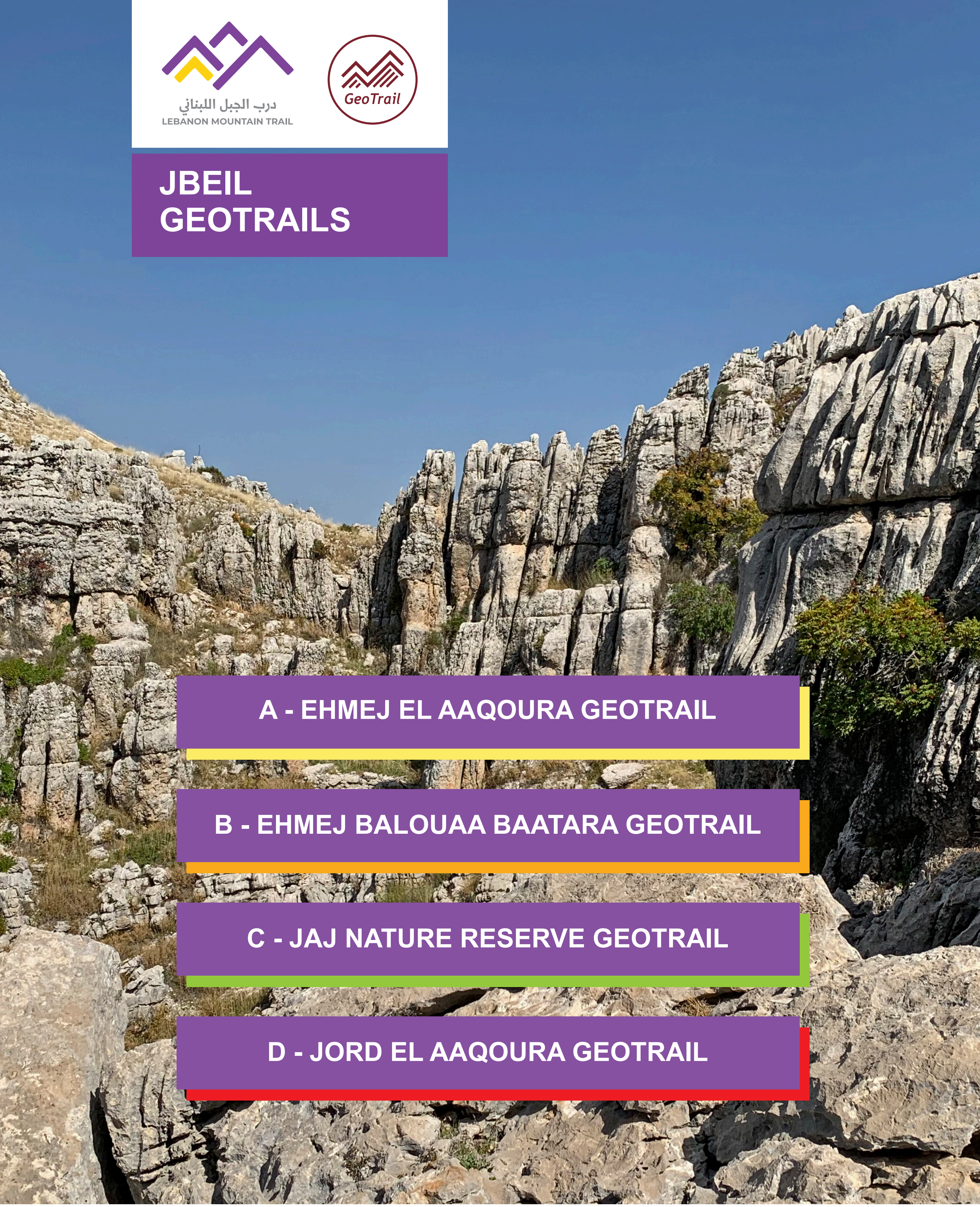


درب الجبل اللبناني
LEBANON MOUNTAIN TRAIL

GeoTrail

JBEIL GEOTRAILS

A - EHMEJ EL AAQOURA GEOTRAIL

B - EHMEJ BALOUAA BAATARA GEOTRAIL

C - JAJ NATURE RESERVE GEOTRAIL

D - JORD EL AAQOURA GEOTRAIL

REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT

gef

UNDP

AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

GEOLOGY OF LEBANON

Lebanon's geological history spans millions of years and showcases a wide array of captivating phenomena. Jbeil Geotrails constitute an invaluable pathway to explore this geological heritage. This network of Geotrails in Jbeil mountains does not only reveal Lebanon's geological heritage but also its influence on the physical and cultural landscapes. Beyond being hiking trails, the Jbeil Geotrails offer an immersive educational experience for adventurers and nature enthusiasts.

They invite hikers to embark on a journey of enjoyment and learning to understand Lebanon's geological diversity. With each step, hikers will be transported through epochs of time, tracing the geological processes that formed the Lebanese landscape. Beyond their scientific significance, Jbeil Geotrails celebrate Lebanon's rich heritage, connecting the geological, natural, and cultural dimensions, and reflecting the symbiotic relationship between humans and their environment.

A - EHMEJ - EL AAQOURA GEOTRAIL

On the Trail of Ehmej - El Aaqoura, you will go through different geological times from Jurassic (180 Ma) to Cretaceous (Cenomanian - 100.5 and 93.9 Ma). The rock layers along this trail have been folded (bent) because of a late structural tectonic deformation leading to the beds having an inclination with respect to the horizontal. The beds become more horizontal as you move towards the eastwards the highest parts of Mount Lebanon. On the way, you will pass by a cave developed in limestone and observe the relationship between agriculture and geology on basaltic terrains. The trail ends with the landslides of El Aaqoura.

Trail Direction	Total Length	Total Ascent	Total Descent	Duration	Difficulty Level
El Mathkouba - El Ouata	3.5km	209m	356m	2h	Difficult
Type of terrain	Dirt road, goat trail, footpath				

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT

gef

U N D P

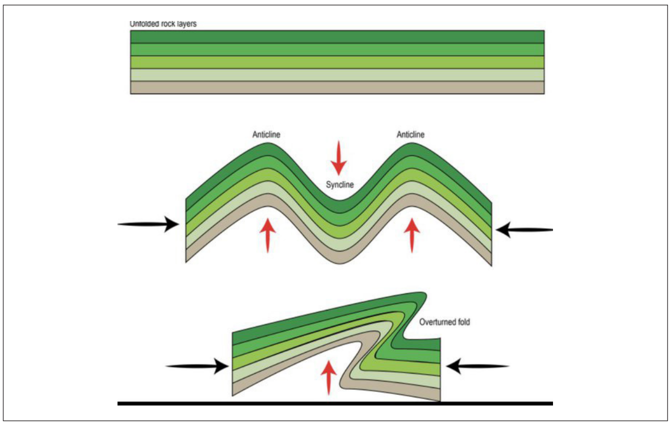
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

A1-A INCLINED BEDS

STRUCTURAL DEFORMATIONS

All geological beds (sedimentary layers and rock sequences) are originally deposited horizontally in a sedimentary environment. (e.g., beach, river, sea etc.). Folding is one example of structural deformation. It is the ductile (no rupture) deformation and bending of rocks because of compressive forces (forces pushing towards each other because of regional tectonic stresses), which led to horizontal beds being titled at an angle.

Depending on the degree of inclination and on the stress exerted, the angle with the horizontal will range between 0°: non-titled beds, to 90° vertical beds.



REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

A1-B FRACTURES

FRACTURES AND FISSURES ASSOCIATED WITH TECTONIC STRESSES

This site reveals fractures, which are the result of the brittle deformation of rocks when subject to stresses that exceed their rupture yield (forces applied over an area that are above what the rock can withstand before it breaks). These stresses come from regional tectonic stresses associated with tectonic movement of the plates in the region.

Usually a rock formation will break along a plane (Fault plane) where movement will occur (the movement can be horizontal, vertical or oblique).

The stress will result in fractures close to the fault plane. These fractures constitute a zone of weakness and a preferential flow path for water. This will lead to faster weathering along these zones.

A2 STREAM & AIN NASSOUH SPRING

SPRINGS AND GEOLOGY

A spring is formed when groundwater flowing underground gets in contact with the topography or emerges from a weak zone (fractures/ faults or along a preferential flow). Groundwater is rain and snow water infiltrating to the subsurface reaching the saturated zone (where all the voids and pores are filled with water) and starts flowing by gravity, until it is intercepted by a well or emerges as a spring.

Examples of springs are: Ain el Nassouh, Ain Echahir, Ain En Nounou, and Ain Bouhmar.

Streams running along the road can originate from snow melt, from springs or groundwater baseflow (groundwater (water flowing in the rocks in the subsurface) which will flow into streams when the water table intersects with the stream.

Ain Nassouh (Ehmej-El Aaqoura) emerging along inception horizons developed along fractures in dolomites (Rock age of 180-157 Ma)

REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

A3-A MECHANICAL WEATHERING

ACTIVITIES BY ROOTS

The roots of trees can play an important role in breaking the rocks. They can grow into small fractures and with subsequent growth exert pressure to open the cracks wider. This is one form of mechanical weathering that will lead to the physical disintegration of rocks because of root activities.

A3-B DOLOMITIZATION AND DIAGENESIS

DOLOMITIZATION

At this site we observe two main types of colored rock formations: 1) beige dolostones, and 2) creamy white dolomite veins. The rock sequence was originally limestone ($CaCO_3$) deposited around Early to Middle Jurassic (206-160 Ma). Limestone precipitated biogenically in a marine environment. Locally, around 159 Ma, an episode of magmatism due to extensional rifting (Abdel Rahman 2002) led to a slight uplift of the area, and to dolomitizing fluids (rich in Magnesium) to replace calcium with magnesium in limestone in two phases (pervasive: beige, and vein: white).

Two phase dolomitization: White and grey dolomite

Fact: The sand observed in this location is sometimes quarried as sand, however sand (SiO_2) is composed of the mineral quartz (hardness 7), compared to sandy dolomite (hardness 3); both have the same size of sand (1/64- 2mm), but have different composition, hardness and mineral properties.

Grey Dolomite

A4 BIOTURBATION

BIOTURBATION

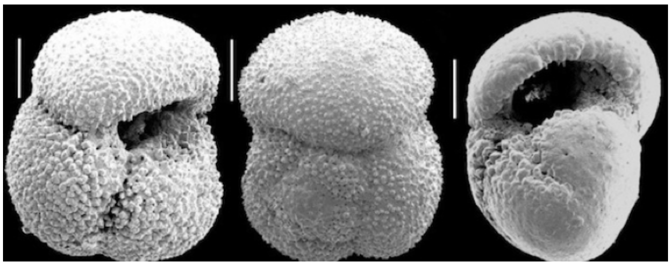
This aspect of crumbled rock with shapes of burrows is due to bioturbation. During the deposition of the soft sediments below the sea (before the sediments gets consolidated, cemented and compacted to become a rock), some organisms dwelling on the bottom of the seafloor dig into the sediments, extract the organic matter, digest it and excrete the reworked sediments to form a network of burrows into the rock. The sediments preserve the signature of bioturbation when they are turned into a rock by lithification. Depending on the type of burrows (shape and extent), one could estimate the depth of water and type of organisms. Such index organisms are called ichnofacies.

A5 LIMESTONE (JURRASIC AGE)

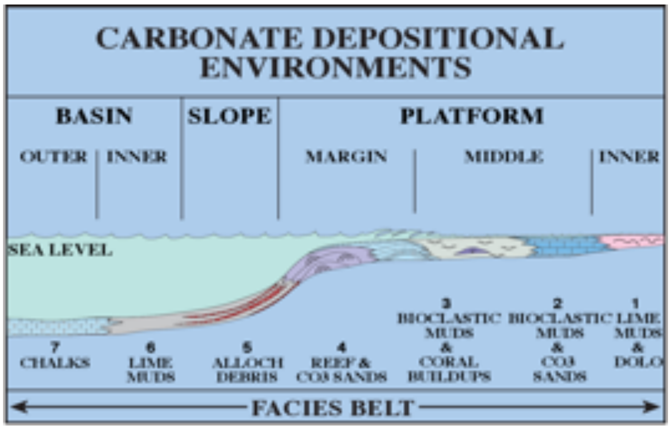
LIMESTONE DEPOSITION

This site is composed of Limestone (Calcium Carbonate; rock formed by small crystals of calcite $CaCO_3$). This limestone sequence is of Jurassic age (180-157 Ma). Usually limestone deposits biogenically under the sea on carbonate platforms.
Very small foraminiferal organisms (average size 10-100 µm) build their skeleton using calcium and bicarbonate from sea water. When they die, they deposit in the sea or ocean, while the organic material decays, the skeleton is recrystallized into calcite to form limestone with burial.

The rate of deposition varies between 7.3 mm per year e.g., coral reef, to 33 mm per 1000 years. When sea level drops (or the land gets uplifted), the limestone rock sequence that deposited under the sea is exposed. With more exposure, this rock undergoes weathering and erosion, forming valleys and mountains.



Pic of foraminiferal skeletons average size 10-100 µm

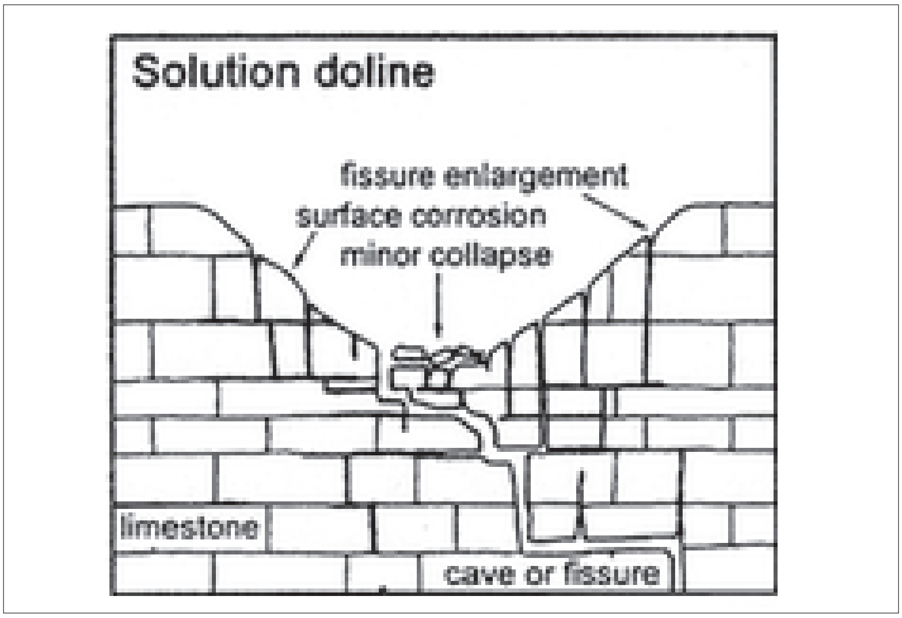


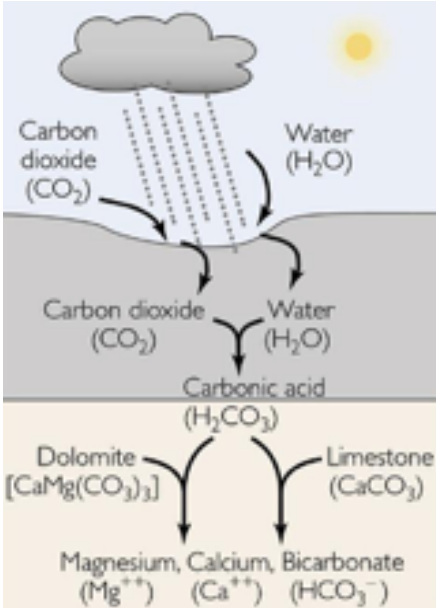
A6-A JOURET BOUHMAR

DOLINES

The depression observed in the landscape is called a doline.
It is characteristic of a karst landscape. These features are very common in limestone ($CaCO_3$) that is prone to dissolution by carbonation, where the calcium carbonate is dissolved into calcium and bicarbonate ions by slightly acidic water that infiltrates in the subsurface. With time, limestone will be weathered, where preferential flow of water is prevalent. With further weathering, soil will form, and the area becomes unstable, leading to a slight collapse of the weathered bedrock, resulting in a small depression in the landscape.

The dissolution started to occur in dolostone and limestone rocks that deposited under the sea in the Jurassic age (180 Ma-157 Ma ago). These dolines constitute rapid infiltration point sources.
Generally, during rain or snow melt, water will infiltrate fast into the doline and reach the saturated zone relatively more rapidly than the water infiltrating diffusively in other areas.
Therefore, these dolines should be protected because any contamination occurring at the doline will rapidly reach the connected water resource downstream.





REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

A6-B EL TELLAJ

EL TELLEJ LAPIAZ

The depression observed in the landscape is called a Lapiaz feature. It is characteristic of a karst landscape. These features are very common in limestone ($CaCO_3$) prone to dissolution by carbonation, where the calcium carbonate is dissolved into calcium and bicarbonate ions by slightly acidic water that infiltrates in the subsurface.
With time, limestone will be weathered, where preferential flow of water is prevalent. With further weathering, soil will form, and the area becomes unstable, leading to a slight collapse of the weathered bedrock, resulting in a small depression in the landscape.
The dissolution started to occur in dolostone and limestone rocks that deposited under the sea in the Jurassic age (180 Ma-157 Ma ago).

This area has been renowned for having perennial ice lasting till later in the year, due to its high altitude and its location in a shadowed area away from sunlight.

REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

A7 SPRING NABAA BOUHMAR

SPRINGS

A spring is formed when groundwater flowing underground gets in contact with the topography or emerges from a weak zone (fractures/ faults or along a preferential flow). Groundwater is rain and snow water infiltrating to the subsurface reaching the saturated zone (where all the voids and pores are filled with water) and starts flowing by gravity, until it is intercepted by a well or emerges as a spring.

Examples of springs are: Ain el Nassouh, Ain Echahir, Ain En Nounou, and Ain Bouhmar.

Streams running along the road can originate from snow melt, from springs or groundwater baseflow (groundwater (water flowing in the rocks in the subsurface) which will flow into streams when the water table intersects with the stream.

Ain Bouhmar (Ehmej-El Aaqoura) is a spring located at a preferential flow within the same rock formation. It emerges when the water is overflowing along a conduit or a big fracture (Rock age of 180-157 Ma)

Reservoir structure for Ain Bouhmar

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

A8 AIN EL NKHAA

SPRINGS

A spring is formed when groundwater flowing underground gets in contact with the topography or emerges from a weak zone (fractures/ faults or along a preferential flow). Groundwater is rain and snow water infiltrating to the subsurface reaching the saturated zone (where all the voids and pores are filled with water) and starts flowing by gravity, until it is intercepted by a well or emerges as a spring.
Ain El Nkhaa emerges from the limestone of Jurassic age confined between two basaltic layers.

Panoramic view observed in the vicinity of Ain Nkhaa

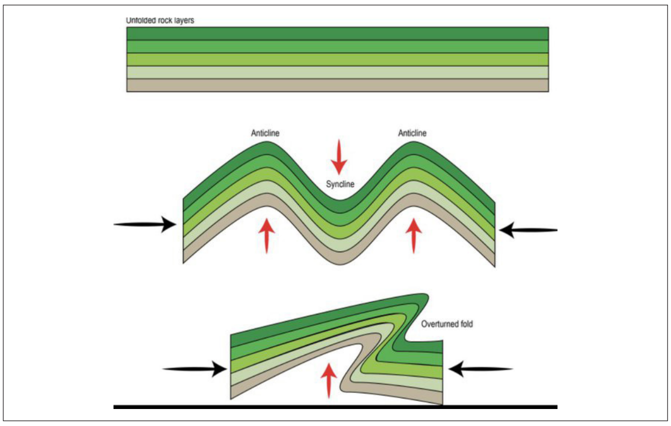
REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

A9 INCLINED BEDS

INCLINED BEDS

All geological beds (sedimentary layers and rock sequences) are originally deposited horizontally in a sedimentary environment (e.g., beach, river, sea etc.). Folding is one example of structural deformation. It is the ductile (no rupture) deformation and bending of rocks because of compressive forces (forces pushing towards each other because of regional tectonic stresses), which lead to horizontal beds being titled at an angle.

Depending on the degree of inclination and on the stress exerted, the angle with the horizontal will range between 0°: non-titled beds, to 90° vertical beds.



A10 AGRICULTURE PONDS IN BASALTS

MAGMATISM AND VOLCANISM IN LEBANON: AGRICULTURAL PONDS

The oldest volcanic rocks in Lebanon are believed to have a Kimmeridjian age and they are included in the Bhannes formation dated back to around 155 Ma. These volcanics have been associated to block faulting and local uplifts and/or the opening of the Neo-Tethys. Volcanism persisted intermittently during the Early Cretaceous, especially in northern Lebanon. Some volcanic deposits of Aptian age (dated to 118 Ma) are due to Magmatic events during the Aptian age (Cretaceous period- Mesozoic).

These rocks are prone to weathering by dissolution by carbonation (slightly acidic water chemically disintegrating the minerals in the basalts) and by oxidation (turning from black to brown to red by the oxidation of the ferric ion). This weathering will result in the formation of black clayey soil that is considered highly fertile, and relatively impermeable. This can explain why farmers use the basalts to construct irrigation ponds for rainfall harvesting or spring water storage, since the weathered basaltic soil doesn't allow water to infiltrate.

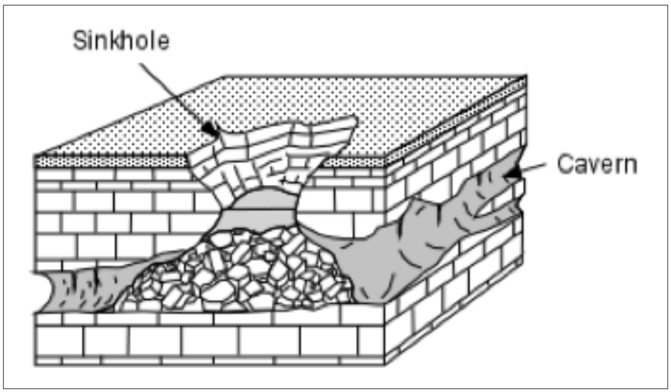
Basalts of Aptian Age (118 ma)- Mesozoic Era -Cretaceous period.


Terraces constructed on basalts of Kimmeridgian age (155 Ma)- Mesozoic era- Jurassic period. These types of rocks and soil are considered highly fertile.

A11 EL MATHKOUBA CAVE

CAVE FORMATION

Mgharet El Mathkouba developed in a rock formation of lower Aptian to Lower-Upper Aptian (126-113 Ma), known as C2b (or Mdairej formation or according to other nomenclatures “Falaise de Blanche”or “Falaise de Jezzine”). It is made up of a distinctive pale grey of massive unit of a 50-m thick limestone and shows little variation across Lebanon. Tectonic stresses during the uplift of Lebanon from the sea, lead to intense fracturing. Subsequently, water flowing into fissures and fractures dissolves the limestone (chemical weathering) and enlarges the fractures. At one point the weakened rocks, which are no longer able to remain stable, collapse in steps forming an arch known as Mgharet El Mathkouba. Mathkouba is in Arabic, المَثقوبَة, means perforated, or “with a hole” : ثقب. The location of this feature in specific location is related to the presence of fractures, weak zones, and preferential flow of water (former stream).



Example of collapse and formation of cavernous shapes when the rocks are weakened by chemical dissolution along fractures.


Al Mathkouba (Ehmej-Balouaa Baatara)


Massive formation of Limestone of Aptian age. Fractures and fissures consisting of preferential flow of water and chemical weathering

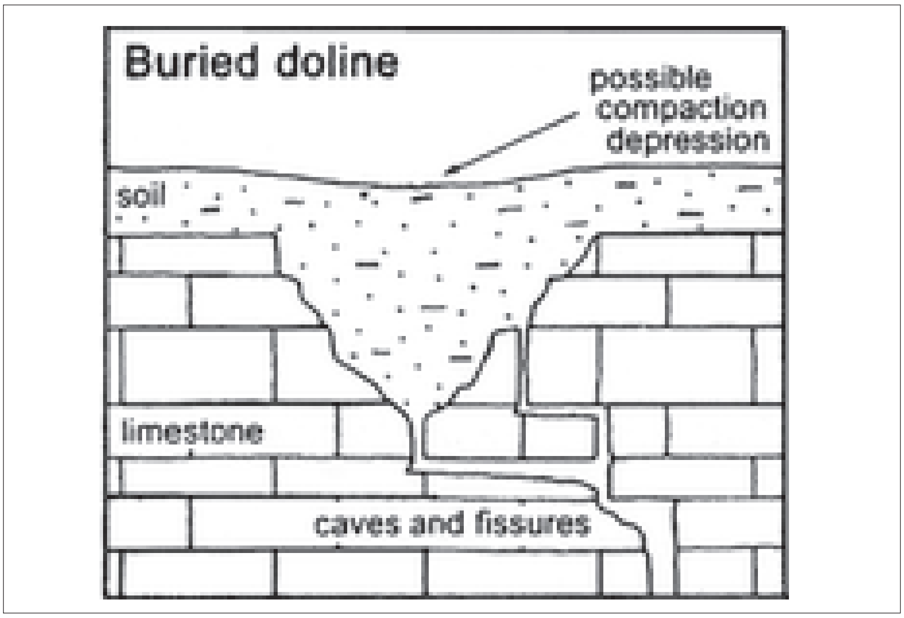
A12 DOLINE & KARSTIFICATION

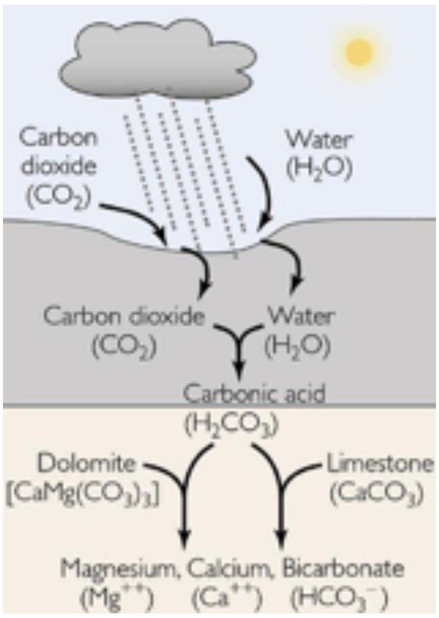
DOLINES

The depression observed in the landscape is called a doline. It is characteristic of a karst landscape. These features are very common in limestone ($CaCO_3$) prone to dissolution by carbonation, where the calcium carbonate is dissolved into calcium and bicarbonate ions by slightly acidic water that infiltrates in the subsurface. With time, limestone will be weathered, where preferential flow of water is prevalent. With further weathering, soil will form, and the area becomes unstable, leading to a slight collapse of the weathered bedrock, resulting in a small depression in the landscape.

The dissolution started to occur in dolostone, and limestone rocks that deposited in the sea in the Albian-Cenomanian age (112 Ma-93 Ma). These dolines constitute rapid infiltration point sources. Generally, during rain or snow melt, water will infiltrate fast into the doline and reach the saturated zone relatively more rapidly than the water infiltrating diffusively in other areas.

Therefore, these dolines should be protected because any contamination occurring at the doline will rapidly reach the connected water resource downstream.





REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

A13 BASALTS PONDS IN AGRICULTURE

MAGMATISM AND VOLCANISM IN LEBANON: AGRICULTURAL PONDS

The oldest volcanic rocks in Lebanon are believed to have a Kimmeridjian age and they are included in the Bhannes formation dated back to around 155 Ma. These volcanics have been associated to block faulting and local uplifts and/or the opening of the Neo-Tethys. Volcanism persisted intermittently during the Early Cretaceous, especially in northern Lebanon. Some volcanic deposits of Aptian age (dated to 118 Ma) are due to Magmatic events during the Aptian age (Cretaceous period- Mesozoic).

These rocks are prone to weathering by dissolution by carbonation (slightly acidic water chemically disintegrating the minerals in the basalts) and by oxidation (turning from black to brown to red by the oxidation of the ferric ion). This weathering will result in the formation of black clayey soil that are considered highly fertile, and relatively impermeable. This is explain why farmers use the basalts to construct irrigation ponds for rainfall harvesting or spring water storage, since the weathered basaltic soil doesn't allow water to infiltrate.

Basalts of Aptian Age (118 Ma)- Mesozoic Era -Cretaceous period.

Terraces constructed on basalts of Kimmeridgian age (155 Ma)- Mesozoic era- Jurassic period. These types of rocks and soil are considered highly fertile.

A14 EL AAQOURA LANDSLIDE

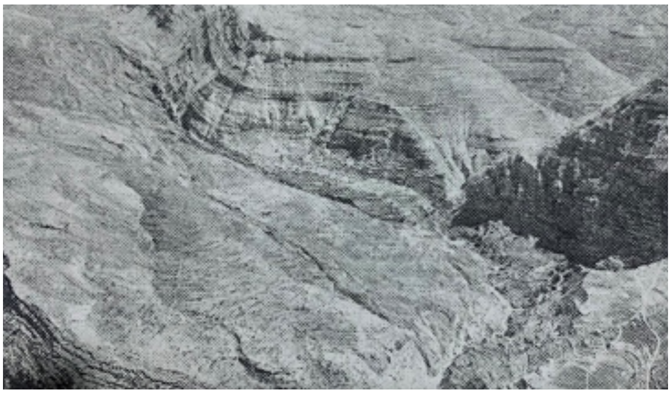
LANDSLIDES (MUD SLIDE/ EARTHFLOW)

When you look at El Aqoura village, you can see that it has developed to the east only. The volcanic and marly layers of Aptian age are rather friable because of extensive weathering. They are also unstable because they are located at the bottom of an Albian Cenomanian cliff in a saddle (direction North-South).

In summer 1929, following snow melt, a portion of the marls and volcanics slumped (parabolic mud slide of 15-30 m) and went about 500-1000 m downslope destroying the western part of the village.
It was reported that "only the doors remained, the houses were found 200-300 meters downslope" (Dubertret, 1945).

In spring 1937, the Mud slide/ Earth flow occurred again.
The locals had constructed water retention ponds in the impermeable basalts leading to pressure exerted on unstable terrains.

Every year, following snowmelt and intense rain, the upper portion of the friable reddish marly and clayey soil gets remobilized with water and gets flushed downlope into the upstream tributaries of Nahr Ibrahim River leading to its coloration in reddish/ brown because of suspended fine particles in river water. In the Greek mythology, this color is attributed to the blood of Adonis killed by the boar close to Afqa Cave. The blood mixed with river water, gave his name to this tributary of the River: Nahr Adonis.



REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

B - EHMEJ - BALOUAA BAATARA GEOTRAIL

On the Trail of Ehmej - Balouaa Baatara, you will go through different geological times from Jurassic (180 Ma) to Basal Cretaceous (145 Ma). The Jurassic beds start with limestone and dolostone (limestone rich in Magnesium), then a basaltic layer due to an episode of volcanism, then limestone of about 140 Ma of age. During the Jurassic, all these layers deposited below the sea. Later, you will pass through a rock formation composed of sandstone deposited in a fluvial network. The latter indicates that Lebanon during these times emerged from below the sea. The beds have been folded (bent) because of a late structural tectonic deformation leading to the beds having an inclination with respect to the horizontal. On the way, you will pass by a spring emerging from the rocks at an impermeable boundary. The trail ends with the extraordinary three- bridges sinkhole:
an outstanding witness of weathering of limestone and karst landscape formation in Lebanon.

Trail Direction	Total Length	Total Ascent	Total Descent	Duration	Difficulty Level
Ehmej - Balouaa Baatara	6km	241m	274m	2h 30m	Difficult
Type of terrain	Dirt road, goat trail, footpath				

REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT

gef

UNDP

AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

B1-B2 TWO-PHASE DIAGENETIC DOLOMITIZATION

At this site we observe two main types of colored rock formations:

1) beige dolostones, and 2) creamy white dolomite veins. The rock sequence was originally limestone ($CaCO_3$) deposited around Early to Middle Jurassic (206-160 Ma). Limestone precipitated biogenically in a marine environment. Locally, around 159 Ma, an episode of magmatism due to extensional rifting (Abdel Rahman 2002) led to a slight uplift of the area, and to dolomitizing fluids (rich in Magnesium) to replace calcium with magnesium in limestone in two phases (pervasive: beige, and vein: white).

Fact: The sand observed in this location is sometimes quarried as sand, however sand (SiO_2) is composed of the mineral quartz (hardness 7), compared to sandy dolomite (hardness 3); both have the same size of sand (1/64- 2mm), but have different composition and mineral properties.

Two phase dolomitization: White and grey dolomite

Dolomitic sands

Sands (Ehmej-Balouaa Baatara)

REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT

gef

UNDP

AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

B3 DOLOMITE

Saydet el Ramliye is called Ramliye (from Ramel; sand in Arabic). This sand does not refer to the common sand (composed of quartz generally, SiO_2), but of dolomitic sand $CaMg(CO_3)_2$ which refers to the grain size of sand (1/64-2mm).

Sources and notes:

[1]Hydrothermal dolomitization is a diagnetic process where calcium in calcium carbonate (limestone; $CaCO_3$) gets replaced partially (50%) by magnesium ($CaMg(CO_3)_2$) by upwelling hydrothermal fluids associated with magmatic activity.

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UN DP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

B4 JOURNEY THROUGH GEOLOGICAL TIMES

Inclined beds going from Jurassic (~155 Ma) till Cretaceous (Cenomanian; ~94 Ma) with variable rock formation depending on the depositional environment of the rock

Inclined beds going from Jurassic (~155 Ma) till Cretaceous (Aptian ~118 Ma) with variable rock formation depending on the depositional environment of the rock

A disconformity indicates a period where deposition did not occur or where the layers were eroded. The reason behind this disconformity is the uplift of Lebanon during Early Cretaceous (145 Ma) and the exposure of a late Jurassic layer, which was fully eroded in the north (but is still present in the south).

Therefore the sandstone of the Basal Cretaceous lies unconformably over the eroded layers of Jurassic age indicating a hiatus in deposition or a marker of missing times.

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
U N D P
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

HISTORY OF THE AREA AND RELATED PROCESSES: INSIGHTS INTO SEA LEVEL CHANGES

The history of the area can be divided into periods of sedimentary deposition below the sea and periods of uplift above the sea due to regional tectonism, during which weathering/ erosion and no-deposition occurred.

In early Jurassic times, the oldest exposed formation (Chouane member of the Kesrouane formation) composed of dolostone was deposited in supratidal conditions (area that was not covered by the sea at all time affected at moments by fresh water and episodes of evaporation). These conditions shifted to slightly deeper environments in middle Jurassic times. Around 155 Ma (Kimmeridgian age), episodes of subaerial volcanism occurred because of block faulting leading to the deposition of volcanic layers called the Bhaness formation. In late Jurassic, when volcanic activity ceased, the area was submerged under the sea, where the deposition of limestone led to the Bikfaya formation (J6). It is assumed that a layer called Salima formation of late Jurassic was overlying the Bikfaya formation. In Early Cretaceous, block uplifting and another episode of volcanism led to the uplift of the area, leading to the erosion of the Salima formation, the deposition of a basal volcanic layer of early Cretaceous age. Therefore, there is a disconformity between the Basal Cretaceous volcanic layer (βC1) and the Bikfaya formation (J6) in this area denoting a period of erosion and non-deposition during late Jurassic.

Sea level during the Jurassic times: Sea level changes are classified either as regional affected by tectonic changes (uplift and subsidence) or because of absolute sea level rise (melting of the ice poles during the interglacial ages). The eustatic sea-level fluctuation curve shows that a general rising sea level trend prevailed throughout the Jurassic (with the lowest sea levels corresponding to the Early Jurassic and the highest levels to the Late Jurassic). This general trend also includes four major events of (sharp) sea level drop. The first one corresponds to the earliest Jurassic, while the second coincides with the Liassic-Bajocian boundary (which is also the boundary between the Chouane and Nahr Ibrahim Members). The third drop of the sea level (shifting from the rising sea-level trend) occurred during the Bathonian times, and the last major sea level drop coincides with the Bathonian-Oxfordian boundary.

During Early Cretaceous times, episodes of magmatism led to the uplift of the area, above seawater, which led to the formation of a network of rivers (alluvial network), with channel beds. In these times (Neocomian and Barremian ages), swamps, rivers and deltas were spread all over Lebanon, which allowed a distribution over a large area of sands and shales (indicative of continental environment instead of marine environment). In the later part of that time, sea levels began to rise, thus yielding to a deposition of marls (50% clays, 50% calcium carbonate), indicating both a continental and marine environment (subtidal environment close to shoreline). This marks the boundary of gradual sea level rise. As Lebanon moved into a transgressive state (sea level rising gradually), sandy limestone deposited in a subtidal environment, Abeih formation (C2a), then a limestone massive cliff known as Falaise de Blanche or Mdairej formation (C2b). During the end of the Aptian time, another episode of volcanism took place leading to a deposition of basalt in subaerial settings, overlain by marls and glauconite (a green iron-rich mineral indicative of continental environments), then by dolostones in a supratidal environment prevalent in the Albian time.
The Albian- Cenomanian age witnessed a sea level rise, leading to the deposition of marly limestone, then gradually limestone forming the middle and upper layer of the Sannine Formation.

During the Cenozoic times, there was an inversion of tectonics in Lebanon affected by the Syrian Arc deformation (extensional features turned into compressional) because of the collision of the Afro-arabian and Eurasian Plate starting Late Cretaceous. The latter event affected the tectonic setup of the area and led to prominent folding and reverse faulting as noted by the tilting and bedding attitudes observed in the area. The second phase of the deformation is believed to account for the major uplift and emergence of the Lebanese mountains.

After the gradual uplift of Lebanon in the Miocene times, the exposure of the rock formation to weathering agents led to a gradual weathering and erosion of the Lebanese mountains at rates of about 4.5-6 mm/1000 years (based on regional denudation rates). Different types of weathering can be observed including carbonation (leading to the formation of karst landscapes; e.g., caves) and oxidation (leading to color molting in the rocks) among others.

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

B5 CONTACT DOLOSTONE - BASALTS

VOLCANIC ROCKS: BASALTS

Basalts of Kimmeridgian age (155 Ma old): The rocks (brownish to reddish) observed at this location are basalts. They form from the cooling of lava flow that erupted in Lebanon around 155 Ma (Kimmeridgian age- Jurassic epoch). They are considered volcanic igneous rocks composed of about 55% silica, mainly Pyroxene and Plagioclase (silicate minerals). During this time, periods of magmatism allowed the uplift of the area from below the sea, leading to subaerial volcanism, while during periods of quiescence, the land subsided, leading to deposition of limestone below the sea.

These rocks are prone to weathering by dissolution by carbonation (slightly acidic water) and by oxidation (turning from black to brown to red by the oxidation of the ferric ion). This weathering will result in the formation of black clayey soil that is considered relatively impermeable. This can explain why farmers use the basalts to construct irrigation ponds for rainfall harvesting or spring water storage, since the weathered basaltic soil doesn't allow water to infiltrate. Basaltic soils are also considered very fertile because they contain important ions and heavy metals important for the growth of plants.

Black basalts and tuffs with limestone indicative of subaerial volcanism (Kimmeridgian age ~155 Ma)

Brown to reddish basalts (Kimmeridgian age ~155 Ma)

Stream coming from Nabaa Echahir and other springs flowing over basalts: The yellow color is due to the oxidation of iron in minerals within basalts into oxides (limonite)

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

B6 INCLINED BEDS & FAULTS

FAULTS AND FRACTURES

This site reveals a fault. A fault is the result of the brittle deformation of rocks when they are subject to stresses that exceed their rupture yield (forces applied over an area that are above what the rock can withstand before it breaks). The rock will break along a plane (fault plane) where movement will occur (the movement can be horizontal, vertical or oblique).

A fault is discerned when two rock formations of different age are found facing each other. The stress will result in fractures oriented similarly to the fault plane or at an angle to it.

These fractures constitute a zone of weakness and a preferential flow path for water. This will lead to faster weathering along these zones.

B7 PANORAMIC VIEW OF LAYERS (INCLINED BEDS)

GEOLOGICAL TIMES AND DEPOSITION

Inclined beds going from Jurassic (~155 Ma) till Cretaceous (Aptian ~118 Ma) with variable rock formation depending on the depositional environment of the rock

A disconformity indicates a period where deposition did not occur or where the layers were eroded. The reason behind this disconformity is the uplift of Lebanon during early cretaceous (145 Ma) and the exposure of a late Jurassic layer, which was fully eroded in the north (but is still present in the south).

Therefore the sandstone of the basal Cretaceous lies unconformably over the eroded layers of Jurassic age indicating a hiatus in deposition or a marker of missing times.

B8 NABAA ECHAHIR SPRING

SPRINGS

A spring is formed when groundwater flowing underground gets in contact with the topography or emerges from a weak zone (fractures/ faults or along a preferential flow). Groundwater is rain and snow water infiltrating to the subsurface reaching the saturated zone (where all the voids and pores are filled with water) and starts flowing by gravity, until it is intercepted by a well or emerges as a spring. Examples of springs are: Ain el Nassouh, Ain Echahir, Ain En Nounou, and Ain Bouhmar

Streams running along the road can originate from snow melt, from springs or groundwater baseflow (water flowing in the rocks in the subsurface) will flow into streams when the water table intersection with the stream.

Ain Echahir: (Ehmej-Balouaa Baatara)
emerging between limestone and an impermeable contact with the basalts (Volcanic rocks) (Rock age of 180-155 Ma)

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

B9 CONTACT BASALTS - LIMESTONE

Around 155 Ma (Kimmeridgian age), episodes of subaerial volcanism occurred because of block faulting leading to the deposition of volcanic layers called the Bhaness formation. In late Jurassic, when volcanic activity ceased, the area was submerged under the sea, where the deposition of limestone led to the Bikfaya formation (J6).

This site represents a geological contact between basalts and limestone characterized by a different depositional environment and geological time.

The youngest layer (J6) is composed of Limestone (Calcium Carbonate; rock formed by small crystals of calcite $CaCO_3$).

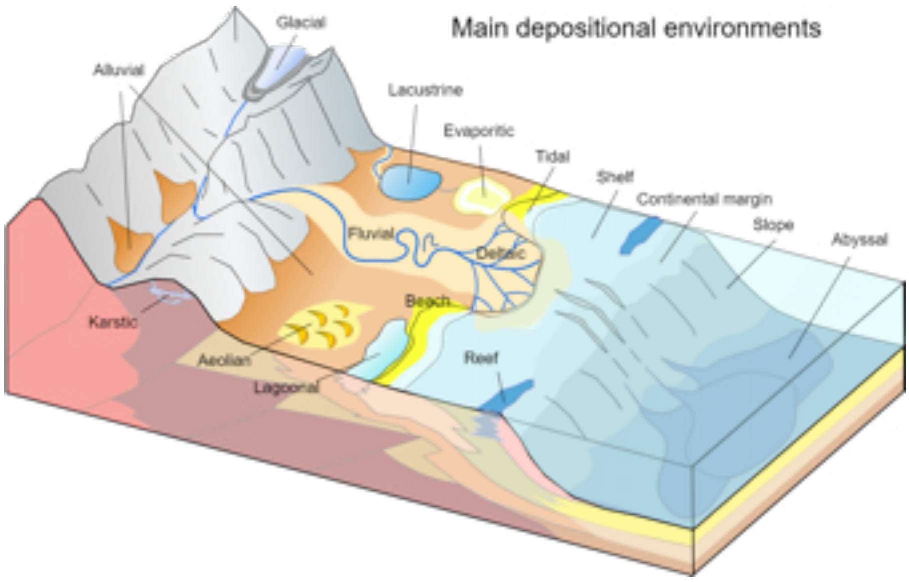
This limestone sequence is of Late Jurassic age (155-150 Ma). Usually limestone deposits biogenically under the sea on carbonate platforms. Very small foraminiferal organisms (average size 10-100 µm) build their skeleton using calcium and bicarbonate from sea water. When they die, they deposit in the sea or ocean, while the organic material decays, the skeleton is recrystallized into calcite to form limestone with burial. The rate of deposition varies between 7.3 mm per year e.g., coral reef, to 33 mm per 1000 years.

The oldest layer (J5) is composed of reddish, brownish basalts that have deposited during a period of magmatism (155 Ma) from fissure eruptions and intermittent periods of quiescence.

B10 CONTACT JURASSIC - CRETACEOUS

DEPOSITION OF LIMESTONE (J6-JURASSIC))

The oldest layer is composed of Limestone (Calcium Carbonate; rock formed by small crystals of calcite $CaCO_3$). This limestone (J6) sequence is of Jurassic age (180-157 Ma). Usually limestone deposits biogenically under the sea on carbonate platforms. Very small foraminiferal organisms (average size 10-100 µm) build their skeleton using calcium and bicarbonate from sea water. When they die, they deposit in the sea or ocean, while the organic material decays, the skeleton is recrystallized into calcite to form limestone with burial. The rate of deposition varies between 7.3 mm per year e.g., coral reef, to 33 mm per 1000 years.



SEA LEVEL DROP AND LAND UPLIFT

At the end of the Jurassic period (145 Ma), the uplift of Lebanon during Early Cretaceous led to the exposure of a Late Jurassic layer, which was fully eroded in the north (but is still present in the south). The uplift was due to a period of magmatism in the north and a regional tectonic setting.

DEPOSITION OF SANDSTONE (C1-CRETACEOUS)

Sandstone is a rock formed by cementation of sand grains. These sand grains have deposited in a fluvial setting 145 Ma ago that is very similar to the fluvial network observed in our current environment. The compaction and cementation of the sand grains make up the rock called sandstone. The cement is rich in oxides (hematite and limonite: oxidized iron) thus giving the sandstone the reddish and yellowish color. Between the limestone (oldest J6) and the sandstone (youngest C1) lies an eroded layer.

Therefore the sandstone of the Basal Cretaceous lies unconformably over the eroded layers of Jurassic age indicating a hiatus in deposition or a marker of missing times.

REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT

gef

U N
D P

AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

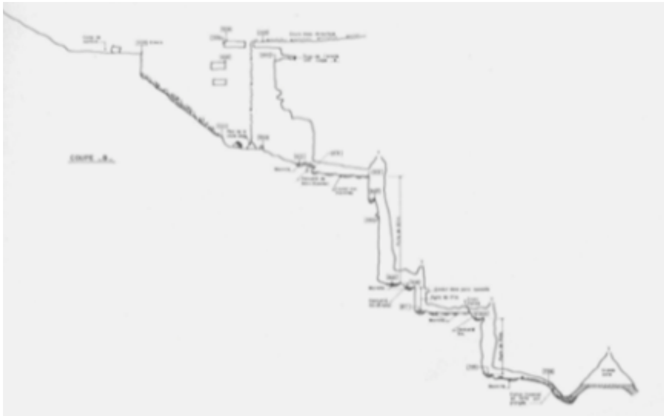
B11 BALOUAA BAATARA SINKHOLE

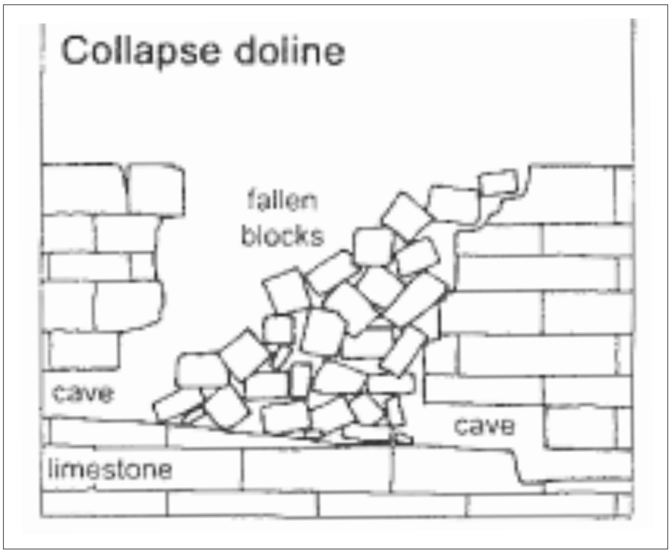
BALOUAA BAATARA CAVE

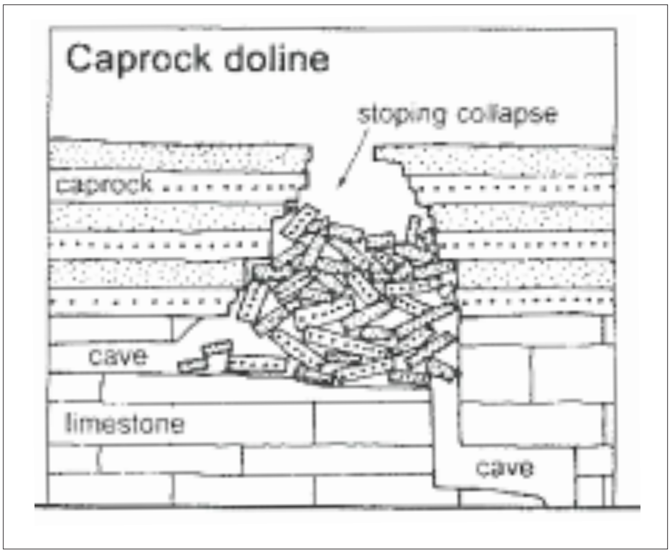
Balouaa Baatara Sinkhole is a hole formed in a rock formation of Jurassic age (168-165 Ma). This massive grey formation is composed of limestone and dolomitic limestone. The sinkhole is formed as a collapsed doline/ caprock doline, from the dissolution of the rocks because of mechanical and chemical weathering. First the rock underwent dissolution/weathering, which in turn led to fissure enlargement and weakening of the rocks and soil. Subsequently, the weakened rocks collapsed forming the first bridge, and with subsequent dissolution, the second and third levels collapsed.

The depth of the sinkhole is 250 m. The remaining bridges indicate highly massive resistant rocks where weathering did not occur, where water flow was concentrated in the collapsed parts. Such processes take substantial time (rate of chemical weathering is in the range of 4.5-6 mm/1000 years). This process started to occur with the final uplift of Lebanon that started around 15 Ma, and persisted with the latest tectonic developments in the region.

This sinkhole connects with springs in Basatine el Ossi: A tracer test was performed in 1985, where Uranine (green dye) was injected in the Baatara Sinkhole and after 12 hours the dye was retrieved in Nabaa el Dalli (Basatine El Ossi; over 6 km). Velocity of groundwater flow= 0.5 km/h (fast). Therefore, there is a need to protect this sinkhole and the stream flowing into it from any potential point source contamination.





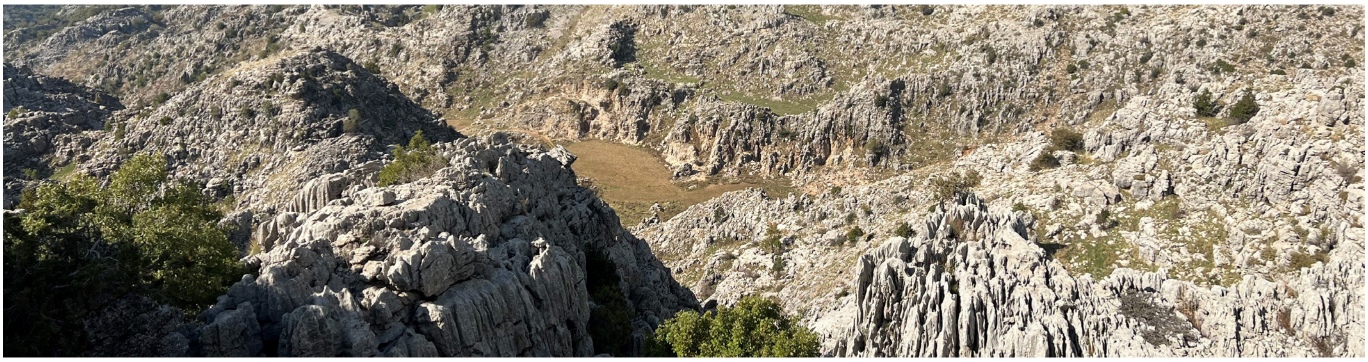


Sources and notes:

[1]Process where water that becomes slightly more acidic (e.g., because of the carbon dioxide from the atmosphere and the soil) is able to dissolve limestone (formed of the mineral calcite; $CaCO_3$) by breaking the bonds between calcium and bicarbonate. This can be observed when pouring vinegar on calcite, it will produce a fizziness, indicating that the calcite is getting dissolved.

[2]Chemical denudation is the chemical alteration of existing rocks subject to dissolution by water, carbonated water or by oxidation

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences



C - JAJ NATURE RESERVE GEOTRAIL

The Jaj Nature Reserve Geotrail Loop is a perfect example of an amazingly developed karst landscape. On this section you will see a grayish landscape made up of dissolved limestone resulting into various surface sculpted forms. This landscape is referred to as Karst (German form of a Slovene word meaning bare stony ground) that describes limestone terrain characterized by a stony ground (sometime rough and edgy), a lack of surface water drainage, and a discontinuous or thin soil cover. The word karst comes from the name of a limestone plateau known as Kras, located in Slovenia (Postojna). This massive rock forming the Jaj Nature Reserve area consists of light bluish to grayish limestone of Jurassic age (150 Ma) (known locally as Kesrouane, because of the presence of best observable section in Kesrouane area, notably Nahr Ibrahim). It was affected later (starting 15 million years ago) by dissolution (type of weathering) by water (lightly acidic, rich in carbonic acid from the carbon dioxide in the air and the soil). This preferential dissolution led to different shapes that highly depend on the direction of the water flow, the stagnation of water, effect of snow, and massiveness of the rock etc. at small and large scales. This explains why you will see along the way many different karst forms. Along the trail, you may find some fossil molds filled with shiny calcite crystals (calcite). These fossils have originally deposited with the rock at the time of the limestone formation in Jurassic times. The fossil itself was not preserved, only its mold remained and was filled by calcite cement during later times. You will have the opportunity to see in the panoramic view a volcanic dyke. This has formed in the Jurassic time (late Jurassic), where lava intruded in the existing limestone and erupted through a large fissure (or fracture). The basalt is locally used as a very good fertile soil.

Trail Direction	Total Length	Total Ascent	Total Descent	Duration	Difficulty Level
Jaj Nature Reserve	5km	369m	384m	2h 30m	Difficult
Type of terrain	Footpath				

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT

gef

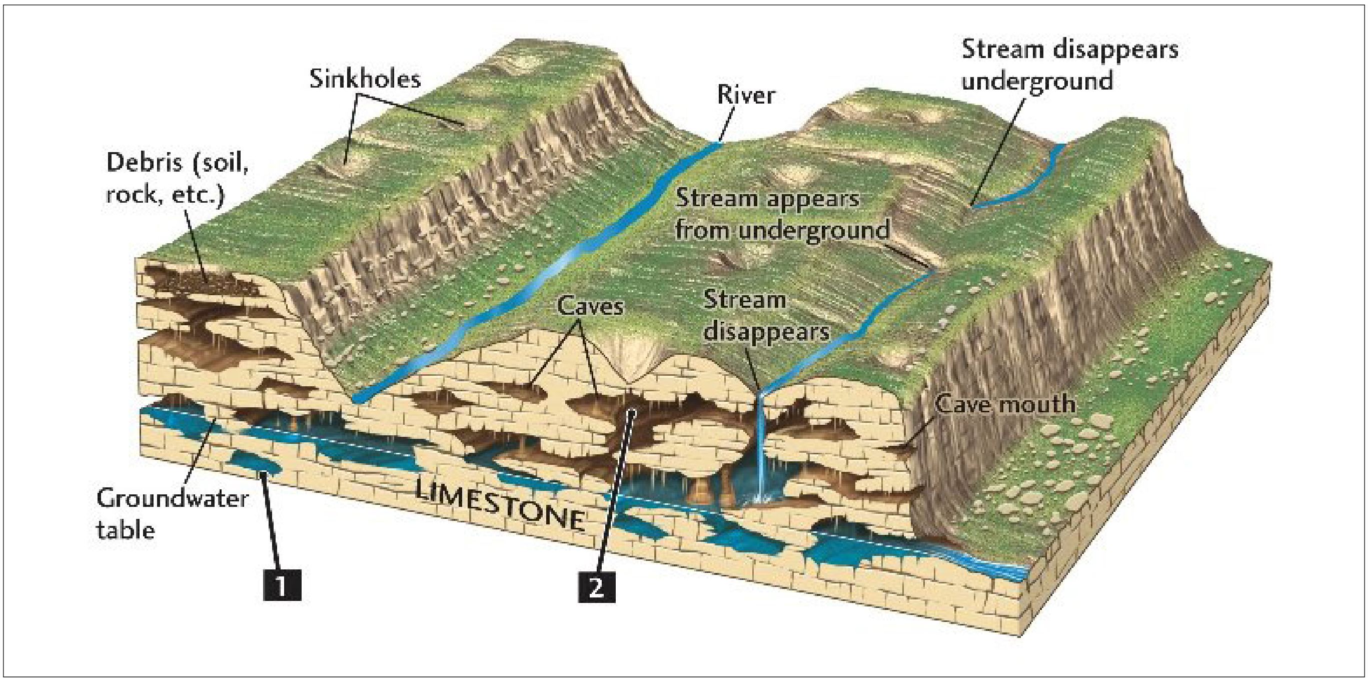
UNDP

AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

KARST LANDSCAPES

WHAT IS KARST?

Karst is the German form of a Slovene word meaning **bare stony ground'** and is used to describe limestone terrain characterized by a lack of surface drainage, a discontinuous or thin soil cover. It comes from the name of a limestone plateau known as **Kras**, located in Slovenia (Postojna)



Example of a karst system developed on the ground and in the subsurface that highlights the different features associated with a karst landscape (Grotzinger and Jordan, 2010).

DISSOLUTION OF SOLUBLE ROCKS (E.G., LIMESTONE) BY CARBONATION

Limestone dissolves along cracks by the action of slightly carbonated waters; Undersaturated water with respect to calcite containing carbonic acid (from atmospheric carbon dioxide) follows bedding planes, joints and dissolving limestone. Carbonic acid reacts with calcite to form calcium bicarbonate and calcium (a soluble material carried away in solution), forming limestone caverns. It starts with a small fracture/crack/ pore leading to further dissolution to fractures in openings filled with water and air (Vadose zone). The differential dissolution of limestone occurs on these landscapes because of a variation in the flow of water films, orientation of water flow, velocity of the dissolving waters, as well as their saturation in calcite, thus giving to the rock a rugged aspect.

ORIGIN OF LIMESTONE

This massive rock forming the Jaj Nature Reserve consists of light bluish to grayish limestone of Jurassic age (150 Ma) (known locally as Kesrouane, because of the presence of best observable section on Kesrouane area, notably Nahr Ibrahim). This rock was affected by a later phase of hydrothermal dolomitization around volcanic dykes. Dolomite is the crystalline rock that looks like sand but that is formed of magnesium rich calcite $CaMg(CO3)^2$.

Sources and notes:

[1]Limestone forms biogenically by the settling and recrystallization of foraminiferal skeletons (average size 10-100 μm) in the sea. These microorganisms build their skeleton using calcium and bicarbonate from sea water. Therefore, limestone is indicative of deposition below the sea (to the exception of charophytes that deposit in fresh water lakes and lead to limestone deposition as well)

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

C1→C8 EXAMPLES OF KARST FEATURES OBSERVED IN JAJ NATURE RESERVE AREA

C1: Typical karst landscape of preferentially weathered limestone intersected by fractures.

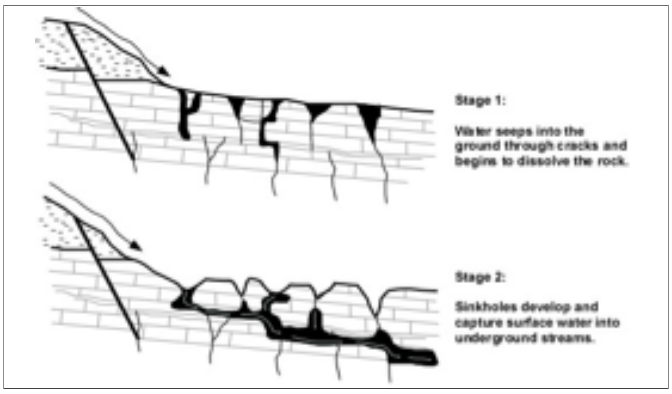
C1: Fractures due to tectonic stresses which later become a weak plane and a preferential flow to water, where more dissolution can occur.

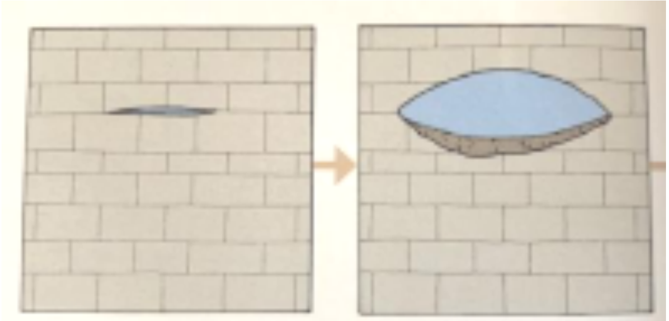
C2: Molds of fossils (corals (round) and bivalves (elongated)) dissolved and filled with recrystallized calcite after final uplift uplift of the rocks

C2: Remains of fossils (bivalves of Jurassic age) indicative of the deposition of this rock under sea environments (Inter-tidal, place along the coast always submerged with water most of the time)

C3: Lapiaz or karren field Structures: Differential dissolution of calcium carbonate in limestone due to the orientation of flow of water (surface streams) or snowmelt, resistence to dissolution of the limestone. Resistent parts will resist dissolution and remain as a field of limestone pillars.

C4: Houyet el Mouchara Sinkhole formed because of the weathering and dissolution of calcite in a major preferential flow zone.
The rocks highly weakened because of dissolution collapse in various steps leading to a collapse doline or sinkhole



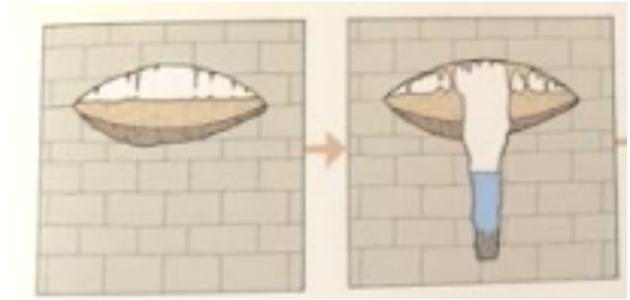


C5: Cave relict developed in limestone, because of preferential weathering and flow of water along fissures. Water slowly enlarges the fissure, that becomes a conduit and gets further enlarged.

Illustration of carbonic acid generation from atmospheric carbon and soil. Slightly acidic water seeping into limestone will lead to calcite dissolution by carbonation and a subsequent enlargement of cavities and cracks.

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

C5: Cave developed in limestone.
When calcite gets weathered by dissolution, in the vadose zone (unsaturated zone), it can precipitate again;
The hanging deposits are called speleothems (stalagtites) that formed when this level of the cave was active. Water loaded with Calcium and bicarbonate ions infiltrate below the surface and flows slowly along fissures. It precipitates calcite very slowly on the walls of the formed cave.



The coating of the cave have a yellowish brown color as a result of weathering and erosion during times were cave formation has ceased.

C6: Illustration of the collapse doline in massive rocks in the absence of soil cover, typical of the grey rocks of Jej area. These vertical shafts may be linked to a well developed cave in the subsurface.

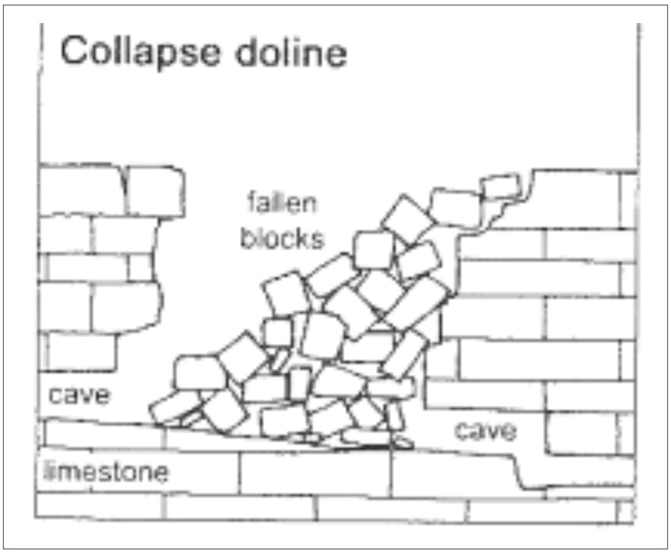
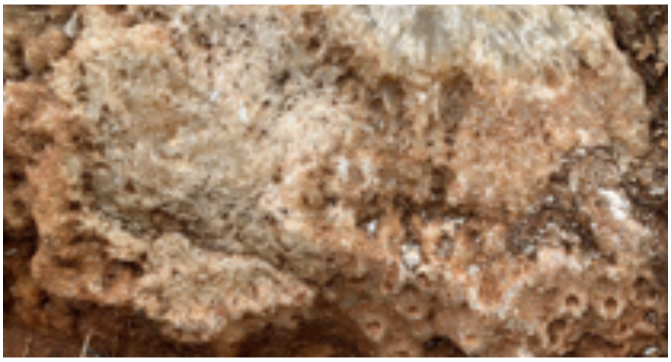


Illustration of the collapse doline in massive rocks in the absence of soil cover, typical of the grey rocks of Jej area. These vertical shafts may be linked to a well developed cave in the subsurface.

C7: Basaltic dykes
Volcanic intrusions* along fissures having occurred during the Jurassic time (155 Ma) in the existing limestone. The brown and friable material used as very fertile soil for agriculture are the product of the weathering of basalt (igneous extrusive rock; ~55% silica rich).
*Magma rises through fractures and penetrates through existing rocks and solidifying quickly as basalts.



C8: Deposition of calcite because of meteoric water (precipitation) infiltrating through rocks an fractures, and depositing $CaCO_3$ (calcite crystals) like in caves. The reddish color is due to the presence of iron oxides in the calcite from the overlying soil.

OTHER FEATURES OBSERVED ALONG THE TRAIL

Rillen Structures due to a preferential flow of water and dissolution

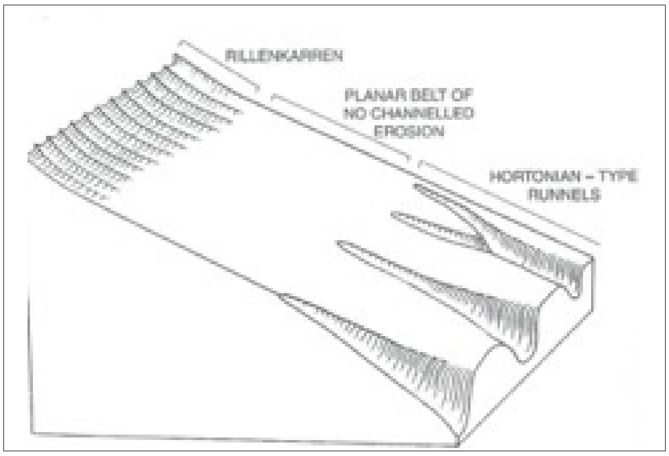


Diagram illustrating the uneven flow of water in rivulets over a heterogenous rock. (Ford and Williams, 2007).

Cockade structures due to a preferential dissolution of calcite in limestone along specific bedding planes (commonly horizontal)- Horizontal face of a stylolite

Typical karst landscape of preferentially weathered limestone intersected by fractures.

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

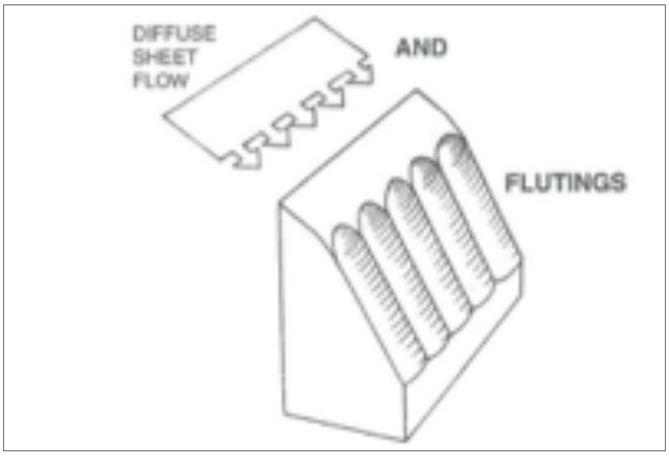


Diagram illustrating the uneven flow of water in rivulets over a heterogenous rock. (Ford and Williams, 2007)

Stylolites in the bedrock indicative of burial of the rock and pressure dissolution before final uplift and weathering by karstification

Crenulated (sinuous) opening indicating a stylolite (stylolites are horizons along which calcite has dissolved at high pressure during burial and compaction of the rock. When the rock is uplifted (exposed from the sea), the stylolite cracks open and becomes a weak plane where water can circulate more freely and dissolve the limestone. Such uplift strated to occur arounf 15 Ma ago.

D - JORD EL AAQOURA GEOTRAIL

From the sections of Afqa el Aaqoura and Tannourine el Aaqoura, you will be going through rocks of Albian-Cenomanian age (113 to 100.5 Ma). The rocks are composed of thinly bedded dolomitic limestone and limestone. You will hike on a vast plateau with multiple small round asymmetrical depression in the land surface: these are called "dolines". They are the result of dissolution of limestone beneath the surface and the collapse of weakened rocks leading to depressions in the land surface. These depressions may be filled by up to 5 m of soil. On the way, you will pass through a phenomenal panoramic view showing the different geological rock layers to the east. This area hosts important caves Afqa cave (south) and Ain El Lebne cave (on the trail), both of a length of more than 4000 m developed as a maze as a result of dissolution by groundwater flowing in the subsurface.

Trail Direction	Total Length	Total Ascent	Total Descent	Duration	Difficulty Level
Jord El Aaqoura	11.3km	589m	589m	5h	Challenging
Type of terrain	Dirt road, goat trail				

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT

gef

UNDP

AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

D1 GROUNDWATER AND SPRINGS

SPRINGS AND GEOLOGY

A spring is formed when groundwater flowing underground gets in contact with the topography or emerges from a weak zone (fractures/ faults or along a preferential flow).

Groundwater is rain and snow water infiltrating to the subsurface reaching the saturated zone (where all the voids and pores are filled with water) and starts flowing by gravity, until it is intercepted by a well or emerges as a spring. Streams running along the road can originate from snow melt, from springs or groundwater baseflow (groundwater (water flowing in the rocks in the subsurface) will flow into streams when the water table intersects with the stream.

Thinly layered horizontal beds

AIN EL ASAFIR

Ain El Assafir emerges from Albian-Cenomanian rocks (112 Ma-93 Ma). These rocks are made of thinly layered horizontal beds that have deposited in a marine setting of variable depths starting with very shallow environments during the Albian age and grading to deeper ones at the end of the Cenomanian age. The first layer is made of thinly layered dolostone and dolomitic limestone characterized by small fissures. Along these fissures water can seep down from snow melt, enlarge the fissures by dissolution and join larger pathways until it reaches an outlet with the topographic profile where it emerges as a spring. These small fractures constitute the porosity of this layer.

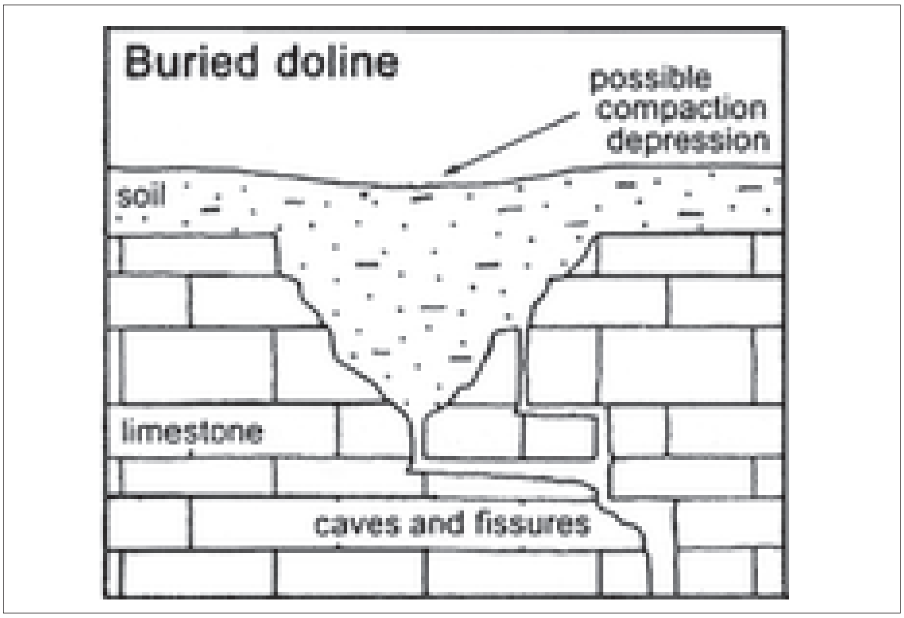
D2 DOLINES

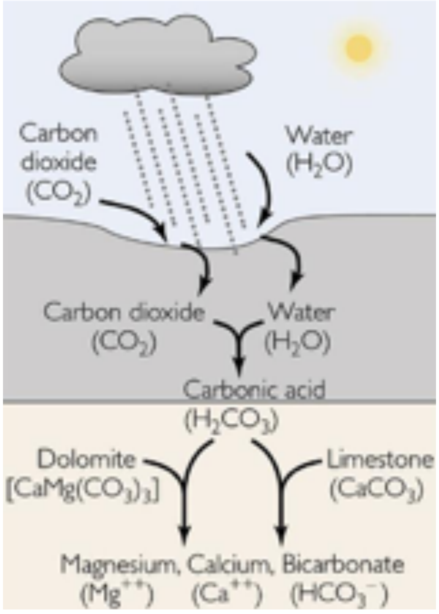
DOLINES

The depression observed in the landscape is called a doline.
It is characteristic of a karst landscape. These features are very common in limestone ($CaCO_3$) prone to dissolution by carbonation, where the calcium carbonate is dissolved into calcium and bicarbonate ions by slightly acidic water that infiltrates in the subsurface. With time, limestone will be weathered, where preferential flow of water is prevalent. With further weathering, soil will form, and the area becomes unstable, leading to a slight collapse of the weathered weathered bedrock, resulting in a small depression in the landscape.

The dissolution started to occur in dolostone, and limestone rocks that deposited in the sea in the Albian-Cenomanian age (112 Ma-93 Ma). These dolines constitute rapid infiltration point source.
Generally, during rain or snow melt, water will infiltrate fast into the doline and reach the saturated zone relatively more rapidly than the water infiltrating diffusively in other areas.

Therefore, these dolines should be protected because any contamination occurring at the doline will reach the connected water resource downstream rapidly.

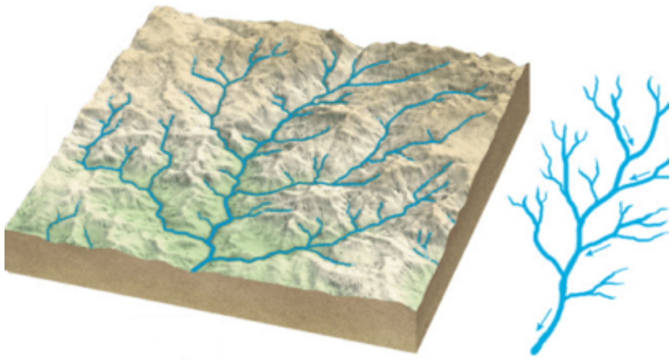


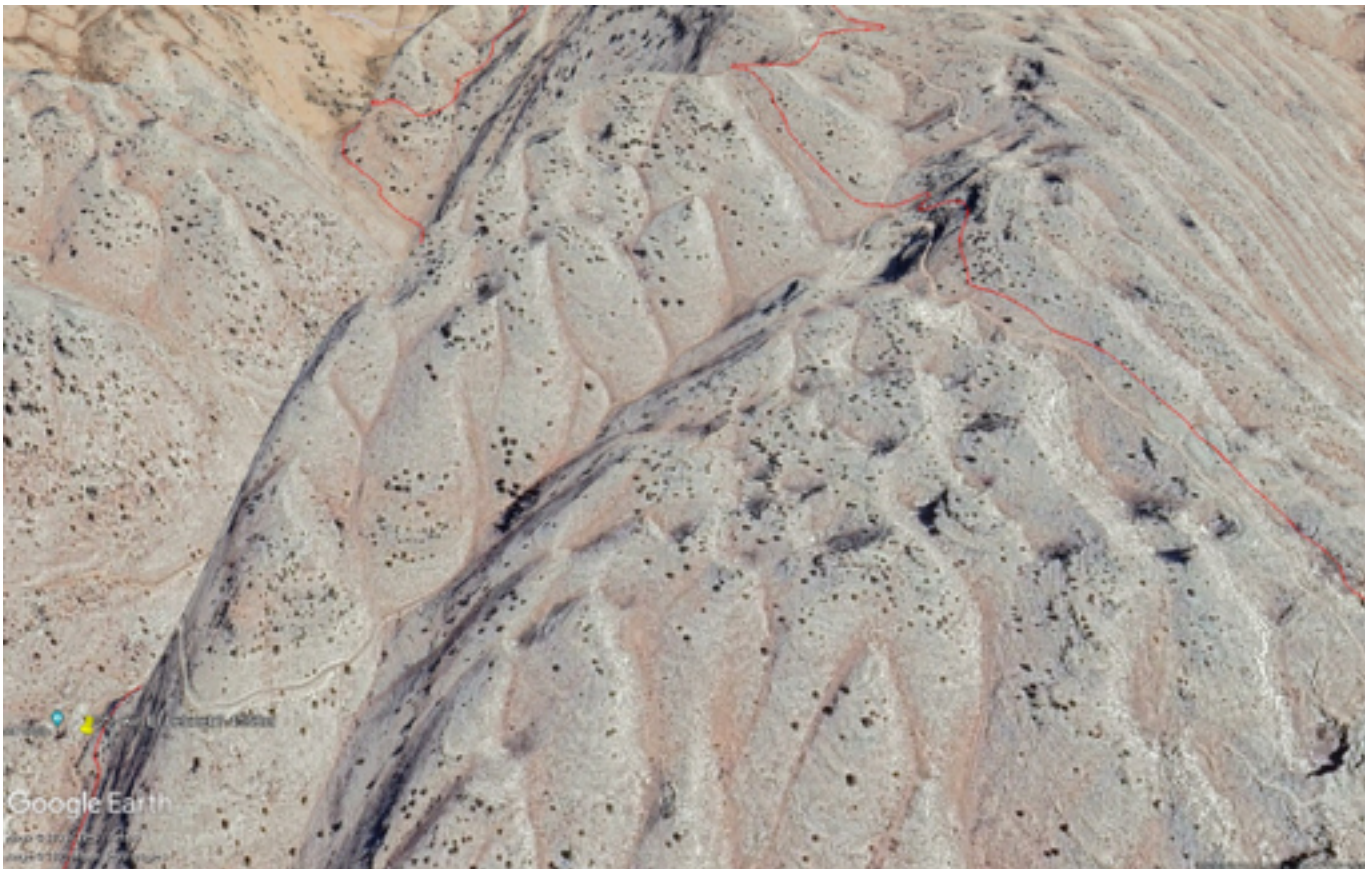


D3 DRY VALLEY

VALLEYS

Valleys form as a result of weathering and erosion. Water and snow melt flow off the surface and start carving the topography downslope in preferential pathways like fractures, or nonresistant rocks. With time, it can develop a small growing dendritic pattern that will grow bigger forming a large surface water basin. A valley is the result of that carving. The stages of valley formation range from young to mature to old depending on how long have the valley-forming processes been taking place. In some cases, the river is ephemeral (not flowing throughout the year) and is active shortly after snow melt or during a heavy storm (this explains why rock debris may be found on the valley flanks). In this area, water tends to infiltrate to form groundwater because of the nature of the geology (fissured limestone rocks).





D4 DOLINES

DOLINES

Dolines in this area are oriented in one direction and follow weakness planes (faults or fractures) can be asymmetrical, with one flank lying at a lower slope than the other flank. This is due to the melting of snow in one direction (the one exposed to the sun) and the erosion of weathered material from flank to the other, leading to more sediments depositing on one side and a steeper erosion on the other side.

REPUBLIC OF LEBANON
MINISTRY OF ENVIRONMENT

gef

UNDP

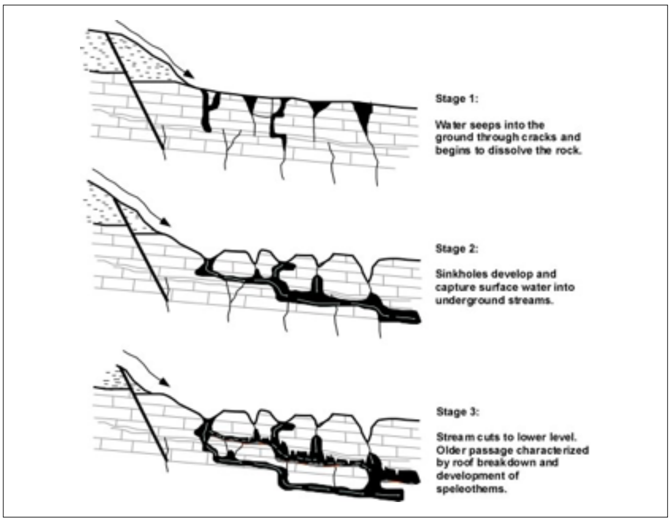
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

D5 AIN EL LEBNE CAVE

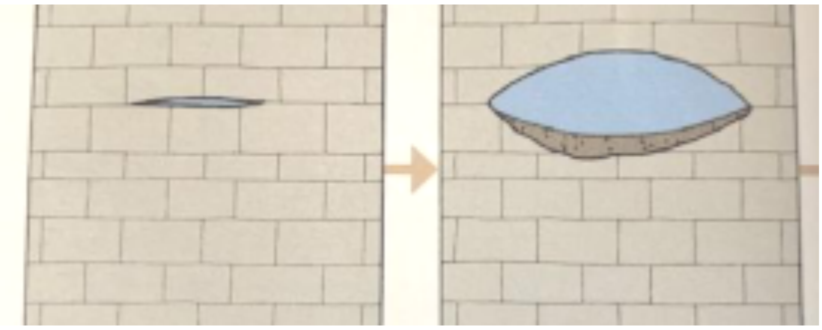
AIN EL LEBNE

Ain El Lebne is formed in rocks of Albian-Cenomanian age
The rocks are composed of thinly bedded dolomitic limestone and limestone.

When a rock formation formed under the sea is brought to the surface (uplifted), it becomes exposed to weathering agents (such as water, ice, and wind). Water from snowmelt or precipitation infiltrates into the subsurface to form groundwater. While it is seeping at very low velocities into small fractures in limestone and rocks prone to dissolution, it is able to dissolve the limestone by a process called carbonation at small rates thus enlarging the fractures at small rates (average of 0.01-0.1 cm/year). With time, enlarged conduits and cavities along preferential flow pathways: major fracture orientations (weak planes) and along thinly bedded layers may lead to the formation of a cave. The Ain El Lebne cave developed in a maze-like fashion over a total length of 4560 m.



Development of an underground network of enlarged fractures forming cavernous openings and caves



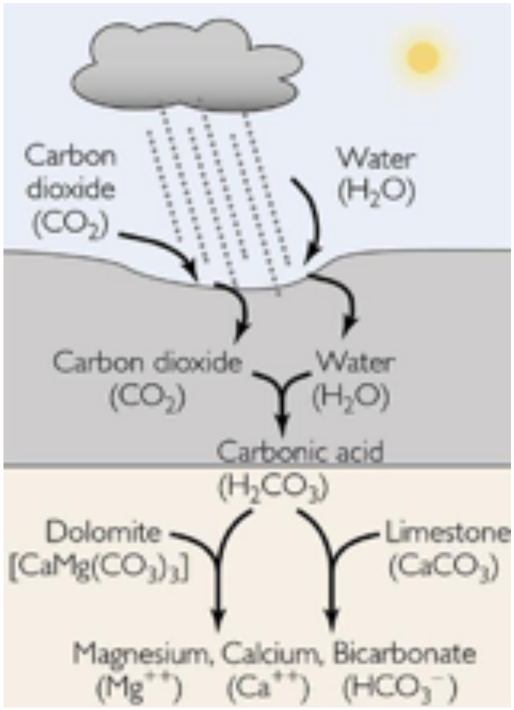


Illustration of carbonic acid generation from atmospheric carbon and soil. Slightly acidic water seeping into limestone will lead to calcite dissolution by carbonation and a subsequent enlargement of cavities and cracks

Sources and notes:

[1]Process where water that becomes slightly more acidic (e.g., because of the carbon dioxide from the atmosphere and the soil) is able to dissolve limestone (formed of the mineral calcite; $CaCO_3$) by breaking the bonds between calcium and bicarbonate. This can be observed when pouring vinegar on calcite, it will produce a fizziness, indicating that the calcite is getting dissolved.

REPUBLIC OF LEBANON MINISTRY OF ENVIRONMENT
gef
UNDP
AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

D6 VOLCANIC PONDS

MAGMATISM AND VOLCANISM IN LEBANON: AGRICULTURAL PONDS

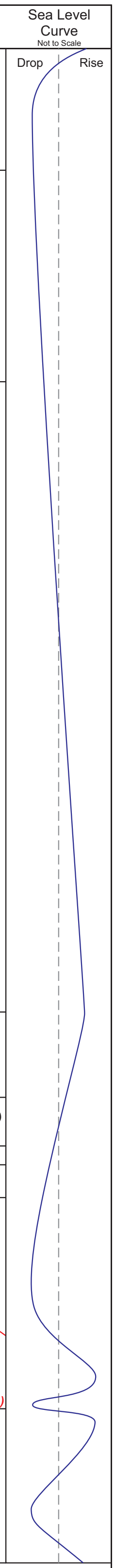
The oldest volcanic rocks in Lebanon are believed to have a Kimmeridjian age and they are included in the Bhannes formation dated back to around 155 Ma. These volcanics have been associated to block faulting and local uplifts and/or the opening of the Neo-Tethys. Volcanism persisted intermittently during the Early Cretaceous, especially in northern Lebanon. Some volcanic deposits of Aptian age (dated to 118 Ma) are due to Magmatic events during the Aprian age (Cretaceous period- Mesozoic).

These rocks are prone to weathering by dissolution by carbonation (slightly acidic water chemically disintegrating the minerals in the basalts) and by oxidation (turning from black to brown to red by the oxidation of the ferric ion). This weathering will result in the formation of black clayey soil that is considered highly fertile, and relatively impermeable. This can explain why farmers use the basalts to construct irrigation ponds for rainfall harvesting or spring water storage, since the weathered basaltic soil doesn't allow water to infiltrate.

Basalts of Aptian Age (118 Mma)- Mesozoic Era -Cretaceous period.

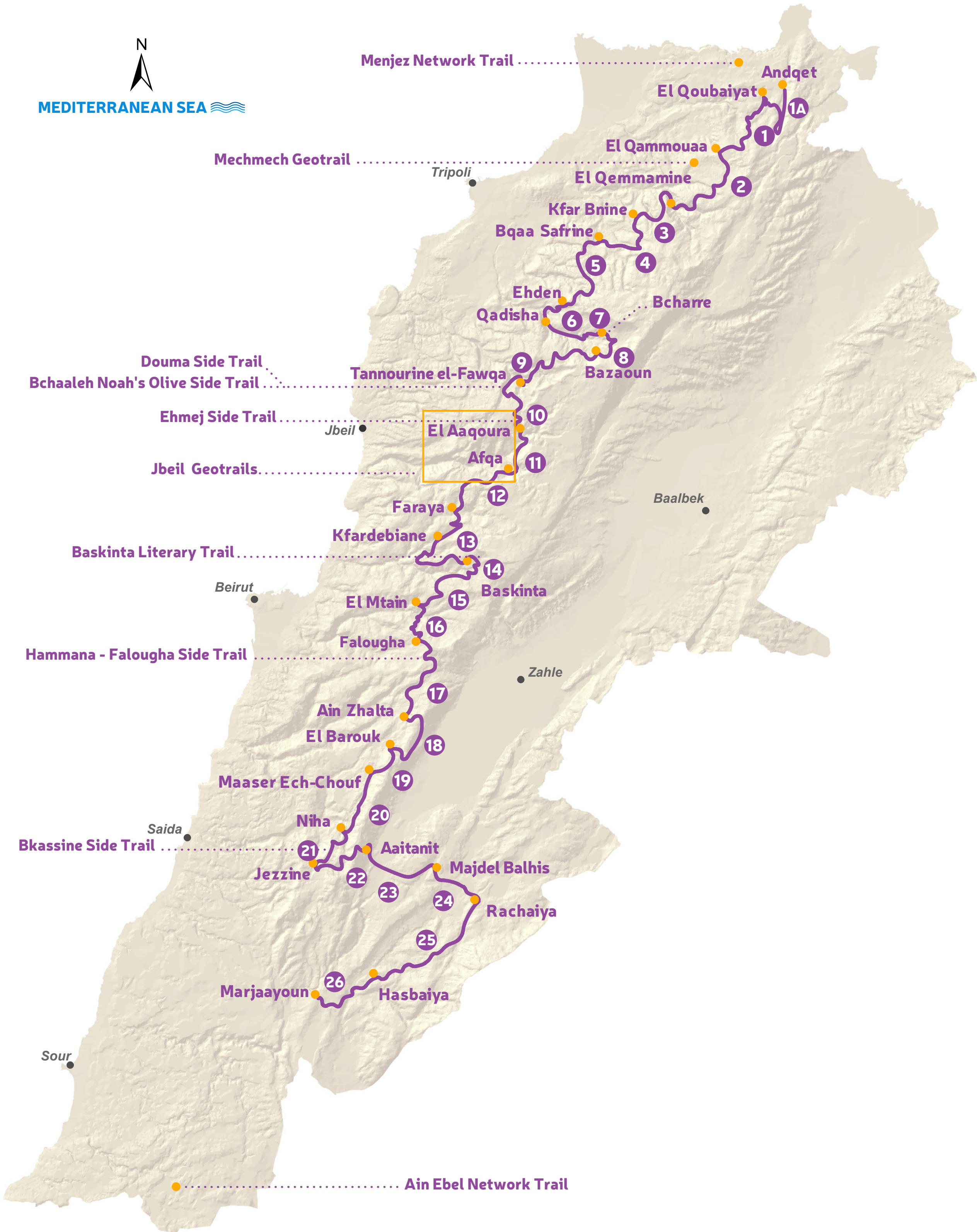
GEOLOGY TIMESCALE

Eon	Era	Period	Epoch	Age	Numerical Age (Ma)*	Main Events**
					Present	
Phanerozoic	Cenozoic	Quaternary	Holocene	Meghalayan	0.0042	Weathering and erosion of existing rocks
				Northgrippian	0.0082	
				Greenlandian	0.0117	
			Pleistocene	*Upper*	0.129	
				Chibanian	0.774	
				Calabrian	1.80	
				Gelasian	2.58	Uplift of Lebanon from under the sea
		Neogene	Pliocene	Piacenzian	3.600	
				Zanclean	5.333	
			Miocene	Messinian	7.246	
				Tortonian	11.63	
				Serravallian	13.82	
				Langhian	15.98	
				Burdigalian	20.44	Rock sequence absent in the geotrail area
				Aquitanian	23.03	
		Paleogene	Oligocene	Chattian	27.82	
				Rupelian	33.9	
			Eocene	Priabonian	37.71	
				Bartonian	41.2	
				Lutetian	47.8	
				Ypresian	56.0	
			Paleocene	Thanetian	59.2	
				Selandian	61.6	
				Danian	66.0	
	Mesozoic	Cretaceous	Upper	Maastrichtian	72.1 ±0.2	
				Campanian	83.6 ±0.2	
				Santonian	86.3 ±0.5	
				Coniacian	89.8 ±0.3	
				Turonian	93.9	
				Cenomanian	100.5	C4: Limestone and Dolostone ***(Sannine Fm.)***
			Lower	Albian	~ 113.0	C3: Limestone and marls ***(Hammana Fm.)*** episode of magmatism
				Aptian	~ 121.4	C2b: Limestone ***(Mdairej Fm.)***
				Barremian	125.77	C2a: Sandy Limestone ***(Abieh Fm.)***
				Hauterivian	~ 132.6	C1: Sandstone and basaltic volcanism ***(Chouf Sandstone Fm.)***
				Valanginian	~ 139.8	
				Berriasian	~ 145.0	Disconformity (erosion and no depositon)
		Jurassic	Upper	Tithonian	149.2 ±0.7	J6: Limestone ***(Bikfaya Fm.)*** J5: episode of magmatism ***(Bhannes Fm.)***
				Kimmeridgian	154.8 ±0.8	
				Oxfordian	161.5 ±1.0	J4: Oldest rocks exposed in Lebanon: Limestone and dolostone marine environment not always submerged ***(Keserouane Fm.)***
			Middle	Callovian	165.3 ±1.1	
				Bathonian	168.2 ±1.2	
				Bajocian	170.9 ±0.8	
				Aalenian	174.7 ±0.8	
			Lower	Toarcian	184.2 ±0.3	Not exposed on the surface
				Pliensbachian	192.9 ±0.3	
				Sinemurian	199.5 ±0.3	
				Hettangian		



AMERICAN UNIVERSITY OF BEIRUT
FACULTY OF ARTS & SCIENCES
Department of Earth Sciences

* Ma = Mega Annum (Million years)
** Rock formations are identified and named according to the types of rocks and Walley (1997) or according to age (from fossil content; Dubertret, 1951)
This sequence is represnetative of the geology of the study area and differs in the rest of Lebanon
(***Local names***) are based on Walley (1997)
Time scale adapted from the International Chronostratigraphic Chart V2023/06



These trails were made possible through the United Nations Development Programme (UNDP) and the Ministry of Environment of Lebanon with the generous funding from the Global Environment Facility (GEF).