An Introduction to the Geology of Jordan

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By

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TABLE OF CONTENTS

PREFACE

This book on the geology of Jordan is written to assist students of geology and other geosciences to gain a general understanding of the geologic configuration of the country and its historic development since Archaicum times.

Like all other sciences, geosciences develop daily, and new knowledge is reached in every scientific paper, report, thesis and study. But the basic knowledge about Jordan's geology does not change at the same pace. This book delivers the basic knowledge for students and scholars of geosciences and related fields.

Details of any part of the big picture portrayed in this book must be obtained from specific, more comprehensive works listed in the references list.

Chapter 1 deals with the staged evolution of rocks and life and the conditions leading to their formation, such as seawater transgressions or regressions, tectonics and depositional environments.

Chapter 2 deals with the main structural elements and their imprints on the geologic formations' deposition and erosion. Meso- or small-scale structural elements are given wider explanations due to their role as tectonic and tectonic indicators of deformational forces and their, until now, absence in the literature dealing with the geology of Jordan.

Chapter 3 concentrates on the tectonics activities which has affected Jordan throughout its geologic history and their effects on topography, geologic set-up, mineral resources, hydrology and human life. It covers epirogenic and taphrogenic activities in the Levant and their relevance to human migration. The chapter also discusses the role of natural resources, climate and environmental conditions in Jordan's human life.

Chapter 4 discusses the climatic conditions resulting from artificial degradation, such as mining processes, construction activities, pollution and groundwater over-exploitation. It summarizes the country's water resources and indicates the way for a safe future of water supply.

Chapter 5 sheds light on the natural resources of the country, which are expected to serve the country's economy and society if they become developed adequately.

Chapter 6 introduces and discusses the major macro invertebrate fossil groups, which have left their marks in the fossil record of Jordan because of their relevance and easy recognition in the field. Emphasis is placed on the main characteristic of such fossils and fossil remains with examples from Jordan.

The authors hope that geoscience students of all levels and scholars of geoscience-related disciplines gain the necessary basic knowledge of the geology of Jordan from this book.

Ikhlas Alhejoj and Elias Salameh

CHAPTER ONE

GEOLOGICAL UNITS: LITHOLOGY AND FOSSIL CONTENT

1.1 Introduction

It all started when an old supercontinent called Rodina, which existed 1000 million years ago, started to split at around 900 myr into several continents separated by oceans to form Africa, South America, Australia, Antarctica, India, Lawarancia, Siberia, Ballica, Khazacistania and Madagascar. Parts of these continents collided, subduced, eroded, uplifted, split, and moved apart, forming new supercontinents, including Gondwana, Lawrancia and others. The Gondwana supercontinent split again about 600 myr ago to form Africa, South America, Australia, India and Antarctica.

Erosion and the accompanying uplift to reach isostasy exposed new materials coming from deep parts of the earth on the surface. At still greater depths, molten materials gradually moved upwards, their temperature reduced, and new minerals crystallized from the molten materials (magma), such as the granitic rocks and minerals of the basement complex of the Arabo-Nubian Shield.

The old continent of Gondwana was built of magmatic rocks, mainly granites and metamorphosed gneisses. A small part of these rocks is found in southwest Jordan, in the Aqaba mountains and at the eastern shoulder of Wadi Araba, extending from Aqaba to the south of Gharandal, or 50 km north of Aqaba. These rocks extend further southeast, building the mountains bordering the Red Sea in Saudi Arabia on the one side and Egypt and Sudan on the other. This rock complex is designated the Granitic Basement Complex or the Arabo-Nubian Granitic Shield. The granitic basement in Jordan is composed mainly of granites with dominant feldspars, quartz, and mica intruded by many basic and acidic dykes up to 20 m thick. Before the opening of the Red Sea, the granitic basement formed a part of the severed Arabo-Nubian shield of Saudi Arabia, Egypt and Sudan. The granitic basement in Jordan dips to the northeast, where it is encountered in the Sirhan Depression/Azarq area at a depth of around 5km, as deduced from seismic data. Due to continental shifts between 550 and 20 million years ago, the Tethys Sea periodically flooded parts of that granitic basement in Jordan and the neighbouring region. This resulted in the deposition of sand layers that formed sandstone and layers of marine life sediment that formed limestone. The hard, red sandstone of Petra, Wadi Rum, and Wadi Dana formed between 550 and 500 million years ago.

1.2 Precambrian rocks

Precambrian crystalline rocks, part of the Arabian Nubian Shield as a crustal block of juvenile Neoproterozoic rocks in Northeast Africa and the western Arabian Peninsula, are exposed along the shoulders of the Red Sea, which formed during the Neoproterozoic Pan-African episode. The exposure of the basement rocks of the Precambrian age in Jordan is located east and northeast of Aqaba and along the eastern side of Wadi Araba to the southern end of the Dead Sea (Fig.1-1). The Precambrian rocks marked by igneous, sedimentary, and metamorphic rocks overlying the Neoproterozoic Basement Complex are divided into the Aqaba Complex (older, ~ 860–626 to 605) and the Araba Complex (younger, ~ 605 to 550 Ma). Each of these complexes is subdivided into several suites (Table. 1-1).

The oldest rocks known from Jordan are those of the Aqaba Basement Complex and the Precambrian Complex, consisting of metamorphic suites (Abu Barqua Metamorphic Suite and Janub Metamorphic Suite) and several granitoid suites. The Aqaba complex crops out around Aqaba and further east along the Gulf of Aqaba and north in Wadi Araba. The Abu Burqa Metamorphic Suite (which takes its name from its location in Wadi Abu Burqa) consists of tonalitic gneiss, granitic gneiss, paragneiss, and metapelites rocks, which crop out 5km northeast of Gharandal (60 km from Aqaba) with a length (S-N) of 7km, a width (W-E) of up to 1km and a thickness of more than 200 m (Fig.1-2). They overlie a rock set of conglomerates (similar to Saramuj) concordantly and are discordantly overlain by Cambrian sandstones. The Janub Metamorphic Suite comprises cataclasites, metavolcanics, meta-conglomerates, meta-arkoses, mylonites, and hornfelses.

The Araba Complex is surrounded by erosional unconformities (The Araba Unconformity and The Ram Unconformity), and it contains cycles of volcanic, volcaniclastic, sedimentary, and igneous rocks. The complex outcrops are exposed on the eastern side of Wadi Araba from Gharandal in the south to the southern shores of the Dead Sea in the north. Outcrops are also present east and northeast of Aqaba as small alkali feldspar granite intrusives. The Araba Complex consists of the Safi Group, the Feinan Plutonic Suite, the Araba Mafic Suite, the Aheimir Volcanic Suite, the Umm Ghaddah Formation, the Ma'an Formation and the Jafr Formation.

After the suturing and extensional tectonic of the Aqaba Complex, the Safi Group of the Wadi Araba Complex was deposited because of the rapid subsidence and deposition of the Saramuj Conglomerate Formation.

The Saramuj Conglomerate Formation, a mainly polymict granitoid conglomerate, represents the Araba Complex of the Safi Group base. This formation consists of poorly sorted, coarse-grained, and well-rounded fluviatile deposits composed of pieces of gravel in a sandy matrix (Fig.1-3). The conglomerate pieces comprise granite, gneiss, diorite, quartzite, porphorite, and acidic dyke boulders cemented by a sandy ground mass and metamorphosed. They crop out at the SE corner of the Dead Sea in the area extending between Wadi Numeira and Wadi Hasa with an N-S length of around 9km, a width of about 1km and a thickness of 200 m. The Saramuj Conglomerate Formation of pebble-cobble clasts were sourced from the Arabian Nubian Shield. The Haiyala Volcaniclastic Formation represents the upper part of the Safi Group. It unconformably overlies the Saramuj Formation. The formation comprises volcaniclastic sediments deposited in a shallow-marine environment. What is very interesting here is that the Abu Burqa Formation contains a few beds with cyanobacterial mats, and in places, the granitic basement is covered by calcareous stromatolites, the oldest known fossils from Jordan and its surrounding countries. In general, the Precambrian rocks contain precious and industrial metals.

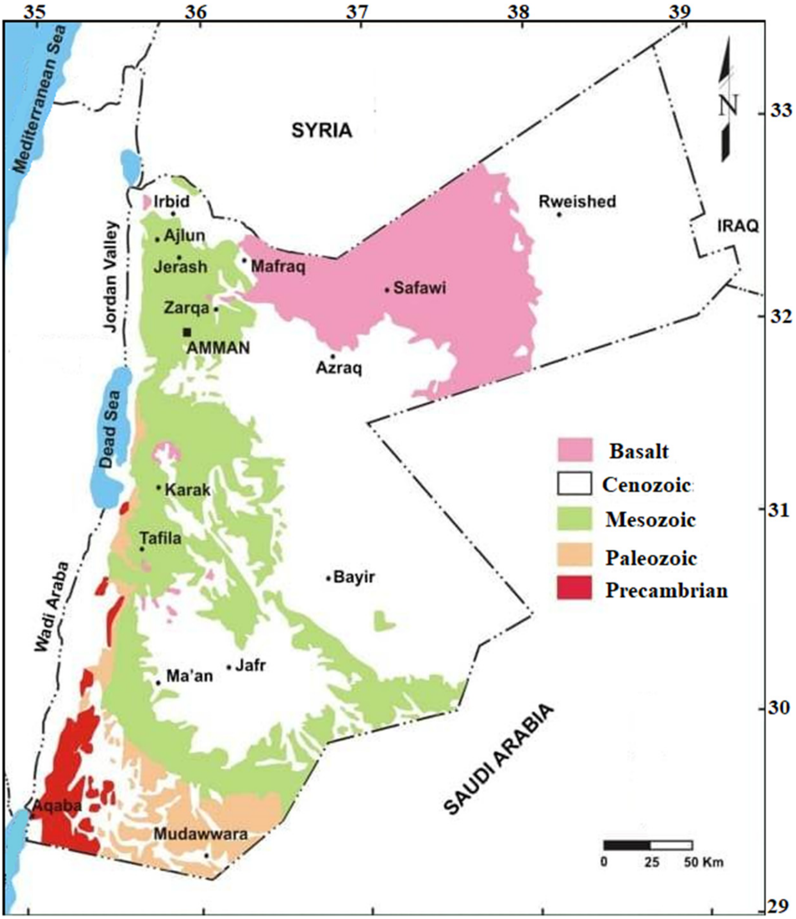

Figure 1-1: General geological map showing the distribution of the different rock eras in Jordan

Table 1-1: Divisions of the Neoproterozoic Basement Complex in Jordan.

Complex	Suite/Group/Formation	
Ram Unconformity ~ 530 Ma		
Araba Complex	Dikes pulse	
	Umm Ghaddah Formation	
	Aheimir Volcanic Suite	
	Feinan -Humrat- Mubarak Granitic Suite	
	Araba Mafic Suite	
	Safi Group	Haiyala Volcaniclastic Formation
		Saramuj Conglomerate Formation
Araba unconformity ~ 605 Ma		
Aqaba Complex	Yutum granitic Suite	
	Rumman Granodiorite Suite	
	Urf Pophyrytic Suite	
	Darba Tonalitic Suite	
	Rahma Foliated Suite	
	Duheila Hornblendic Suite	
	Abu Saqa Schist Suite	
	Janub Metamorphic Suite	
	Abu Barqa Metamorphic Suite (ABMS)	

Figure 1-2: Late Precambrian sediments with basaltic dykes east of the Sabkha of Taba in Wadi Araba.

Figure 1-3: Saramuj Conglomerate Formation composed of strongly cemented clasts of plutonic rocks, mainly granite, diorites and granitic gneiss at Ghour Safi (pictures by Hassan Halaybeh)

1.3 Palaeozoic Rocks in Jordan

Palaeozoic rocks consist mainly of sandy deposits containing trilobites, graptolites, and brachiopods with ichnofossils which are useful index fossils, helping to relatively determine the age of the rocks and the environments in which they are found. The lower Ram Group and the upper Khreim Group represent Palaeozoic rocks. The Ram Group consists of sandstone types varying in colour, mineralogy, sedimentary structures, hardness and other properties, ranging in age from the Cambrian to the Lower Ordovician periods. The whole sequence is called the Ram Group because these sandstones are the backbone of the Ram area in southern Jordan **(Fig. 1-4).** These sandstones are ~ 1000 m thick and are divided into four rock units (formations), from older to younger: Saleb, Umm Ishrin, Disi and Umm Sahm Formations. The overlying Khreim Group is divided into four formations, Hiswa, Dubaydib, Mudawwara and Khushsha **(Table. 1-1).**

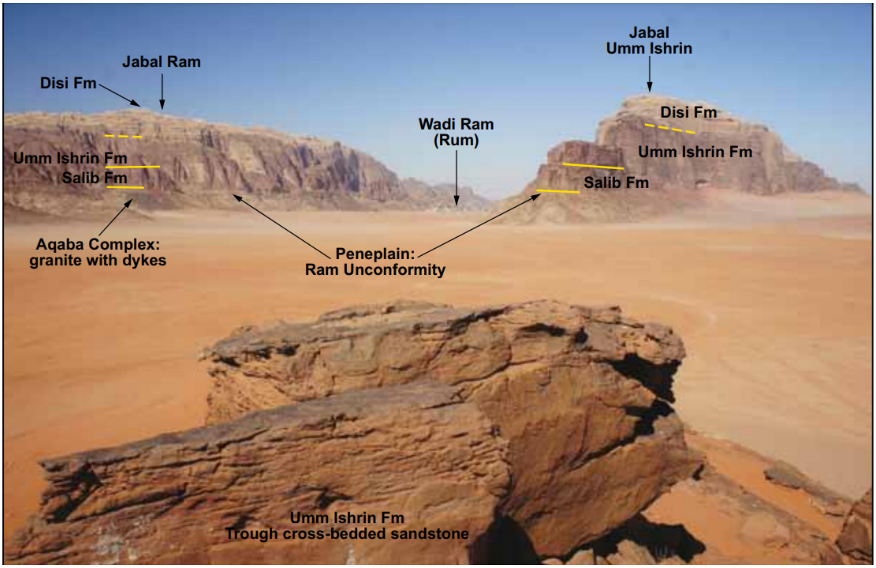

Figure 1-4: Precambrian of Aqaba Complex, Ram Unconformity and Cambrian formations (Ram Group) in Wadi Ram. View northwards from Khazali. (Desert elevation, 950 m above sea level; Jabal Umm Ishrin, 1,733m above sea level). (Photo by J.H. Powell, copied from Powell et al., 2014)

1.3.1 Cambrian

The northeast dipping granitic basement east of Aqaba is directly overlain by a thick sandstone series from the Cambrian age along Wadi Araba from Wadi Darba (45km north of Aqaba) and northward.

In some outcrops, these sandstones start with fluviatile basal conglomerates overlying the granitic basement with a thickness of up to 50 m, overlying former erosional channels or depressions curved in the granitic basement. These basal conglomerates are difficult to date and may differ in age from one place to another, being Precambrian age in one place and Cambrian age in another.

The Salib Formation (Saleb) or layered arkosic sandstones represent the oldest rocks found in the Palaeozoic rocks of Jordan **(Fig.1-5).** It is mainly brownish-yellow sandstone (quartz plus minor feldspar) and pebbly conglomerate sandstone with trough cross-bedding and Skolithos ichnofossils. Criss-crossing rivers deposited it during the Lower Cambrian, where the coastline was north of Jordan. It is found overlying the basal conglomerates or directly overlying the granitic basement. These sandstones, like the basal conglomerates, can also be of the Precambrian age because they are also difficult to date.

To clarify the rock series covering the granitic basement, it can be stated that the eroded clastic materials from the granitic basement must have covered the low areas of that basement during Precambrian times, as can be seen from the example of the outcropping conglomerates south of Wadi Abu Burqa. Elsewhere, such conglomerates may still exist but are not cropping out to the surface. They might have eroded in other areas after deposition, and younger rocks were deposited directly overlying the granitic basement. The question of which is older, the Saramuj conglomerates or the Abu Burqa Formation has not yet been solved, but further fieldwork and age determinations will certainly clarify this question.

Table 1-2: Geological Formations in Jordan

ERA	SYSTEM	EPOCH	GROUP	FORMATION	SYMBOL	LITHOLOGY	THICKNESS [m]
CENOZOIC	QUATERNARY	Holocene	JORDAN VALLEY (JV)	Alluvium	Qal	clay, silt, sand, gravel	
		Pleistocene		Lisan	JV3	marl, clay, evaporites	> 300
	TERTIARY – Neogene	Pliocene, Miocene, Oligocene		Samra	basalt	conglomerates	100 - 350
				Neogene	JV1-2	sand, gravel	
	TERTIARY – Paleogene	Eocene	BELQA (B)	Wadi Shallala	B5	chalky and marly limestone with glauconite	0 - 550
		Paleocene		Umm Rijam	B4	limestone, ckalk, chert	0 - 310
MESOZOIC	CRETACEOUS – Upper	Maastrichtian		Muwaqqar	B3	chalky marl, marl, limestone chert	80 - 320
		Campanian		Amman-Al Hisa	B2	limestone,chert, chalk, phosphorite	20 - 140
		Santonian		W.Umm Ghudran	B1	dolomitic marly limestone, marl, chert, chalk	20 - 90
		Coniacian	AJLUN (A)	Wadi as Sir	A7	dolomitic limestone, limestone, chert, marl	60 - 340
		Turonian		Shueib	A5/6	marl, limestone	40 - 120
		Cenomanian		Hummar	A4	limestone, dolomite	30 - 100
				Fuheis	A3	marl, limestone	30 - 90
				Naur	A1/2	limestone, dolomite, marl	90 - 220
	CRETACEOUS – Lower	Albian, Aptian, Barremian	KURNUB (K)	Subeihi	K2	sandstone, shale	120 - 350
		Hauterivian, Valanginian, Berriasian		Aarda	K1	sandstone, shale	
	JURASSIC		ZARQA (Z)	Azab		siltstone,sandstone, limestone	0 - >600
	TRIASSIC			Ramtha		siltstone,sandstone, shale limestone, anhydrite, halite	0 - >1250
PALEOZOIC	PERMIAN			Hudayb		siltstone,sandstone, limestone	0 - >300
	SILURIAN		KHREIM (KH)	Alna		siltstone,sandstone, shale	0 - >1000
				Batra		mudstone,siltstone	0 - >1600
				Trebeel		sandstone	0 - 130
				Umm Tarifa		sandstone, siltstone, shale	0 - >1200
	ORDOVICIAN			Sahl as Suwwan		mudstone, siltstone, sandstone	0 - 200
			RAM (D)	Amud		sandstone	0 - >1500
	CAMBRIAN			Ajram		sandstone	0 - ca: 500
				Burj		siltstone,dolomite, limestone sandstone	ca: 120
				Salib		arkosic sandstone, conglomerate	0 - >750
PRECAMBRIAN				Unassigned clastic unit		sandstone, argillaceous siltstone, claystone	0 - 1000
				Saramuj		conglomerate, sandstone	up to 420
				Aqaba Igneous			

Figure 1-5: Pebbly conglomerate sandstone of the Salib Formation in the middle of Wadi Araba

In northern and middle Wadi Araba, Cambrian sandstones from the Salib Formation crop out and are covered by limestone and dolomites with shallow water marine sediments named the **Burj Formation,** also known as Wadi Nasb limestone of late early to early Middle Cambrian age based on trilobite fossils. The Burj Formation is subdivided into three members; the Tayan Member (lower older part), composed of sand and silt beds rich in strong bioturbations; the Numayri Member (central part) with limestone and some glauconitic greenish sand; and the Hanneh Member (upper younger part) distinguished by sand with shale and trilobite ichnofossils. To the east of the southwestern end of the Dead Sea, in Wadis Numeira and Isal, the marine dolomite, limestone and clay stone series measure around 50 m thick and 1km north of Wadi Zarqa Ma'in Mouth around 20 m of the same series are exposed. It contains several mainly marine fossils (e.g. brachiopod *Trematobolus* sp.) confirming its Cambrian age and evidencing that the Paleo-Tethys must have transgressed southward to the middle area of Wadi Araba. The fossils found in the Burj Formation are the trace fossils Skolithos and the trilobites Cruziana/Rusophycusichno).

The arkosic Precambrian sandstones are overlain by Cambrian rocks comprising continental sandstones in their southernmost outcrops along southern Wadi Araba south of Gharandal (60 km north of Aqaba), by marine white sandstones in central Wadi Araba, and by marine dolomite, limestone and clay series of rocks in Bir Madkhur area in wadi Araba and northwards along the Dead Sea eastern shore.

In the central Wadi Araba, the Abu Khushebia Formation is composed of fine-grained marine sandstone rich in Skolithos burrows, with a thickness of around 110 m, which crops out in Wadi Abu Khushebia. Copper impregnations are found in the lower third of these sandstones, disappearing upwards towards the middle of the formation.

Umm Ishrin Formation

The Umm Ishrin Formation is a fluviatile deposit of the Late Cambrian age that overlies the Salib Formation and is overlain by the Ordovician Disi Formation. The Formation comprises reddish brown, hard sandstone around 300 m thick **(Fig.1-6).** It is worth mentioning here that the Nabatean ancient city of Petra was carved, in its lower part, in the Umm Ishrin Formation and the Disi Sandstone Formation (Early Ordovician era) in the city's upper part. Cambrian sandstones are covered by Late Permian sands and soils east of the Dead Sea and Early Cretaceous Kurnub sandstone further south. Fossils include Trilobite (e.g., *Myopsolenites boutiouit, Kingaspiscampbelli, Redlichopsblanckenhorni*), brachiopods *Trematobolus*sp), Skolithos and trilobites Cruziana/Rusophycus ichnofossils.

Figure 1-6: A. The Umm Ishrin Formation in Wadi Araba. B. Umm Ishrin Formation in Wadi Mujib, east of the Dead Sea

1.3.2 Ordovician

In the area south of the Ras en Naqab Escarpment, a 300 m thick Ordovician sandstone series is found overlying the Cambrian sandstones. Most of the Ordovician deposits in Jordan have been removed by erosional activities related to the Hercynian (Variscan) orogeny. The sequence includes in its middle part some 70 m of micaceous clay schist and shales containing rich marine fossil remains, indicating a transgression of the sea during the Ordovician. In general, Ordovician sandstones have a thickness of around 700 m.

In the field, it is very difficult to distinguish this sandstone series from the underlying Cambrian sandstones or overlying Silurian or Lower Cretaceous sandstones, but the white weathering of the Ordovician sandstones may hint at their age group.

Ordovician sandstones are pure with ripple marks, and their shale portions contain rich marine fossil remains. The sandstones are partly bituminous deposits in the shallow sea from the north. It is worth mentioning here that in Ordovician times, Gondwana and Jordan, as a part of it, continued their southward drift to the South Pole with a climate of extreme glaciations, which may have left its effects on the rocks formed during that time.

The Disi Formation

The Disi Formation comprising massive white weathered sandstone (Bender 1974) and the Umm Sahm Formations of the upper Ram Group represent the Lower Ordovician age sediments in Jordan. The Disi Formation is composed of sandstone of around 300 m overlying the Cambrian sand of the Umm Ishrin Formation. White sandstones distinguish this formation with a dome-like appearance on the southern Ras en Naqab Escarpment **(Fig.1-7).** The Disi Formation is rich in glass sand with pure silica. The formation is derived from crisscrossing rivers.

Figure 1-7: Domal morphology of the Disi Formation in Dana, Tafeliah (Picture by Hassan Halaybeh)

The Um Sahm Formation

The Umm Sahm Formation of the early Ordovician age is the Ram Group's uppermost formation. The Umm Sahm Formation, of bedded brownish weathered sandstone (Bender 1974), is composed of reddish sandstone (mainly in the lower part) and shale (in the middle and upper part) of around 350 m thickness. This formation is interpreted as a transitional marine environment from fluvial (river) to deep marine (Khreim Group) environments.

The Khreim Group

The Khreim Group is generally composed of a sandstone, siltstone and shale sequence of rocks ranging in age from the Middle Ordovician to the Early Silurian periods overlying the sandy Ram Group. The rock formations of the Khreim Group are (from older to younger): Hiswa, Dubaydib, Mudawwara and Khushsha.

The Hiswa Formation

The Hiswa Formation of graptolite sandstone (Bender 1974) is of the early Ordovician age, mainly composed of shale with bedded sandstone rocks and hummocky cross-bedding structures of about 80 m thickness. The formation contains abundant fossils, including graptolites (*Didymograptussp*), brachiopods, trilobites, and cruziana ichnofossils. The formation is of offshore marine origin, with soft shale-rich lower parts changing into sand-rich lithology, which reflects a shallowing upwards succession.

Dubaydib Formation.

The Dubaydib Formation (Dubeidib), also called Sabellarifex (Skolithos) sandstone (Bender 1974), is predominantly composed of sandstone and greenish shale around 140 m thick. It is characterized by the presence of Skolithos trace fossils, especially in the sandstone, indicating shallow, high-energy near-shore depositional environments.

The Mudawwara Formation.

The Mudawwara Formation, the Conularia Sandstone Formation (Bender 1974) or the Tarifa Formation comprises an alternating sandstone and shale series of a thickness reaching 250 m containing graptolites, brachiopods and Skolithos burrows. Moreover, it contains mineable kaolin deposits. The correlation of fossils suggested that it was deposited in a marine environment during the Late Ordovician-Early Silurian periods.

The upper part of the Mudawwara Formation, also known as the Ammar Formation or Ammar Member, is a glacial deposit of the Late Ordovician-early Silurian periods, which is well exposed at Jebel Ammar. It is a fluvial deposit laid down in large channels with a conglomerate base with well-rounded sandstone pebbles showing striations resulting from probable glacial abrasion processes.

The Khushsha Formation.

The Khushsha Formation of nautiloid sandstone (Bender 1974) is the youngest rock of the Khreim Group, with sandstone rocks deposited in shallow marine environments during the early Silurian period.

Graptolites (*Didymograptussp*), brachiopods (*Schizocrania*), Skolithos and trilobites cruziana ichnofossils are among the fossils found in the Ordovician deposits.

1.3.3 The Silurian Period

Sediments of this age concordantly overlie the Ordovician sediments found in the Batn el Ghul area east of Disi. They consist of a sandstone series of around 160 m thick. The transgression of the sea continued during the Silurian period, as seen from its shale beds.

The lower Silurian sediments consisting of bituminous shale are deposited in a shallow marine environment, but the Upper Silurian deposits show continental features proving the beginning of the regression of the sea.

The Silurian sandstones are similar to the underlying Ordovician sediments in their petrography and facies; hence, it is difficult to distinguish them from the latter. The fossil content allows their classification as of the Silurian period. Lower Cretaceous sediments directly overlie Silurian sediments along outcrops in Jordan, while Devonian, Carboniferous, Permian, Triassic and Jurassic period rocks are not found covering them on these outcrops, but they may still be encountered covering them in boreholes.

Fossils: Graptolites (Monograptus), Brachiopods (*Lingulaus, Platystrophya*) and shells of Conularia.

No sediments are exposed in Jordan from the Devonian to the Early Permian periods because either they were not deposited or their deposits had been eroded before the beginning of deposition of the Lower Cretaceous sandstones all over the country or Late Permian at the central-eastern escarpment of the Dead Sea and to the north.

1.3.4 The Permian Period

After Jordan had long been erosional land during the Devonian, Carboniferous and Early Permian periods due to the continuous sea regression, which started during the Late Silurian period, deposition of continental sediments resumed in Permo-Triassic times. The southernmost deposits of the Permo-Triassic time crop out in the deeply incised wadis east of the Dead Sea, such as Mujib, Zarqa Main, Himara and to the north. The Permian sediments here discordantly cover Cambrian sandstones.

The Um Irna Formation of the Late Permian period consists of coarse-grained conglomeratic sandstone at its base fining upwards to coarse, medium and fine-grained sandstones, silts and some clays at the top**.** It is 85 m thick. The Permian sediments contain diverse marine shore fossils, trace fossils, and plant fossils (*Dicroidiumsp*). The sediments show prominent cross-bedding, ripple marks and iron nodules. The Um Irna Formation was deposited at the same time as the formation of the Pangean Supercontinent produced by the Variscan orogeny processes.

1.4 Mesozoic Rocks in Jordan

The history of Mesozoic deposition in Jordan reflects the eustatic and Tethys Sea level fluctuations around the Arabian-Nubian Shield. The Mesozoic deposits in Jordan hold different lithological, paleontological and mineralogical layers, from detritus and sand to carbonate rocks changing into chalky rocks at the end of this period. During the Mesozoic era, from the Triassic to the Early Jurassic period, extensive rifting associated with the breakup of Pangaea took place. By the Early to Late Jurassic period, Gondwanaland had drifted southwestward. When the Triassic sediments were deposited, Jordan was still part of the large supercontinent (Pangea). Carbonate sediments were widely deposited during the Cretaceous epoch due to the warm climate and high water temperatures. Algae and cyanobacterial organisms partly produced the carbonates, while fluvial and deltaic siliciclastic deposits resulted from rivers originating from the African continent.

1.4.1 The Triassic Period

The transgression of the Tethys during the Late Permian period continued during the Triassic period, covering the same areas in Jordan. Sediments of the Late Permian and Triassic periods overlie the Cambrian sandstones in central and northern Jordan. The Triassic sediments in Jordan are subdivided into three formations: the Ma'in Formation of Early Triassic times, mainly composed of sandstones, the Dardur Formation of Middle Triassic times, mainly composed of limestone and the Ain Musa Formation of Upper Triassic times, mainly composed of salty and clayey sandstones. The exposed thickness of Triassic rocks measures around 660 m, concordantly covering the Late Permian rocks. They crop out in Wadi Zarqa Ma'in, Wadi Himara and northward to the Zarqa River, where they become overlain by Jurassic rocks. The thickness increases northward and reaches some 1000 m encountered in deep wells in north Jordan. Triassic deposits were laid down in an interior epicontinental sea (Sephardic) environment.

Based on the lithological composition, the Triassic deposits are subdivided into three units: A lower colourful sandy unit (the Ma'in, Dardur and Ain Musa Formations), a central unit with many limestone beds (the Hisban, Mukheiris and Iraq al-Amir Formations) and an upper unit commonly deposited under saline conditions (the Um Tina and Abu Ruweis Formations) **(Figs. 1-8 & 1-9).**

The Ma'in Formation is of the Early Triassic period ranging from 35 to 45 m thick. The lower portion of the formation, also called the Himara Member, consists of purplish-coloured sandstone, siltstone and rich lime claystone with Rhizocorallium ichnofossils. The upper member of the formation, or Nimra Member, is composed of sandstone, siltstone, and reddish and greenish clay with carbonate-rich beds indicating a beach rock environment. Cross-bedded whitish sandstone beds of about 50 to 150 cm in thickness are found in the uppermost part of this member.

The Dardur Formation, about 60 m thick, was also deposited in the tidal zone or very shallow water. The lower part of the formation consists of bioturbated sandstone with desiccation cracks, load casts, and ripple marks, which reflect a coastal intertidal mud flat depositional environment. In the middle and upper parts, cross-bedded sandstone and finely laminated dolomite and marl lithology indicate deepening upward to nearshore to a shallow marine environment.

Figure 1-8: Coloured sandstones of the Triassic Ma'in Formation exposed in Wadi Durdur, Dead Sea area

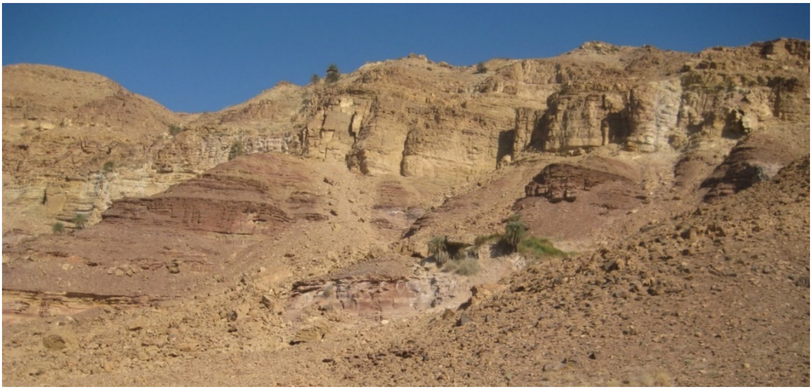

Figure 1-9: Exposure of Triassic deposits near the Panorama Dead Sea Road

The Ain Musa Formation (Early Triassic period) is well exposed in Wadi Ain Musa and has three members (Muhtariqa, Jamala and Siyale), each with its type section in the localities with the same name. The base of the formation was in part deposited by rivers, and most of the layers above are in a near-shore environment reflected in a fining upward cycle. The upper part of the Ain Musa Formation is characterized by alternations of sandstone, siltstone and marlstone beds with marine fossils such as ceratitid ammonites and terebratulid brachiopods (*Lingul sp*).

The Middle Triassic deposits of the Hisban Formation, with a thickness of about 30-35 m in Wadi Hisban and Wadi Dardur, are composed of strongly bioturbated wavy bedded grey limestone with stylolite structures. Marine fossils of ammonites, bivalves and crinoids indicate a shallow marine depositional environment.

The Mukheiris Formation consists of sandstone, siltstone, and claystone, about 80 m thick, cropping out in Wadi Mukheiris. It overlies the massive thick-bedded limestone. The formation is rich in fossils, including Conodonts, holothurian sclerites, ammonites (Ceratitida), brachiopods (Coenothyris) and bivalves.

The Iraq al-Amir Formation is a 160 m thick sequence of Triassic rocks that exposes the Iraq al-Amir and Um Tina formations. The base of this formation (the Bahhath Member) consists of sandy limestone, marl, calcite-cemented sandstone, fine sandstone, siltstone, and marly, laminated claystone with fossils (e.g., ceratitid ammonites, Placunopsis, crinoid ossicles, terebratulid brachiopods and Ophiomorpha trace fossils). The Abu Jan Member in the middle part of this formation, around 40 m thick, is composed of limestone and glauconitic. The upper Shita Member is characterized by marly limestone, marly claystone, and dolomitic limestone around 25 m thick. This member's brachiopods, bivalves, conodonts, *holothurian sclerites* and Zoophycus ichnofossils are documented.

Two formations represent the Upper Triassic (around 550 m thick), Um Tina and Abu Ruweis Formations. The presence of carbonate and evaporite deposits characterizes it. The Um Tina Formation of 70 m thick dolomitic beds contains stromatolitic lamination cropping out in Wadi Um Tina. The Abu Ruweis Formation is well exposed in the lower Zarqa River and contains gypsum intercalated with silt, black clay, dolomite, and preserved fern plant remains (*Phlebopteris*) reflecting a terrestrial environment **(Fig.1-10).** Generally, the Upper Triassic Formations are interpreted as a shallowing upwards carbonate-sabkha sequence. The most interesting stromatolites site in Jordan can be visited in the valley below Naur, not far under the truncation of the Triassic rocks by the Kurnub Sandstone (Fig.1-11).

Fossils: Crinoids, brachiopods (*Lingula*), bivalves (Myophoria, Placunopsis), Conodonts (*Pseudofurnishius priscus*), ammonites (Ceratididae), brachiopods (Coenothyris), palynomorph (*Camerosporites secatus, Corollina torosa, Duplicisporites verrucosus*) and Rhizocorallium, Zoophycus, Ophiomorpha ichnofossils.

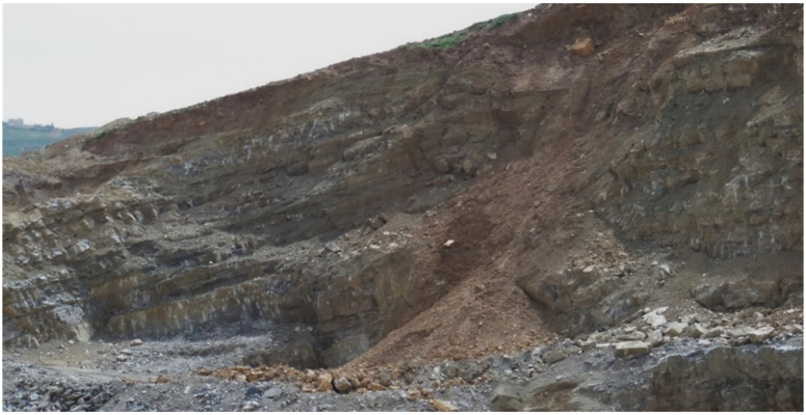

Figure 1-10: Upper Triassic deposits of the Abu Ruweis Formation in the gypsum quarry of the Zarqa River, west of King Talal Dam.

Figure 1-11: A. Triassic deposits near Naur (Prof. Klaus Bandel), B**.** Stromatolite structures in the same location.

1.4.2 The Jurassic Period

Overlying the Triassic rocks is the Jurassic Azab Group, which consists of seven formations: Hihi, Nimr, Silal, Dhahab, Ramla, Hamam, and Mughanniyya **(Table 1-3).** The Jurassic rocks in Jordan crop out 5 km north of the Wadi Shueib entrance into the Jordan Valley and northwards to Wadi Zarqa and along its course eastwards to the King Talal dam area **(Fig.1-12).**

The sediments consist of 25 cycles of deposition, where each cycle starts with sand on tidal flats or shores, followed by marine limestone, and then by dolomite reflecting the rising and falling sea levels. Complete exposures of Jurassic rocks in Jordan occur in the Zarqa Valley that cuts into the eastern slopes of the Jordan River Valley. The thickness of the sediments reaches about 440 m, covered in the area of the Zarqa River by thick Cretaceous rocks.

In some areas, along the fluctuating shorelines of the Jurassic period, interior seas, only intermittently connected to the ocean, formed where gypsum and anhydrite deposits were laid down to become covered by soil. Moreover, sand and mud deposits were brought in by rivers from the south. The Jurassic period deposits were partly eroded before the Lower Cretaceous epoch sandstone was deposited on a flat margin of the southern Gondwana continent.

Figure 1-12: Exposure of Jurassic Period deposits in the Wadi Zarqa area near King Talal Dam

Table 1-3: Formations of Azab Group of the Jurassic Period in Jordan.

Formation	Rock types	Thickness (m)	Fossils	Depositional environment
Mugha-nniyya	Dolomitic sandstone, dolomite	110	Ostracods (*cytherelloidea besireensis*), brachiopods (Terebratulida)	Marine, lagoon or swamp to tidal zone.
Hamam	Carbonate, clastic sandstone	76	Ammonite (*Micromphalites Jordanicum*).	Marine, tidal zone
Ramla	Clastic sand with clay and some carbonate rocks	80-130	Bivalves, trace fossils	Marine, tidal zone
Dahab	Carbonate limestone deposits	43-57	Bivalves, gastropods, brachiopods	Marine deepening upward
Silal	Sandstone	59-75	Corals, bivalves, brachiopods	Tidal zone to nearshore
Nimr	Limestone, dolomitic beds	20-26	bivalves, brachiopods, trace fossils	Marine
Hihi	Paleosol, sandy clay, pisolites, limestone, iron cemented sandstone	20-50	Bivalves, trace fossils	Terrestrial

1.4.3 Cretaceous rocks

Cretaceous rocks comprise three lithostratigraphic groups, Kurnub, Ajlun and Belqa, distinct in their depositional environments. The Kurnub Group consists mainly of fluviatile sandstone, while the Upper Cretaceous Ajlun and partly the Balqa Groups represent one of the major transgressions of the Tethyan Ocean, with their deposits covering almost all Jordan from the Yarmouk River in the north to the Ras en Naqab escarpment in the south **(Fig. 1-13).**

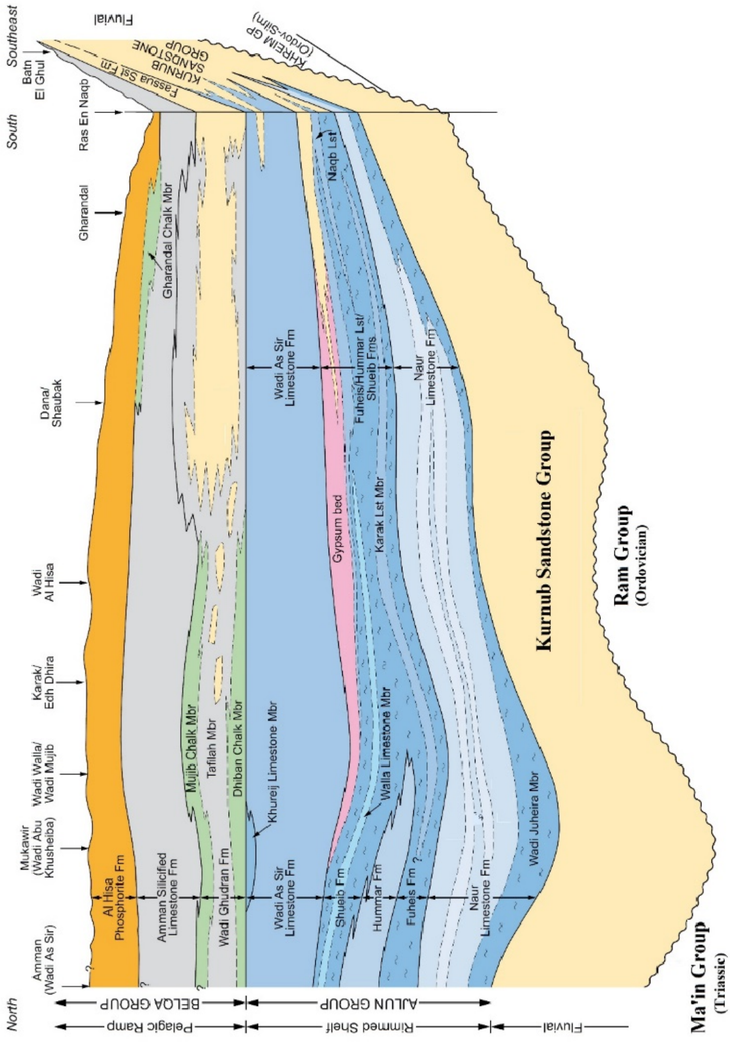

Figure 1-13: Simplified section of Cretaceous deposits from Amman to Batn El Ghoul, southern Jordan (after Powell, 1989, Powell and Moh'd, 2011).