated to ripple cross-laminated micaceous siltstone overlies the Numayri Dolomite Member. The overlying beds are laterally variable, but consist predominantly of thinly bedded green or red-green micaceous ripple cross-laminated siltstone and micaceous fine-grained sandstone, with thicker beds (0.5 m) of buff, medium-grained, bimodal trough cross-bedded sandstone; mudstone and dolomite clasts are common at some horizons. Small, circular surface burrows and *Rusophycus* (?) traces are present on siltstone surfaces. The top (Figure 11; Plate 21) is clearly marked by the overlying red-brown, massive, medium- to coarse-grained large-scale trough cross-bedded sandstone of the Umm Ishrin Formation. This boundary is easily traced in the field and on aerial photographs.

At Wadi Zarqa Ma'in on the Dead Sea, the member is 51 m thick and is composed of units of fine- to medium-grained bimodal trough cross-bedded sandstone with small dune forms intercalated with parallel-laminated, ripple cross-laminated green to mauve micaceous siltstone and fine-grained sandstone with oscillation and interference ripples. The ichnofauna consists of burrows and trilobite grazing and resting traces in the fine-grained siliciclastics; examples are, *Rusophycus, Cruziana, Diplichnites, Harlania, Monocraterion* and *Planolites*.

Age and Fauna

Inarticulate and articulate brachiopods and trilobites were first identified from the Burj Formation by Blanckenhorn (1912, 1914) who assigned a Cambrian age. His specimens and other collections have been re-evaluated by various authors (Dienemann, 1915; King, 1923; Richter and Richter, 1941; Picard, 1942; Parnes, 1971; Cooper, 1976). Various ages have been assigned to the fossil assemblage, ranging from early to mid-Cambrian. In a re-study of material from the east side of the Dead Sea, and from Timna near the Gulf of Aqaba, Cooper (1976) suggested a late early Cambrian (Caerfai) age. In addition to species identified by previous authors, Rushton (1988) and Rushton and Powell (1998) collected new material and reviewed the trilobite faunas from the Safi and Wadi Zarqa Ma'in areas. They suggested that the Zarqa Ma'in outcrop is stratigraphically slightly younger than the Safi/ Numayri outcrop and gave a tentative age of earliest mid-Cambrian, rather than the early Cambrian of earlier workers.

A more recent and comprehensive review of the trilobite faunas and their stratigraphical significance by Elicki and Geyer (2013), established new genera and species (see below) from the Safi and Wadi Zarqa Ma'in areas and other localities nearby. They regarded the *Kingaspis campbelli* faunule at Wadi Zarqa Ma'in to be an ecostratigraphic horizon, reflecting different depositional conditions from the *Redlichops* faunule in the Safi outcrops at the southern end of the Dead Sea, and, therefore, not necessarily indicative of a slightly younger age. However, they tentatively correlated *Kingaspis campbelli* and *Redlichops* faunules of the Burj Formation within the *Morocconus* Zone of the Anti-Atlas (Morocco), possibly with the upper part of the latter, and with the *Paradoxides (A.) mureroensis* Zone of Iberia. This correlation is, overall, slightly younger than the correlation with the *Hupeolenus* Zone of Morocco proposed by Rushton and Powell (1998). In relation to the recent international geologic time scale (Peng et al., 2012), the biostratigraphical age proposed by Elicki and Geyer (2013) equates approximately to the base of Cambrian Series 3 and Stage 5 (Gradstein et al., 2012). This boundary has an approximate geochronological age of 509 Ma. A mid-Cambrian marine flooding surface (Cm20) has been traced throughout the Arabian Platform to which a geochronological age of 505 Ma has been attributed (Sharland et al., 2001, 2004; Simmons et al., 2007); this might be equivalent to the top of the Burj carbonate (Numayri Member) maximum marine flooding surface identified here, although the precise geochronological ages are not well defined.

The most important age-diagnostic fauna are listed below:

Trilobites: (from Rushton and Powell, 1998; Elicki and Geyer, 2013 and references therein): *Redlichops blanckenhorni* Richter & Richter 1941; *Kingaspis campbelli* (King 1923); *Kingaspidoides* cf. *obliquoculatus* Geyer, 1990; *Onaraspis palmeri* (Parnes, 1971); *Realapsis* sp. nov.; and *Timnaella? orientalis* (Picard, 1942); *Issalia scutalis* Elicki and Geyer 2013; *Tayanaspis bulbosus* Elicki and Geyer 2013; *Palaeolenus antiquus*

(Chernysheva, 1956); *Hesa problematica* Richter and Richter 1941; *Uhayamiria glabra* Elicki and Geyer 2013; *Cambrunicornia? jafnaensis* Elicki and Geyer 2013; *Myopsolenites hyperion* Elicki and Geyer 2013; *Myopsolenites palmeri* (Parnes,1971); *Enixus* cf. *antiquus* (Chernsheva, 1956).

Brachiopods: *Trematobolus palaestinensis* (Richter & Richter, 1941); *Trematosia radifer* (Richter & Richter, 1941); *Psiloria alata* (King, 1923); *Psiloria dayi* Cooper, 1976.

Hyolithids: *Hyolithes kingi* Richter and Richter, 1941.

In addition, the calcareous algae *Girvanella* sp. has been identified in thin sections of the oncolite lithofacies; benthic microfauna includes sponge (poriferid) and octocoral spicules, echinoderm fragments and bradoriid arthropods (Elicki, 2011).

A diverse ichnofauna has been identified, mostly from the siliciclastics in the Tayan and Hanneh members (Powell, 1989; Amireh et al., 1994; Rushton and Powell, 1998; Mángano et al., 2007; Shinaq and Elicki, 2007; Hofmann et al., 2012). Present are circular, horizontal to sub-vertical burrows (*Planolites; Skolithos*), arthropod resting traces *(Rusophycus*), arthropod grazing traces (*Cruziana* including *Cruziana aegyptica* Seilacher, 1990), as well as *Diplichnites, Tigilites, Harlania, Diplocraterion, Scolecia* and *Monocraterion*. Indeterminate small spar-filled tube fossils (?burrows) are present in the purer carbonate facies.

Depositional Environment and Sequence Stratigraphy

Early workers recognised the marine nature of the formation by the presence of brachiopods, trilobites and hyolithids, in the carbonates. This interpretation is supported by the presence of a rich and diverse marine ichnofauna in the siliciclastics, and oncolites of the blue-green alga *Girvanella* sp. in the carbonates. The Burj Formation succession shows a clear pattern of marine transgressive and regressive sequences indicated by the fauna, sedimentary structures and lithofacies distribution (van Wagoner et al., 1988; Galloway, 1989; Catuneanu et al., 2009).

The Tayan Siltstone Member represents a transgressive systems tract (TST) overlying prograding, trough cross-bedded fluvial sandstones of the Salib Formation (Figures 2 and 7). Wave ripples, straight-crested oscillation ripples, small-scale bi-directional cross-bedding, sigmoidal megaripples (tidal bundles) (Plate 19), intra-clasts, *Cruziana* assemblage traces and *Planolites* burrows and thin dolomite laminae in the Tayan Siltstone indicate a southward marine incursion over a low-lying alluvial plain, and deposition in a shallow subtidal to intertidal environment (Powell, 1988, 1989; Amireh et al., 1994; Rushton and Powell, 1998; Mángano et al., 2007; Shinaq and Elicki, 2007; Hofmann et al., 2012).

The succeeding carbonates of the Numayri Dolomite Member marks part of the continued transgressive systems tract with the maximum marine flooding surface (MFS) taken at the top of the thick carbonate unit. Traced southwards towards the alluvial plain, this surface is probably a correlative conformity between the fluvial Salib and Umm Ishrin formations in the Southern Desert (where the Burj Sequence is absent). Algal oncolites, ooids, disarticulated brachiopod shell-lenses, low-angle cross-bedding with shallow scours in the purer carbonates, and ripple cross-lamination in the siliciclastic-rich carbonates indicate deposition in a warm, shallow carbonate-lagoon with periodic storm-events redistributing ooids, bioclasts and quartz-sand (Figures 2 and 7) (Powell, 1988, 1989; Amireh et al., 1994; Rushton and Powell, 1998; Mángano et al., 2007; Shinaq and Elicki, 2007; Hofmann et al., 2012). Domal, laterally-linked stromatolites indicate intertidal conditions near the top of the unit. The carbonates range from limestone to dolomitic limestone and dolomite with wackestone, packstone and grainstone textures (Plates 19 and 20) (Powell, 1989; Shinaq and Bandel, 1992).

At Wadi Zarqa Ma'in (Figure 9) the carbonates show an upward coarsening (shoaling) trend from shallow-water ripple cross-laminated siltstones and sandy carbonates to ooidal shelly packstone and cross-bedded (trilobite-rich) grainstone that were deposited in the shallow subtidal zone. Bi-directional dune sandstones (tidal bundles) and mega-ripples (Plates 18 and 19) overlain by bioturbated, ripple cross-laminated siltstones indicate an influx of quartz sand deposited by rivers prograding north into the shallow, tidally influenced coastal margin. An upper carbonate bed marks a brief transgressive to highstand phase deposited in a shallow subtidal to intertidal environment; it was succeeded by a further pulse of tidally influenced shallow-marine siliciclastics sedimentation, similar to the Hanneh Member in the southern localities near Safi.

The Hanneh Siltstone Member represents the regressive system tract (RST), and is marked by a renewed influx of siliciclastics in a shoreline environment (Figure 7), probably a result of siliciclastic shedding from the uplifting ANS to the south that resulted in termination of the carbonate system (Catuneanu et al., 2009). Palaeocurrent measurements from coeval Burj sandstones indicate a northward dispersal within the fluvial sands in the Southern Desert (Wadi Ram area) to an increasingly dispersed north-northeast to north-northwest pattern along the palaeoshoreline in the Petra-Wadi Dana area (Amireh et al., 1994). Sedimentary structures and trace fossils similar to those present in the Tayan Member suggest deposition in a tidal-dominated shoreline (Plate 15). Coarse-grained, trough cross-bedded sandstones deposited by braided to meandering rivers prograded over the wedge of marine sediments resulting in mostly continental, fluvial deposition (Umm Ishrin Formation) throughout the Cambrian Period in this area (Plate 21).

A pattern of southwest- to west-trending lithofacies belts derived from deep boreholes in Jordan (Andrews, 1991) indicate a northward passage from fluvial and intertidal siliciclastic environments in south Jordan, to shallow-marine and intertidal environments in central and north Jordan. This pattern is consistent with a progressive transgressive onlap during Tayan to Numayri times, with maximum flooding during deposition of the Numayri carbonate ramp (Rushton and Powell, 1998). The carbonate ramp can be traced, in the subsurface, northward for at least 700 km in Syria (Best et al., 1993) and has also been reported in Iran (Mila Formation; Stöcklin and Setudehnia, 1972; Wolfart, 1981, 1983; Al-Husseini, 2010). The maximum transgression (maximum flooding) represented by the Numayri Member has been tentatively placed, on trilobite biostratigraphy (Rushton and Powell, 1998; Elicki and Geyer, 2013) at the base of Cambrian Series 3/Stage 5 boundary (ca. 509 Ma). If correct, the base of the Burj Formation represents a major sequence boundary, the Burj Sequence Boundary, which marks a tilting of the Arabian Platform and a significant rise in relative sea level that can be correlated throughout the Middle East (Al-Husseini, 2011).

ABU KHUSHEIBA SANDSTONE FORMATION

Type and Reference Sections

The type section at Wadi Abu Khusheiba (Figure 1) is given in Bender (1974, figure 134). Useful reference sections (Powell, 1989) for the southern and northern outcrops, respectively, are found at Wadi Museimir (Figure 8) and Seil el Ja'jar (Figure 1). The formation as described here is based on Bender (1974), on sections measured by Powell (1989) in Wadi Museimir (Figure 8), and in detailed studies in the Feinan-Dana area (Amireh et al., 1994; figure 2) (Plate 22).

The Abu Khusheiba Sandstone Formation forms part of the Ram Sandstone Group (Table 1), and is broadly coeval with the middle and upper part of the Burj Formation of northern Wadi Araba, and with the upper part of the Salib Formation in the Southern Desert of Jordan where a marine ichnofauna has been described from transitional marine-fluvial siliciclastics (Powell, 1989; Amireh et al., 1994).

Subsurface Reference Section

Definitive Abu Khusheiba-type strata are absent in wells penetrating the Ram Group. However, Andrews (1991, p. 25) interpreted the mixed carbonate-arenaceous facies in Jafr-1 in southeastern Jordan as at least in part representing the Abu Khusheiba Formation and may include Abu Khusheiba transitional shoreface lithofacies (61 m of 'limestone and arenaceous facies') interfingering with true Burj type facies (Andrews, 1991). The formation is not present north of the Wadi Dana-Feinan area. Boreholes located north of 30° (Figure 1) penetrated the broadly coeval, carbonate-dominated Burj Formation (e.g. WS-9; WS-10; GTZ-2D; GTZ-3D; WG-2; SA-1 and NH-1) (Andrews, 1991).

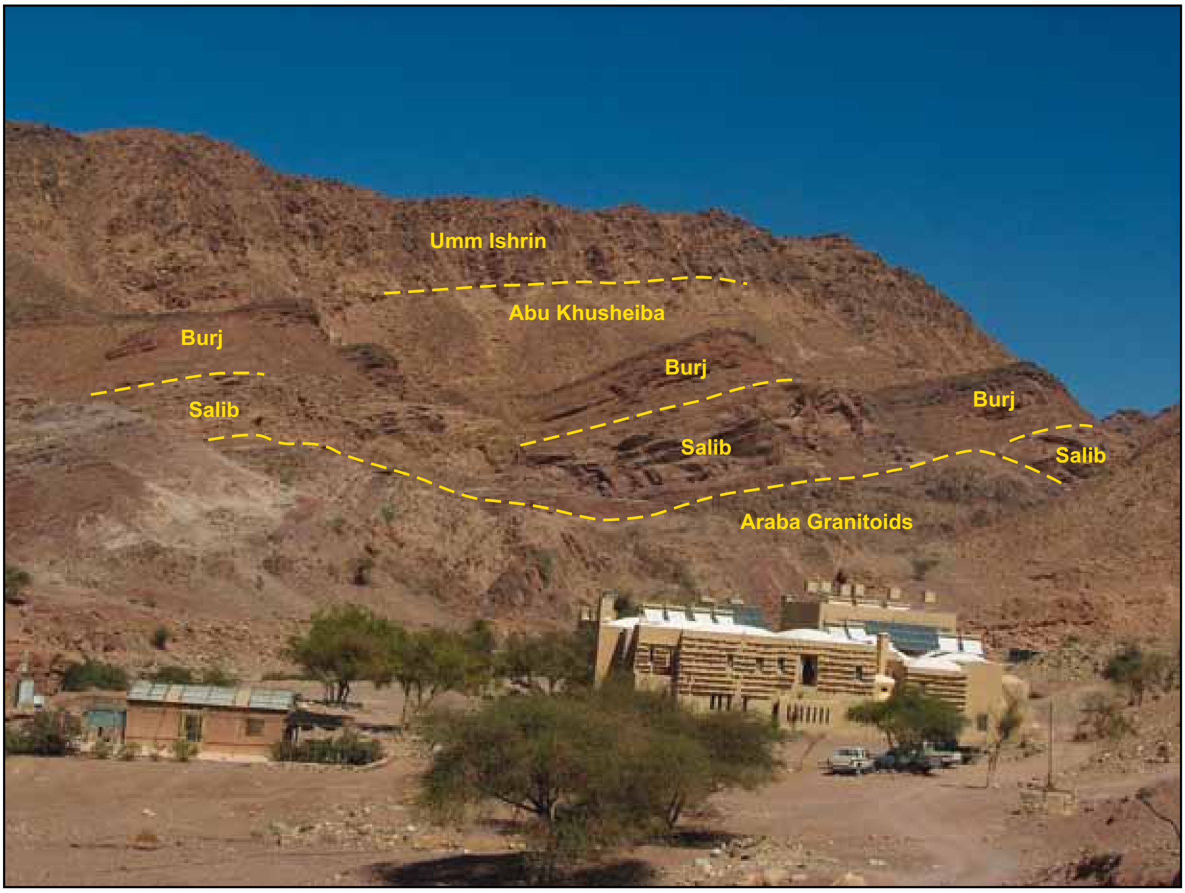


Plate 22: Abu Khusheiba Sandstone conformably overlying the Burj Formation, with thin Salib Formation below; the latter is markedly unconformable (palaeorelief) on the Araba Complex. The Umm Ishrin Sandstone forms the upper part of the cliff. Jordanian Society for the Conservation of Nature guest house, lower Wadi Dana. Photo by A.M. Abed.

Distribution

The formation crops out (Figure 1) in central Wadi Araba from Wadi Quseib northwards to Seil el Ja'jar (Bender, 1974, figure 39; Powell, 1989, figure 3). It is also well exposed between Gharandal and Wadi Mogatha, and in Wadi Abu Khusheiba (Amireh et al., 1994).

Authors and Nomenclature

The name is taken from Wadi Abu Khusheiba in central Wadi Araba (Powell, 1989), where the type section was first defined by Bender (1968, 1974, p. 46 and figure 134) who used the term 'white fine-grained sandstone formation.' Amireh et al. (1994) described several marginal-marine lithofacies that are equivalent to the Abu Khusheiba Formation. It is probably a correlative of the upper part of the Timna Formation, west of the Dead Sea Rift (Weissbrod, 1970), but these localities are offset from the type area in Jordan by about 110 km of left-lateral (southerly) shear on the Dead Sea Transform Fault (Freund et al., 1970).

Lithology and Bedforms

The formation consists of white to pale-grey and pinkish, fine- to medium-grained, micaceous, sandstone that is clayey in part. Locally, in the type area and Feinan area, it is green due to the patchy impregnation of copper carbonate (malachite) in pore spaces and partially replacing the cement

(Plate 23). Where the Abu Khusheiba Formation rests unconformably (Figure 2) on the palaeohigh formed by the Aheimir Volcanic Suite it contains scattered fragments of quartz porphyry or rhyolite (Figure 8; Plate 25). These lithoclasts were formerly considered to be volcanic ejecta (Bender, 1974), but are here interpreted as erosional clasts, derived locally from the Araba Complex basement rocks (Powell, 1989). The sandstone of the formation shows a high degree of sorting (Lillich, in Bender, 1974, figure 50) and, diagnostically, quartz pebbles and granules, common in the Salib and Umm Ishrin formations, are rare in the Abu Khusheiba sandstones.

Small-scale, trough cross-bedding in tabular sets is common. These sets, up to 2 m thick, are commonly separated by thin (0.7 to 1.3 m), planar bedded, laminated, micaceous, fine-grained sandstone or siltstone beds. Foreset-dip measurements indicate a bi-modal or poly-modal distribution. Amireh et al. (1994) illustrated widely dispersed northeast to northwest palaeocurrent directions for the intertidal and subtidal siliciclastic lithofacies in the area near Wadi Abu Khusheiba. A conspicuous feature of the formation in sections at Wadi Museimir (Figure 8) are vertical *Skolithos* burrows that have penetrated the cross-bedded sandstone beds and, in places, destroyed the original laminae; individual burrows are as much as 0.75 m long and 4 mm in diameter, with a density of 25 per 5 sq cm on bedding planes (Plate 24). Some of the planar-bedded, micaceous siltstones exhibit arthropod grazing and resting traces (*Cruziana* and *Rusophycus*, respectively). Ripple cross-lamination and bi-directional tidal bundles are also present.

Boundaries

The base of the Abu Khusheiba Formation in the type area (Bender, 1974, figure 134) and at Wadi Museimir (Figure 8) is marked by a sharp junction between mauvish-red, pebbly, medium-grained sandstone (Salib Formation), below, and white, fine-grained micaceous sandstone, above. The top of the formation is defined by the base of the coarse-grained sandstone of the fluvial Umm Ishrin Formation, which in many places has a sharp, erosional contact (Figure 8).

South of Wadi Quseib, the formation interfingers with, and passes gradationally into, the top of the Salib Formation and the base of the Umm Ishrin Formation (Powell, 1989, figure 1; Amireh et al., 1994, figure 2). Between Petra and Beida, including Wadi Abu Khusheiba, the formation overlies the 'basement' palaeohigh that consists of rhyolites and quartz porphyries of the Aheimir Volcanic Suite (Powell, 1989). To the north, in the Feinan area, however, it rests on the southernmost, feather-edge of the Hanneh Siltstone Member of the Burj Formation (Bender, 1974, figure 134; Powell, 1989, figure 1; Amireh et al., 1994, figure 2). In the Safi-Numayri area adjacent to the southern Dead Sea, and farther north, the Abu Khusheiba Formation cannot be defined; here, it appears to pass laterally into the marine Hanneh Siltstone Member at the top of the Burj Formation.

Thickness

The Abu Khusheiba Formation is about 110 m thick in the type area, but it thins gradually northwards to 50 m at Feinan (Plate 22), and southwards to 50–60 m at Wadi Museimir (Figure 8). It wedges out north and south of these localities. Andrews (1991) gave a thickness of 61 m for the Abu Khusheiba Formation in Jafr-1, southeast Jordan, but this probably includes carbonate lithofacies ascribed here to the Burj Formation.

Age and Fauna

Macrofossils such as trilobites, brachiopods and hyolithids have not been reported from the Abu Khusheiba Sandstone; these shelly fossils are restricted to the carbonate lithofacies of the coeval Burj Formation. However, the maximum flooding and high-stand phases of the early mid-Cambrian transgression represented by the Burj Formation to the north of the type area, is reflected in an abundant and diverse ichnofauna in the Abu Khusheiba Formation (Powell, 1989; Amireh et al., 1994; Geyer and Landing, 2000; Hofmann et al., 2012). These include dense suspension-feeding, vertical *Skolithos*

Plate 23: Secondary copper ore (malachite) impregnating the matrix of trough cross-bedded sandstone (Abu Khusheiba Formation) at Feinan. Black manganese staining along joint faces. Hammer head 0.20 m. Photo by J.H. Powell.

Plate 24: Abu Khusheiba Sandstone, Wadi Araba, with deep vertical *Skolithos* burrows. Pen 0.13 m for scale. Photo by A.M. Abed.

Plate 25: Abu Khusheiba Formation (right) with pebbles of Aheimir rhyolite resting unconformably on Aheimir Suite rhyolite, indicating that the Araba Complex formed a palaeohigh during deposition of the Abu Khusheiba Formation in middle Cambrian time. Height of the outcrop is about 4 m. Photo by A.M. Abed.

burrows and infaunal horizontal *Planolites* in the white and pale-yellow, fine- to medium-grained, cross-bedded sandstone in the upper part of the unit. Trilobite grazing and resting traces consist of *Cruziana* (*Cruziana aegyptica* and *C. salomonis*) that together with rare examples of *Rusophycus* and *Diplichnites* indicate the presence of marine arthropods (Figure 8). Although the *Skolithos* and *Cruziana* ichnofacies have no precise biostratigraphical significance, when traced laterally over relatively short distances from the type area to Quweira in the south, they act as distinctive marker horizons that enable regional 'event' correlation during the maximum flooding and high-stand phases in the transitional marginal marine sequence in south Jordan (Powell, 1989; Amireh et al., 1994). On the basis of its correlation with the Burj Formation an early mid-Cambrian age is likely (Rushton and Powell, 1998; Elicki and Geyer, 2013); see discussion under Burj Formation.

Depositional Environment

The stratigraphical position of the Abu Khusheiba Formation, coeval, in part, with the Burj Formation to the north (Safi area), and with the fluvial sandstones above and below the formation to the south (Quweira; Southern Desert), suggests a transitional marginal-marine depositional environment. Lithofacies characteristics such as the absence of marine macro-fossils, the presence of diverse trace fossils (*Skolithos*, *Planolites*, *Rusophycus*, *Diplichnites*, *Cruziana* and *Tigilites*), bi-directional trough cross-bedding, a high degree of sorting, and relatively fine grain-size. These characteristics indicate shallow-water, marine or brackish intertidal to subtidal environments, probably representing the shoreface zone of a prograding clastic shoreline that was subjected to oscillating wave and tidal currents

(Powell, 1989; Amireh et al., 1994). This shoreface facies lay intermediate between the fully marine carbonate lagoon (Numayri Member of the Burj Formation) to the north, and the alluvial plain to the south (Salib and Umm Ishrin formations). Rivers draining from the hinterland deposited fine-grained sand along the coastal margins that was reworked and sorted by oscillating, near-shore tidal currents. Periodic stabilisation of the sandy substrate, including tidal bundles and marine dune bedforms, allowed deep penetration by suspension-feeding *Skolithos* worms, prior to the subsequent phase of erosion and deposition. Organic-rich substrates were grazed by trilobites that produced crawling and resting traces, although the mobile sandy substrates were not suitable for the preservation of arthropod exoskeletons.

The presence of *Skolithos* burrows in both the Abu Khusheiba Formation and, more rarely, in the top of the Salib Formation in the Southern Desert of Jordan, suggests a tentative correlation of a marine maximum flooding event at this level (Figure 2), but this cannot be confirmed in the absence of age-diagnostic fauna.

Outcrop and borehole data indicate a transition towards the southwest from marine carbonate (Burj) lithofacies to transitional shoreface (Abu Khusheiba) to fluvial (upper Salib) facies (Figure 3). This model of a gently inclined carbonate to marginal siliciclastic marine ramp (Powell, 1989) is supported by subsurface data (Andrews, 1991). This data proves marine facies throughout the subsurface, except in Jafr-1 in the extreme south of Jordan where mixed Burj-Abu Khusheiba lithofacies were proved, thus defining an east-west or northwesterly orientation of lithofacies belts (Figure 5). South of Feinan, in the Petra region, there is evidence of a palaeohigh onto which Burj and Abu Khusheiba lithofacies onlapped (Bigot, 1981; Powell, 1989; Amireh et al., 1994).

CONCLUSIONS

The Cambrian succession (Ram Group) in Jordan records a significant period of Earth history subsequent to the uplift and erosion of the Neoproterozoic granitoid Arabian-Nubian Shield (ANS; Aqaba Complex in Jordan) and the later, but more localised, Ediacaran Araba Complex in the Feinan-Petra region. The Ram Unconformity (ca. 530 Ma) marks the base of early Cambrian sedimentation, which was characterised predominantly by fluvial siliciclastics derived from the rapidly eroding Neoproterozoic basement rocks, located to the south, but includes a brief, but biostratigraphically significant, transgressive-regressive wedge of marine carbonates and siliciclastics.

Uplift and erosion of the granitoid basement (ANS) resulted in a peneplain that developed over millions of years in the Southern Desert area of Jordan. Early Cambrian pebbly sandstones and locally derived conglomerates (Salib Formation) were deposited on the peneplain by high velocity-high discharge, northward flowing (NNE to NNW) braided rivers characterised by trough cross-bedding and erosive tabular sets. Brief, and rare, marine influence on the lower alluvial plain is marked by thin cross-stratified sandstones with vertical *Skolithos* burrows.

A major regional, or perhaps global, sea-level rise in the early mid-Cambrian marks a major marine transgressive-regressive cycle, and southerly thinning wedge (in Jordan) that thickens to the north and east throughout the Arabian Platform. During deposition of the marine Burj Formation, the palaeoshoreline was oriented WNW-ESE in southern Jordan. The transgressive depositional phase (TST) is represented by tidal-dominated siltstones and fine-grained sandstones (Tayan Member) containing a diverse *Cruziana/Rusophycus* ichnofaunal assemblage. The overlying carbonate ramp sequence (Numayri Member) comprises shelly wackestone, packstone and grainstone lithologies with ooids and oncolites, and yields a diverse trilobite, brachiopod and hyolithid fauna. It represents the late transgressive to highstand (HST) and maximum marine flooding (MFS) across the low-gradient alluvial plain. A return to regressive tidal-influenced sandstone and siltstone, with thin carbonates in central Jordan (Hanneh Member) represents a regressive wedge (RST) deposited in response to renewed uplift and siliciclastic shedding from the ANS located to the south. Trilobites in the carbonates, represented by the *Kingaspis campbelli* and *Redlichops* faunules, suggest a biostratigraphical age of early mid-Cambrian for the MFS, which equates approximately to the base of the Cambrian Series 3

(Stage 5), and probably represents the Cambrian marine flooding surface Cm20 to which a tentative geochronological age of 509 to 505 Ma has been attributed. However, south of Feinan the carbonates pass laterally to marine, tidal-influenced sandstone (Abu Khusheiba Sandstone) characterised by extensive *Skolithos* burrows and *Cruziana/Rusophycos* traces. When traced southwards (towards the palaeohinterland) the marine influence diminishes so that the Burj / Abu Khusheiba units are absent in the Southern Desert.

Ediacaran granite and extrusive volcanic and volcaniclastic rocks (Araba Complex) associated with the rifting in the Feinan-Petra area produced a younger, immature palaeotopography, in marked contrast to the Neoproterozoic Aqaba Complex peneplain in the Southern Desert. Early and mid-Cambrian fluvial and shallow-marine siliciclastics (Salib and Abu Khusheiba formations) onlapped progressively onto this immature (Ediacaran to early Cambrian) topography that was buried by mid-Cambrian time. Increased rates of subsidence during the early Cambrian, to the north of the Araba Complex 'high', provided accommodation space that resulted in deposition of a thicker Salib sandstone succession in this area. The rifted Feinan-Petra region appears to have acted as an east-west hinge line in the Cambrian, with greater subsidence of the Arabian Platform to the north.

Following the Burj transgression, renewed uplift and erosion of the ANS, to the south, resulted in deposition of a thick succession of fluvial-dominated sand deposited by large braided rivers characterised by high velocity and high sediment flux (Umm Ishrin Formation); trough cross-bedding and overturned cross-bedding are common. Fluvial sedimentation continued through mid to late Cambrian times and the Ordovician (Disi and Umm Sham formations), but episodic shallow-marine or estuarine flooding of the alluvial plain resulted in colonisation locally by arthropods and worms that produced a diverse and abundant *Cruziana/Rusophycus/Planolites* assemblage of tentative Floian (Arenig) age for the upper part of the Disi Formation.

Overall the Ram Group siliciclastics (Salib-Umm Ishrin-Disi-Umm Sahm formations) show an upward increase in sand maturity from arkose (Salib) to orthoquartzite (Disi) reflecting recycling of the siliciclastics; heavy mineral signatures (ZTR), specifically datable zircons indicate provenance from a predominantly distant Neoproterozoic granitoid source rock area (ANS) that was undergoing intensive weathering; a small zircon component derived from older pre-Neoproterozoic rocks is consistent with the general trend in the Levant.

The highly permeable Cambrian siliciclastics of Jordan and surrounding countries provide an important regional groundwater aquifer, albeit 'fossil' water. In a suitable structural setting these reservoir rocks might be suitable for hydrocarbon exploration where source rocks of Neoproterozoic, Silurian or Permian age are faulted and in close proximity, at depth, in the central Arabian Platform.

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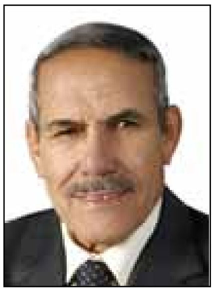
ABOUT THE AUTHORS

***John H. Powell** was formerly Chief Geologist, England, with the British Geological Survey (BGS) and is currently an Honorary Research Associate with the BGS. He gained his BSc and PhD at the University of Newcastle upon Tyne, UK. John has over 30 years professional experience in sedimentology, applied geology and geological mapping in the UK and internationally. He has worked with the Natural Resources Authority, Jordan, on mapping, sedimentology and basin analysis of the Phanerozoic succession, especially the Lower Palaeozoic, Permo-Triassic and Cretaceous-Eocene sequences. John was BGS Regional Geologist for the Middle East and Africa from 1998 to 2000, and has worked in Syria, Morocco, Mauritania and Mozambique. He serves on the Geological Society of London Stratigraphy Commission.*

jhp@bgs.ac.uk



__Abdulkader M. Abed__ is a Professor in the Department of Geology at the University of Jordan. He received his BSc in Geology in 1964 from Damascus University (Syria) and his PhD in Sedimentology in 1972 from Southampton University (UK). His research is concentrated on the geology of Jordan in the field of sedimentology and geochemistry of phosphorites and the study of organic-rich sediments including oil shales as a source rock for petroleum. More recently, he is interested in the paleoclimate of Jordan in the late Pleistocene. He has published 110 papers and 19 books. He is a member of the Mineralogical Society of Britain, SEPM, IAS, Jordanian Geologists Association, and the Jordanian Academy of Arabic and has served on the IGCP Scientific Board (1989-1995).

aabed@ju.edu.jo

__Yves-Michel Le Nindre__ has been contributing to Middle East geology since 1979, particularly in Saudi Arabia. After his PhD in marine Biology and Sedimentology in 1971, he received his Doctorate of Sciences from the University of Paris (France) in 1987 with a dissertation on the 'Sedimentation and geodynamics of Central Arabia from the Permian to the Cretaceous'. Yves-Michel joined the Bureau de Recherches Géologiques et Minières (BRGM) in 1973. He was involved in many research and consulting projects in France and abroad (Saudi Arabia, Oman, Kuwait, U.A.E. Jordan, Iran, Tunisia, Morocco, Bolivia, Ethiopia, India, Russia), for sedimentary basin analysis and modeling, especially in hydrogeology. As a Sedimentologist, Yves-Michel worked in France on present-day littoral integrated management. Since 2000, he has been involved in international projects for CO2 storage, working with EU state members and CSLF countries (Russia, China, Saudi Arabia) as Expert or Project Manager and directed two PhD theses.Since July 2012, Yves-Michel is retired from BRGM, notwithstanding still continuing a scientific and consulting activity in his preferred domains of expertise. He is a member of the EAGE, ASF and of the GeoArabia Editorial Board. Yves-Michel is so far author or co-author of 62 publications related to Saudi Arabia.

yc.lenindre@wanadoo.fr

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