

# Karst system developed in salt layers of the Lisan Peninsula, Dead Sea, Jordan

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**Abstract** The Lisan Peninsula, Jordan, is a massive salt layer accumulated in the inner part of the Dead Sea's precursory lakes. This tongue-shaped, emergent land results in a salt diapir uplifted in the Dead Sea strike-slip regional stress field and modified by the water level fluctuations of the last lake during the Holocene. These two elements, associated with dissolution caused by rainfall and groundwater circulation, resulted in an authentic karst system. Since the 1960s, the Dead Sea lowering of 80 cm to 1 m per year caused costly damages to the industrial plant set up on the peninsula. The Lisan karst system is described in this article and the components of the present dynamic setting clarified.

**Keywords** Jordan · Dead Sea · Lisan · Dynamic karst · Salt karst · Hazards

## Introduction

The Dead Sea occupies the bottom of a ~43,000 km<sup>2</sup> depression (USGS 1999) in the Near-East (Fig. 1). In 2006, with an elevation of 418 m below sea level (mbsl), it is the lowest place on Earth. Over geologic time, the Dead Sea has acted as a dynamic base level for karst development in the area.

The lake is 15 × 80 km and consists of two sub-basins: a northern sub-basin, whose sea-bottom is 730 mbsl deep and a southern sub-basin with a sea bottom of 402 mbsl (Hall 1997). Until 1978, they were connected by the Lynch Strait (now dry) and separated by the Lisan peninsula (Fig. 1). The climate is arid, with ~70 mm of precipitation per year. The lake level since the 1960s has lowered at an accelerating rate (~1 m per year in 2006) owing to an increasing amount of water being diverted from surface and groundwater sources to meet domestic, agricultural, and industrial needs. Water is also pumped directly from the Dead Sea into solar evaporation ponds in the shallow southern basin and on the recently emerged lands, to the west and north of the Lisan. The lake level has declined 26 m in 45 years.

As the Dead Sea has diminished in area since the beginning of the 1990s, salt dissolution and resulting subsidence and collapse problems caused important losses for the Jordanian company exploiting the Dead Sea minerals (Taqieddin et al. 2000). Between 2000 and 2001, a minimum of 70 M US\$ (Closson 2005a) were lost due to an insufficient understanding of the Lisan karst system. Solid gypsum and halite layers of relatively greater bearing capacity are interbedded with voids at shallow depth that threaten dike foundation integrity. Natural cave passages created

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complex conditions, and the unpredictability of these features increased the problem for the engineers in the destruction of the saltpan on March 22, 2000 (Closson et al. 2003a) and the emptying of a second production unit to prevent total destruction.

This paper describes the karst system of the Lisan Peninsula and provides guidelines to the potential variation in landforms and ground cavities that may be encountered. Field observations identify karst dynamics responsible for damage and future threats.

## Geological background and landforms

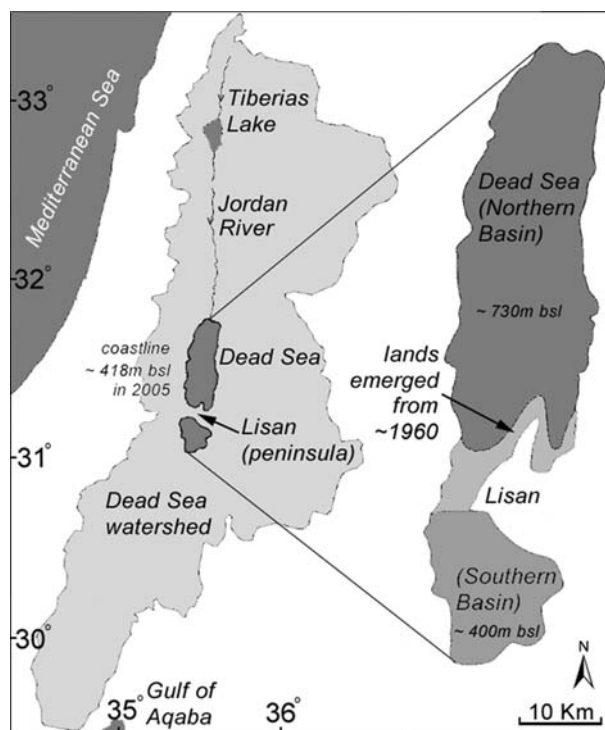
### Geology

The Jordan–Dead Sea–Araba graben is a major active tectonic feature resulting from the counterclockwise displacement between the Arabian plate and the Sinai sub-plate. Repeated structural subsidence resulted in the accumulation of sedimentary rocks, as much as 10 km-thick (e.g. Garfunkel and Ben Avraham 1996). The sediments deposited in this 400 km-long depression are mainly coarse continental conglomerates, some marine sediments, and sediments of a series of Pleistocene saline lakes that preceded the formation of the Dead Sea (mainly chalk, clay, and gypsum) during the Neogene-Quaternary. The earliest of these water bodies was the marine “Sedom lagoon” (Stein 2001 and references therein). After its disconnection from the open sea, saline lakes developed in the rift valley: “Lake Amora” or “Samra” that existed from early to late Pleistocene, and “Lake Lisan” (~70,000–15,000 B.P.)—that is the late Pleistocene precursor of the Dead Sea—and the Holocene Dead Sea (Stein 2001, and references therein). The Dead Sea occupies the largest pull-apart basin along the Jordan–Dead Sea Transform fault.

Lake Lisan level changed between ~330 and ~150 mbsl between ~70,000 and 15,000 B.P. It has submerged completely the present Lisan peninsula area. The water-level fluctuations were related to cold and warm cycles of the northern hemisphere. During wet periods, the water level in the lake was high and accompanied by the development of a layered configuration and precipitation of aragonite from the upper layer which also acted as a sulfate accumulator. During low lake stands, thick clastic layers accumulated in the shallow shoulders of the lake basin (Stein 2001 and references therein). Lake Lisan was less salty than the present Dead Sea as evidenced by relict fossils of stromatolites observed in the southern part of the peninsula. Bartov and others (2002) showed that the

sediments of the Lisan Formation were deposited in two environments: an offshore one with alternating aragonite and detrital laminae consisting mainly of silt-sized calcite, dolomite, and quartz; and a shore–delta environment with clastic sediments, which consist of sand, pebbles, and boulders.

Lake Lisan receded during two main periods, from around 17,000 to 15,000 B.P. (Bartov et al. 2002, 2003; Begin et al. 1985; Neev and Emery 1995), and from 12,000 to 11,000 B.P. (Stein 2001). The post-Lisan water body declined to its minimum level. During most of the Holocene, the lake (paleo-Dead Sea) stabilized at ~400 mbsl. In consequence, with a maximum elevation of 318 mbsl, a large part of the present Lisan peninsula was emerged (Fig. 2a). The level reached a minimum stand of 420 mbsl ~3,900–3,400 years ago (Bookman (Ken-Tor) et al. 2004; Frumkin et al 1991; Kadan 1997; Neev and Emery 1995). The sediments deposited in the Holocene Dead Sea are essentially similar to those deposited in Lake Lisan, alternating sequences of aragonite and detritus laminae (~1–2-mm



**Fig. 1** the Dead Sea is the lowest place on Earth at 418 mbsl (current 2006). Its watershed has a size comparable to Switzerland (43,000 km<sup>2</sup>). Until the end of the 1970s, the lake comprises two sub-basins separated by the Lisan Peninsula. When the Lynch strait dried up, the two basins were disconnected. Since then, the southern one has been progressively covered by solar evaporation ponds for exploitation of the Dead Sea minerals, while the size of northern one decreases year after year because of the sea-level lowering (1 m/year). Its bottom has an elevation of 730 mbsl

thick), gypsum and clastic units (Bookman (Ken-Tor) et al. 2004; Migowski et al. 2004).

Geologists Sunna (1986) and Bartov et al. (2002) studied the Lisan Formation of the peninsula and divided it into three members:

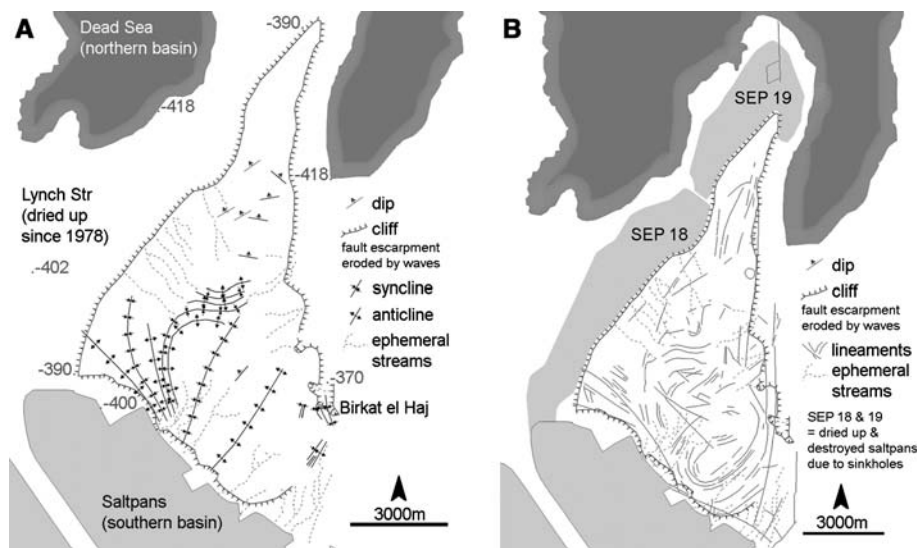
- The lower member includes alternating laminae of aragonite and detritus, with thin salt layers (1–2 cm). This member is capped by three gypsum layers with a total thickness of 50 cm. The total exposed thickness of this member is about 8 m;
- The middle member includes thick gypsum layers (up to 20 cm each), detritus layers (up to 30 cm each) and alternating laminae of aragonite and detritus. This member is capped by a 0.5 m gypsum layer with the appearance of rounded concretions. This layer covers most of the Peninsula. The total thickness of the second member is about 12 m;
- The upper member is made of alternating laminae of aragonite and detritus and its total thickness is about 10 m. This member is exposed in the northern part of the Peninsula.

Layers of sediment are generally sub-horizontal. However, in the southern and central parts, deformations are more apparent. They are the consequence of a salt-diapir uplift. The topography of the Lisan reflects the morphology of the top of a wide salt dome, 100 m

beneath its surface (Figs. 2, 3). This diapir is made up of a several-kilometre-thick sequence of mostly marine salt with interbedded gypsum, shale, and dolomite rock of Pliocene to Pleistocene age (Sedom Formation). It has an elongated dome-shape of about 9 × 6 km in the N–S direction. It includes several sub-domes and a structural depression. Fig. 2b shows the lineaments underlying the main sub-dome affecting the Southern Lisan. Northward, it is closed by folds and a structural depression. Folds, with wavelengths of about 100 m, underline the dome and the bedding inclinations change their orientation gradually around it. At Birkat el-Haj there is another structural depression, about 2 km wide.

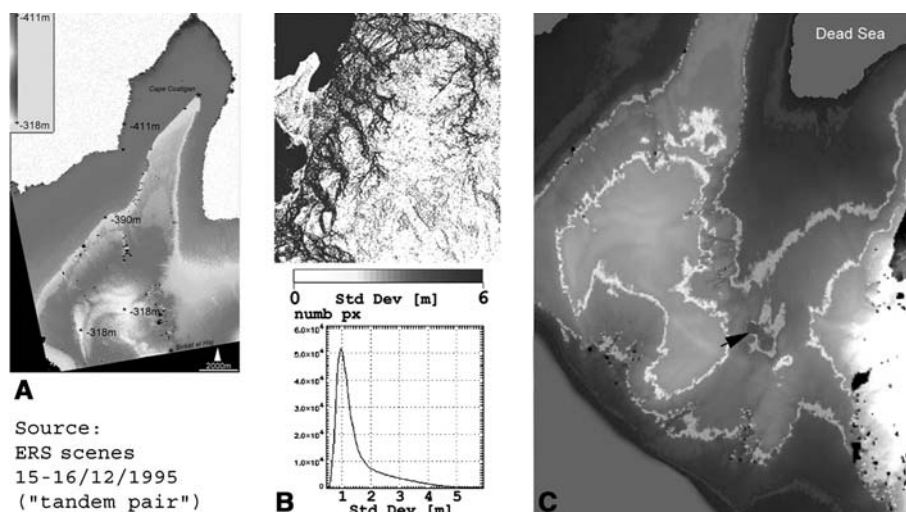
Assessment of structural or tectonic information by interpretation of geomorphic features included: drainage-pattern anomalies; tonal contrast caused by topography and variation in water content; topographical features explained by structural or stratigraphic conditions; and linear features.

Aerial photographs, scale 1:25,000 (1953) and 1:30,000 (1992), were used for plotting lineaments (Fig. 2b) which may be produced by faults, folds, joints, fractures, or bedding. The origin of these lineaments required considerable fieldwork to interpret them. A number of prominent lineaments represented straight or gently curved wadies. The direction and



**Fig. 2 a** The Lisan (tongue, in Arabic) peninsula, corresponds to the area delineated by a cliff. It is a fault escarpment eroded by the waves' action (sea cliff). Salt layers are generally horizontal. In some parts, they were deformed due to the uplift of a kilometre-size salt diapir. The top of the dome is only 100 m beneath the surface. It presents digitations that could explain both the complex topographic variations of the Southern part, the distribution of the lineaments (**b**), as well as the radial

drainage pattern. Data available in Sunna (1986); **b** lineaments are extracted from aerial photographs at 1:25,000 (1953) and 1:30,000 (1992) scale. They may be produced by faults, folds, joints, fractures, bedding, or any other cause. Two saltpans were built during the nineties over the flat area that emerged following the recession of the Dead Sea. At present they are either totally destroyed or emptied



**Fig. 3** **a** Digital elevation model of the Lisan Peninsula based upon two ERS satellite images (15–16 December 1995). The altitude of ambiguity, or the elevation comprises between the two limits of a radar interferometric fringe, is 33.4 m. In 1995, the Dead Sea level was about 411 mbsl; **b** the theoretical standard deviation, in meters, for measured altitudes, that is the expected precision for measured altitudes in the absence of artifacts. Histogram presents the theoretical standard deviation for

measured altitudes over the scene. The average precision is 1 m (very rare with ERS); **c** shows the Lisan Peninsula and the graben of Mazra'a–Ghor Al Haditha. Light grey color emphasizes particular elevations (~380, 390 and 400 mbsl) and improve the delineation and the interpretation of the complex structure of Birkat el Haj (arrow): both grabens and salt collapses interpenetrated

length of these lineaments vary considerably. Several of these lineaments mark previously unmapped faults while others are either controlled by lithologic changes or resulted from erosion along a set of fractures or joints (Sunna 1986; Closson et al. 2005). Two important sets of lineament are related to faults having north–south and east–southeast and west–northwest directions (Sunna 1986). The north–south set of faults occurs in the Eastern part of the Lisan Peninsula; the second set occurs in the Southern part. A normal fault bounds the western side (Bartov 1999). Closson (2005b) studied the recent emerged platform surrounding the Lisan and analyzed the intersection areas between the Eastern and Western fault zones in the northern part with ERS radar images.

Another important set of lineaments is the concentric, semi-ellipsoidal lineaments, which indicate the possible occurrence of a major plunging anticline in the Southern part of the peninsula (Sunna 1986). Field investigations indicate that these lineaments relate to changes in the resistance of the different strata to erosion. Minor faults affecting the Lisan Formation have north–south orientations.

#### Landscape and topography

From topography and landforms (Fig. 3), the Lisan area can be divided into four main zones:

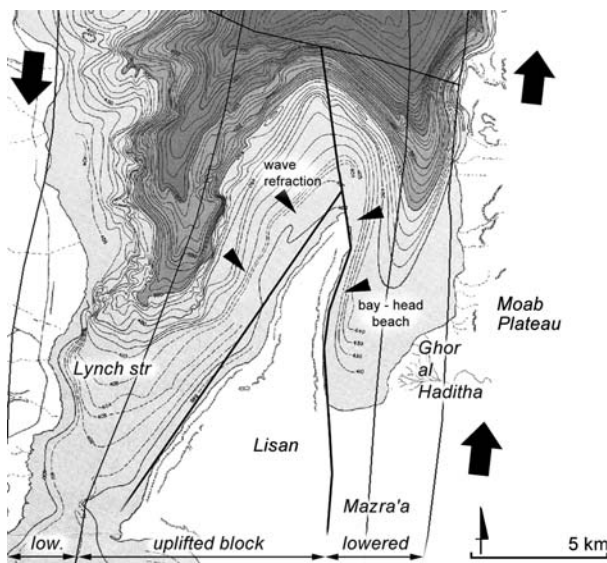
- the relatively high land in the south-central part of the peninsula, which is a plain with isolated hills (318 mbsl), corresponds to the area affected by the Lisan salt diapir uplift;
- the badlands is typified by rugged topography in the southern part and along the periphery of the Peninsula. Deep canyons with cliffs more than 10 m high predominate;
- the lowland area which occupies the eastern part of the Peninsula (Birkat el Haj and surroundings) is mainly cultivated land traversed by many tributaries originating from the Moab Plateau. Recent wadis that developed during the last 40 years are a result of regressive erosion and floods;
- a wave-cut platform area bounds the Lisan to the north, east, and west. Older beach lines can be easily recognized. On the western side, the platform had been strongly modified by the construction of two kilometre-size salt pans. The raw materials used to build the dikes were extracted from the cliffs in the northern part (former Cape Costigan).

The highest elevation point is 318 mbsl and the lowest point is 418 mbsl in 2006 (411 mbsl in 1995—see Fig. 3). The outcropping sediments reach a total thickness of 100 m, of which 40 m consists of the Lisan Formation.

## Marine erosional process and coastal evolution

The Lisan landscape results from abrasion, hydraulic action, attrition (marine environment), and solution processes. Figure 4 provides an explanation for the present “tongue” (Lisan in Arabic) shape. Geophysical studies (e.g. Ben Avraham 1997) showed that, at the Lisan, the pull-apart Dead Sea basin is roughly constituted by three North–South elongated fault-bounded tectonic blocks: an uplifted block bearing the Lisan, and two lowered adjacent areas corresponding to the Lynch strait in the west and the fertile plain of Mazra’a–Ghor al Haditha in the east.

Depending on the Dead Sea level fluctuation, the lowered blocks were sometimes covered by water or dried up. This is documented in the sediments of these areas which contain an alternation of salt and fluvial deposits (e.g. Taqieddin et al. 2000). The Lisan sea cliffs are well marked by the action of waves. Caves, arches, and stacks (Fig. 5) are visible along the former destroyed saltpans covering the wave-cut platform.



**Fig. 4** At the Lisan Peninsula, the Dead Sea pull-apart basin consists of three roughly parallel, North–South elongated, up-and-down tectonic blocks. From East to West, they are the lowered Mazra’a–Ghor al Haditha graben, the uplifted Lisan block and the Lynch strait graben. The bathymetric chart shows that the Northern parts of the lowered tectonic units were strongly eroded, creating canyons, when the Dead Sea level was far below its present level (Neev and Emery 1967). During the Holocene, depending on the Dead Sea level, the lowered units formed either two bays or one bay and a strait. The uplifted Lisan headland was eroded back as a result of wave refraction. Normally, the bays advance slowly as the deposition takes place at their heads to form bay-head beaches. However, the present Dead Sea lowering of one meter per year hides this process. Background image is the bathymetric chart of the Dead Sea compiled by Hall (1978)

## Karstic phenomena of the Lisan Peninsula

Karst is a mass-transfer system consisting of soluble rocks with a permeability structure dominated by interconnected conduits dissolved from the host rock that are organized to facilitate the circulation of fluid in the down-gradient direction wherein the permeability structure evolved as a consequence of dissolution by the fluid (Klimchouk 1996; LaMoreaux 1991 and references therein). Surface drainage and pattern, remaining tracks of fluctuant base level, sinkholes, uvalas, salt-collapses, subsidence, springs, caves, caverns... are diagnostic of karst (Fig. 6). The dataset of Fig. 6 comes from exploration campaigns in 1998, 2001, 2002, 2004, and 2005, ERS satellite images interferometric processing (Closson 2005a; Closson 2005b), and geological maps drawn by Sunna (1986) and Bartov (1999).

### Surface drainage and pattern

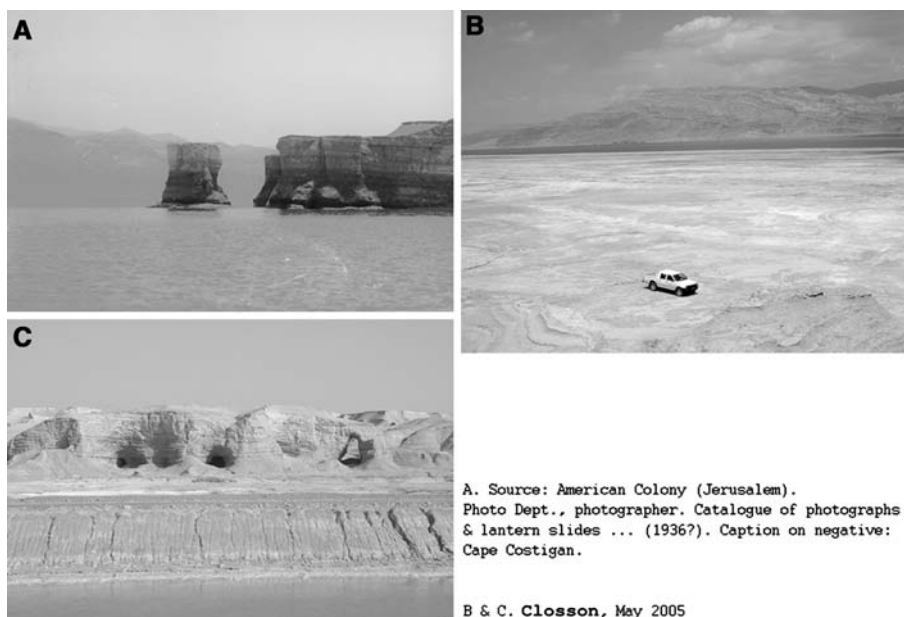
Figure 2 shows that the drainage patterns are dendritic (South and East) and parallel (West). At regional scale, the drainage pattern can be considered as radial, suggesting a superposition to the networks of fractures emanating from the Lisan diapir uplifted area.

Two systems of faults and fractures affect the Lisan. The fault pattern associated with the Lisan diapir is made of two sub-systems: radial and circular, like a spider web, centred over the main doming zone. Here, however, the pattern is deformed because regional strain exists during the uplift. In consequence, the “spider web” has an elliptic shape (see Withjack and Scheiner 1982, for a discussion of this point). The second system is the complex strike-slip fault system of the Jordan–Dead Sea Transform Fault zone (Ben Avraham 1997). The Dead Sea area is a pull-apart basin made of fault segments roughly oriented north–south and connected by transfer faults oriented south–east–north–west. The intersection between the two faults systems is particularly obvious in the eastern part of the Lisan, where the wadis drain to the northeast and then shift to the north, toward the Dead Sea (Fig. 2).

### Hydrogeological setting

#### At regional scale

The Dead Sea area is particularly hot and arid, with less than 100 mm of rain per year (USGS 1999). To develop dissolution features, such as interconnected conduits, the karst system thus needs a regular supply



**Fig. 5** **a** Subset of a picture acquired in 1936 showing a stack at Cape Costigan headland (north of the Lisan Peninsula). The present wave-cut platform (see Fig. 5b) was then covered by water because the Dead Sea level was then about 390 mbsl; **b** wave-cut platform discovered after the Dead Sea shrinking back during the last 45 years (26 m). When the level is stable during a certain period of time, waves undercut at the base of the cliff. As a result, an overhanging cliff appears and then may collapse.

Decametric breakdown blocks are always visible along the present cliff. As the steep escarpment retreats landwards, a flat terrace at the foot of the cliff is exposed: the wave-cut platform. The eroded materials which are transported away may be deposited in the sea to form an offshore terrace (Closson 2005a, b). See also the corresponding wide area around the Lisan Peninsula (Fig. 3a), **c** Remaining caves and an arch visible along saltpan 18 of the Arab Potash Company (Closson 2005a, b)

of fresh water from outside. The Judean Hills and the Moab Plateau edge the terminal lake. They receive, respectively, 6–700 mm and 3–400 mm of precipitation per year (USGS 1999) and constitute a kind of water tower above the lake. Owing to the very high topographic gradient (“rift” valley), a significant part of this water reaches the valley floor rapidly. Water movement is strongly influenced by numerous faults and fractures crossing the graben. At the Near East scale, Abou Karaki (1987) described the Lisan as a zone of coalescence of major faults.

Surface and fresh groundwater literally flood parts of the Jordanian Dead Sea coast. This is evident when considering the vegetation shown on old maps, or the present development of intensive agriculture in Ghor al Haditha, Mazra’a, and Ghor Safi. Moreover, numerous archaeological sites attest the presence of human settlements during past millennia along the ancient Dead Sea coastline. The graben is thus not as hostile as it seems at first glance and can be described as an oasis close to the Dead Sea.

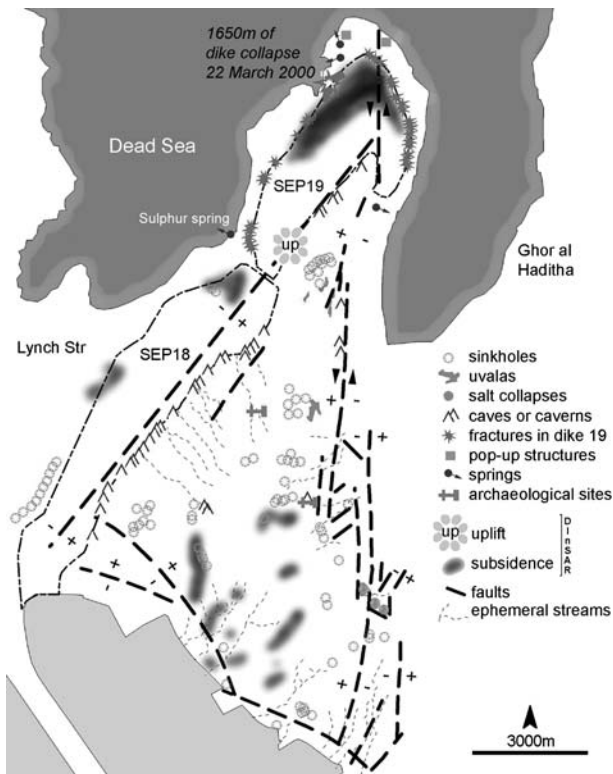
Another way to recognize the rapid, dynamic transfer of water from the Moab Plateau to the Dead

sea is the spectacular development of the Wadi Mujib canyon, the fifth deepest canyon in the world.

#### *At coastal level*

The Dead Sea water body is not only a lake but it extends into the subsurface. The configuration and depth of the fresh-water/salt-water interface (Fig. 7) depends on a variety of factors, but the most important is the density difference between the fresh-water and the salt-water. For oceanic water, this difference is 0.025 g/cm<sup>3</sup>; but for water in the Dead Sea, it is 0.23 g/cm<sup>3</sup>. Thus, the depth of the interface will be different. Ghyben–Herzberg’s equation gives the configuration of the fresh-water/salt-water interface (Eq. 1).

The position of the fresh-water/salt-water interface can be approximated. The boundary that separates the fresh-water layer from the salt-water is not a sharp boundary line, as it is a transition zone of brackish water. Theoretically, in the case of Ghyben–Herzberg, however, it is a line across which no flow can occur. Ghyben–Herzberg’s approximation for two immiscible fluids with a common interface is expressed as



**Fig. 6** Relevant karst and other features in the area. Subsea karst features may develop in deposits carrying drainage from adjacent land and may also include features inherited from erosion during past times of lower sea levels. DInSAR means differential interferometry techniques (applied to the ERS synthetic aperture radar satellite images)

$$Z = \left[ \frac{\rho_f}{\rho_s - \rho_f} \right] hf \quad (1)$$

where  $Z$  is the depth below sea level to a point on the interface;  $\rho_f$  is the density of fresh water;  $\rho_s$  is the density of salt water;  $hf$  is the fresh water level above sea level.

If the  $\rho_f$  is taken as  $1.0 \text{ g/cm}^3$  and that of seawater as  $1.025 \text{ g/cm}^3$ , then  $Z \approx 40hf$ . If this condition is approximately correct, a fresh water level of 1 m above sea level corresponds to 40 m of fresh water below sea level. The Dead Sea is  $1.23 \text{ g/cm}^3$ : therefore,  $Z \approx 4hf$  and the Ghyben-Herzberg’s law defines the fresh-water/salt-water interface.

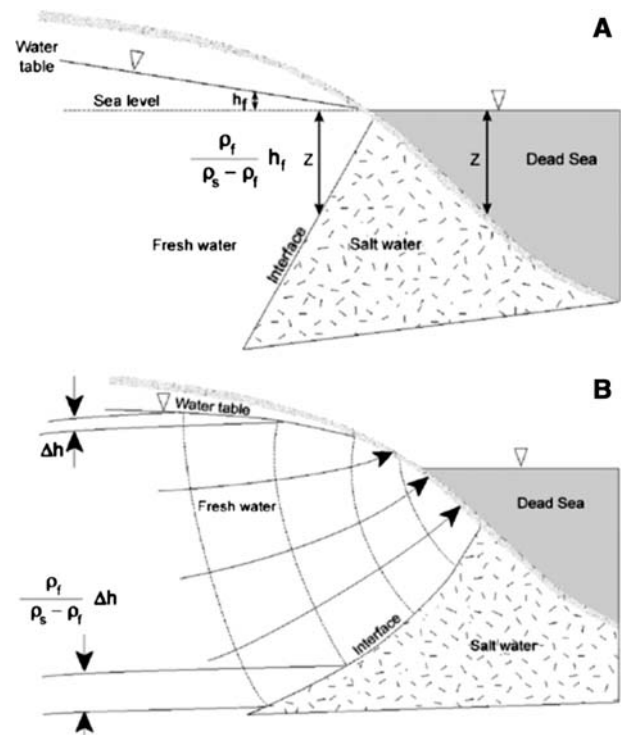
Bouwer (1978) and Freeze and Cherry (1979) argued that the fresh-water/salt-water interface is affected by the form of the water table near the surface, and that the surface tip of the interface is pushed beneath sea level by groundwater flows under a high hydraulic potential (Fig. 7b).

As the Dead Sea level has been dropping, the continuous lowering has resulted in the following effects (Fig. 8):

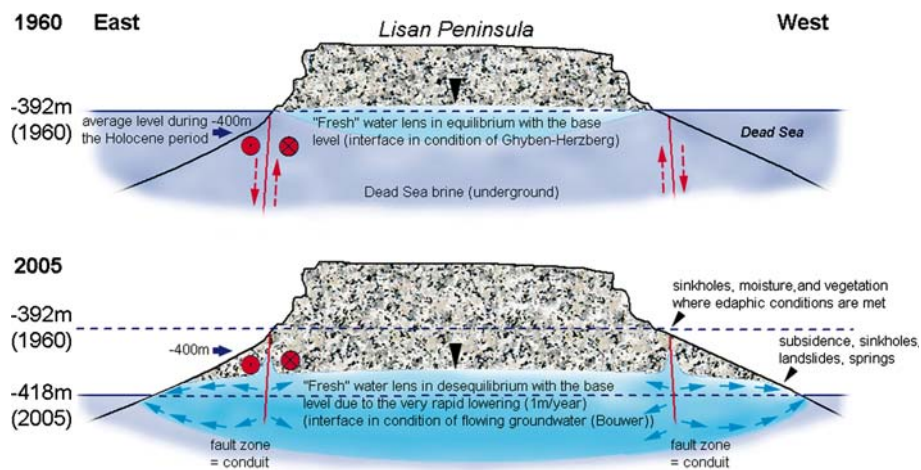
- an increase in the head differences between the Dead Sea and the groundwater levels causes greater amounts of groundwater to drain into the Dead Sea;
- modification of the interface configuration and equilibrium state between the saline surface body and a fresh groundwater body receiving recharge.

These field observations described in Figs. 9 and 10 are in agreement with the water circulation model. For example, as the fresh-water/salt-water interface is pushed below the sea level, dissolution takes place to create voids that migrate upward and cause ground instability near the shoreline. Figure 9 shows an example of sinkholes, beneath the sea level, in front of the Lisan. Such features have been observed in the northern part of the peninsula too.

Another consequence of the rapid Dead Sea lowering is the blowouts of fresh groundwater (Salameh and Naser 2000a, b). In the Lisan, the thin lens of “fresh” water below the peninsula in the 1960s becomes thicker and its upper surface bulged upwards (Fig. 8). Pictures in Fig. 10 support this statement and emphasises the major role played by the numerous



**Fig. 7 a** Hydrostatic conditions of the Ghyben-Herzberg relation (example from Domenico and Schwartz 1990); **b** actual interface in the condition of flowing groundwater (after Bouwer 1978). Adapted from Marui (2003)



**Fig. 8** Schematic east–west cross section through the Lisan Peninsula. The Lisan karst is born with the disappearance of Lake Lisan at the end of last glacial period. The late Holocene Dead Sea levels fluctuated within elevation range of 390–415 mbsl. Most of the time, the lake did not rise above ~400 mbsl. The vertical extension of the karst seems thus mainly situated above 400 mbsl. Since the 1960s, the level decreased

26 m, creating disequilibrium in the fresh-water lens beneath the peninsula. With a present elevation of 418 mbsl, hydraulic-gradient conditions are met to reactivate old karst conduits developed during past millenniums and along buried (active) faults. As a consequence, new sinkholes and subsidence hazards appear in the vicinity of the shoreline

faults and fractures and the 70 mm per year rainfall, that feeds the fresh-water lens.

The climate of the peninsula is arid. Frumkin (1996) mentioned a yearly deficit precipitation–evaporation over 2 m! The edaphic conditions are exacerbated because of salt. Vegetation is extremely rare and is confined to the few places where “fresh” water is present, i.e. some sinkholes and depressions visible on aerial photographs.



**Fig. 9** Sinkholes are widespread along the Dead Sea coast. Sometimes they appear below sea level. An underground circulation of fresh water triggers such collapses. The picture was taken a few kilometres north of Ghor al Hadiitha, Jordan. Similar features were observed along the Lisan shore. Closson (2005a, b)

All along the kilometre-long dike of saltpan 19 there is no vegetation, with the exception of the one presented in Fig. 10a. This atypical alignment of natural vegetation, nearly 200 m long, started growing after the pond was abandoned (22 March 2000). Thus, it is 5 years old.

To grow, plants need at least favourable edaphic conditions and a regular supply of “fresh” or “absorbable” water, due to the strong evapo-transpiration.

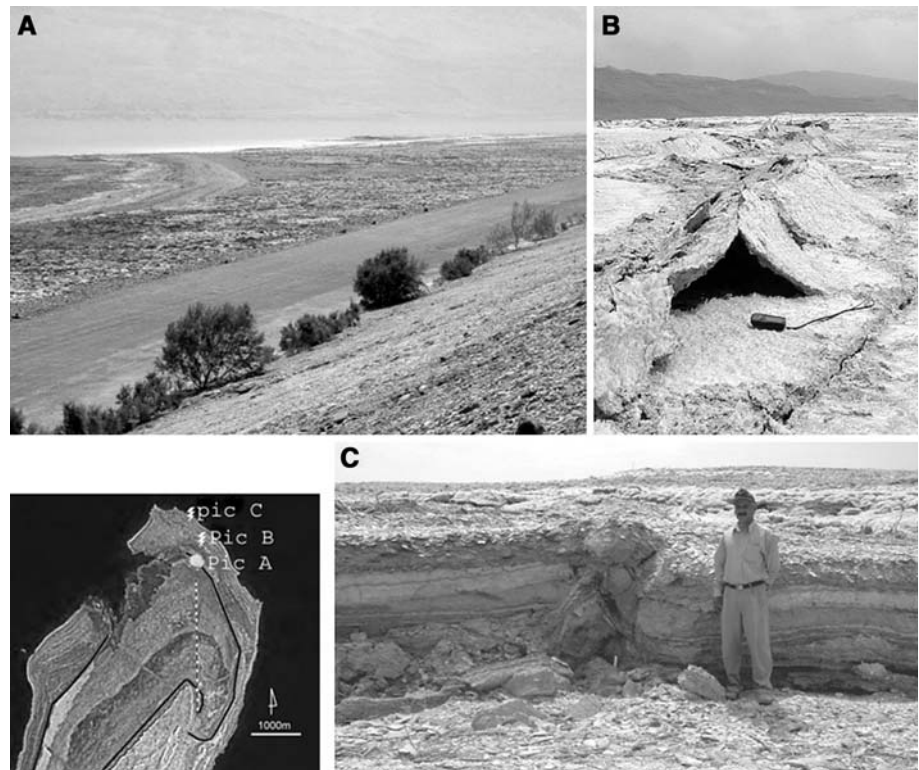
Figure 10a proves that such basic conditions are met along a 200 m-long segment of the former saltpan 19, in the “hostile” place of the northern part of the Lisan wave-cut platform.

The ground is a landfill extending outside the peninsula. This material is not salty. The thickness allows roots to penetrate several m below the surface. Their development is probably stopped when reaching the first (shallowest) salty horizon. The vegetation survives because, “fresh” water circulates in the subsurface. Capillary water feeds the plants and the water table is quite high above the sea level (Fig. 8).

The shrubs are better developed in the central part of the lineament than in the extremities suggesting the existence of a type of fresh water conduit in the underground surrounded by a wet buffer zone.

Satellite images show that this fresh-water conduit corresponds to a well-visible lineament (Closson et al. 2003a) in the extension of the strike-slip fault bounding the eastern side of the Lisan (Figs. 2, 4, 6, 10).

**Fig. 10** **a** The Lisan Peninsula is a salty desert with only 70 mm of rain per year. Over a period of 5 years, a 200 m long lineament of shrubs has grown in the landfill of saltpan 19. The main water-supply area is in the central part, as attested by the development of the vegetation. **b** Pop-up structures. This feature could be due to the hydration of anhydrite ( $\text{CaSO}_4$ ) to gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) due to groundwater circulation. **c** intrusion of gypsum into horizontal layers. Closson 2005a, b. Satellite view is a subset of a Space Shuttle photograph (July 14, 2005). Mission ISS011; Roll E; Frame 10551. Image Science and Analysis Laboratory, NASA-Johnson Space Center. “Astronaut Photography of Earth—Display Record”



This vegetation also suggests that the flow rate of the groundwater could be quite high. In order to live, the plants need to absorb water with a relatively low salinity. To explain the occurrence of “fresh” water in a very salty environment, so far from the surrounding sources of the Moab Plateau or the Judean Hills, the water has to flow rapidly to avoid much salt dissolution when crossing through the layers of the Lisan deposits. The numerous faults and fractures act like an effective network of irrigation canals and could be locally reactivated. This assumption is supported by 1 km subsidence area detected in the northern Lisan (e.g. Closson et al. 2003a). It is bounded by linear features, giving it a nearly rectangular shape.

To circulate quickly, water needs energy; this comes from the difference in elevation between the surrounding water table and the Dead Sea level. Since the starting of its lowering in the 1960s, the water table had not followed the movement at the same rate (Closson 2005b), increasing the whole potential energy of the (karst) system. The very rapid decline of the Dead Sea had created a situation of disequilibrium increasing in time. Owing to faults and fractures, by the principle of the communicating vessels, the balance phenomenon occurs. As they convey water under pressure, the water table can be deformed, locally, until reaching the

topsoil to create springs, as can be observed in the northern part of the Lisan (Fig. 6).

The fate of this vegetation is not so clear and should be monitored. As an example, the “hedge” will die because the top of the groundwater lens will lower more and more, accompanying the Dead Sea movement. Due to the salt deposits, the roots will be not able to reach the wet buffer zone above the “fresh” water lens. One also can postulate that the vegetation will grow because the rapid lowering will attract more and more groundwater, increasing the charge of the conduits, and the upward movement of the water along the fault planes (see Fig. 8, deformation of the top of the “fresh” water lens near the faults).

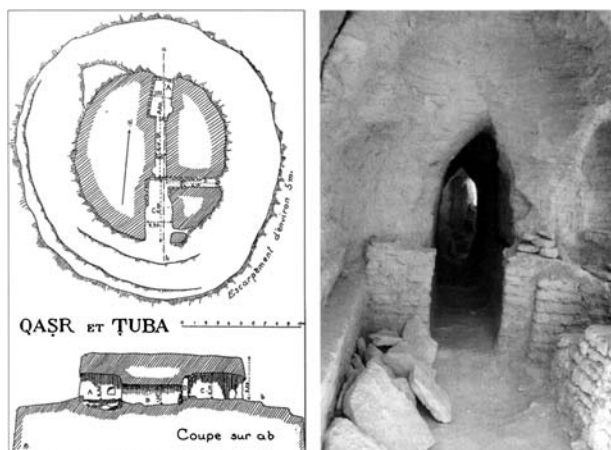
In the extension of the strike-slip fault mentioned earlier, features can be observed, suggesting the presence of unsaturated water (with respect to salt) circulating along this weakness zone. Figure 10b shows pop-up structures resulting from compression. Professor Camille Ek, of the University of Liege, Belgium, suggested that such features could be due to the hydration of the anhydrite ( $\text{CaSO}_4$ ) to gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ). As the gypsum molecule occupies more volume ( $2\text{H}_2\text{O}$ ) than the anhydrite molecule, tensions have to exist, leading to superficial deformation and even intrusion (Fig. 10c).

## Caves and caverns

Rosendahl et al. (1999) described different types of caves from the Lisan-beds of Jordan. On the Lisan peninsula, caves develop along bedding planes and rock fractures. By incision and progressing erosion, these caves get transformed into narrow canyons and rock arches. Being used as hermitages, some caves were reshaped in Byzantine times (Fig. 11).

Several authors (Higginbottom 1966; Jennings 1968; White 2000; Waltham and Fookes 2003) have shown that caves and caverns resulting from dissolution develop best on competent, fractured rocks whose intact unconfined compressive strength is generally 30–100 MPa. Lithified evaporite sediments lack the strength to span large cavities, and then develop limited suites of karst features that are generally smaller than those on stronger limestones. Differences in permeability stimulate the formation of long, tube-like caves (Figs. 11, 12, 13).

Caves and caverns in the Lisan salt deposits are formed when rainwater percolates through cracks (Fig. 12c), dissolving the rock. The process continues as the water moves sideways along bedding planes and joints, faults, and fractures in the rock itself. This occurs over the whole thickness of the Lisan, down to the “fresh” water lens horizon. The underground extension of the Dead Sea acts as an impermeable layer due to the contrast of density. It causes the accumulation of “fresh” water that forms a lens where the gradient of salinity increases from the top to the bottom. If the salinity is sufficiently low in the upper part of the lens, then this potable water could be a possible element to



**Fig. 11** Qasr et Tuba, drawing of Abel (1929) and picture from Rosendahl et al. (1999). Caves develop along bedding planes and rock fractures. Differences in permeability stimulate the formation of long, tube-like caves

explain the existence and the survival of hermitages of the past centuries.

Conduits enlarge over time, and move the water by gravity, further enlarging the conduits through a combination of solution and abrasion. Eventually, water, under pressure, reaches the surface of the land as an artesian spring. A spring may emerge high on a cliff (Fig. 13b) or at the base of it, or even be forced upward from below sea level (Fig. 6 sulfur spring), depending on the nature of the surrounding rock, and the altitude of the groundwater level with respect to base level.

## Sinkholes and uvalas

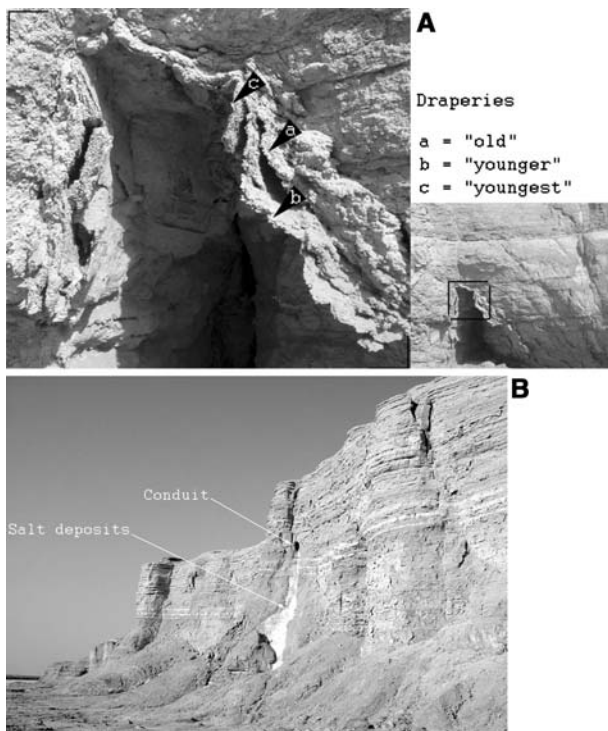
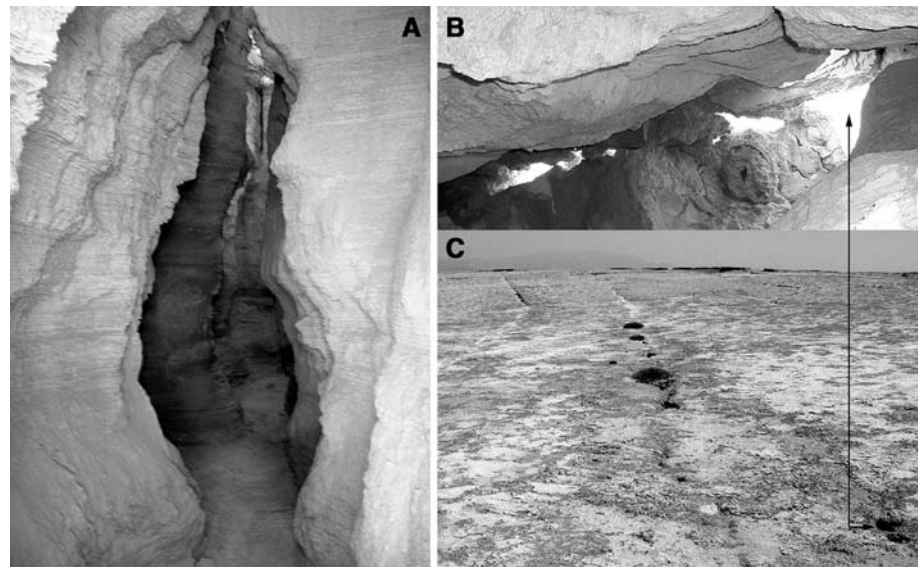
From aerial photographs dating back to 1953, a large number of sinkholes and uvalas can be observed over the whole peninsula. They appear as dark spots over a greyish-white background of salt deposits. The dark colour corresponds to vegetation in the depression where there is moisture (Fig. 14a).

Sinkholes are most common in the south–central zone, underlining the periphery of the elliptical dome of salt beneath the Lisan (see Fig. 6). Others exist in the northern part, a few km south of Cape Costigan. Previous studies have shown that a sub-dome may be rising in that area (e.g. Baer et al. 2002; Closson et al. 2003b). It suggests that sinkhole distribution could be related to structural elements coming from diapiric uplift, where groundwater circulation could be concentrated in the elliptic and radial fracture networks.

New features appear regularly in the surroundings of the shore, where faults and fractures submerged before the 1960s are reactivated (Figs. 8, 9).

Water, coming from the highlands moves toward the sea. Conduits developed at the time the Dead Sea was as low as present, were filled by sediments when the level of Dead Sea rose (Bookman et al. 2004), and their reactivation removes sediments and then causes subsidence and sinkholes. The differential interferometric techniques applied to a pair of ERS images acquired in 1992 and 1993 supports this statement (Fig. 15). Areas of subsidence in saltpan 18 are in the extension of a set of faults and fractures, emanating from the doming zone in the south-central Lisan (salt diapir). When analysing in detail, the topography of particular subsidence areas, and the distribution of sinkholes inside, a kind of “flower” pattern appears. All around a main collapsed, central zone, several sinkholes gravitate at the periphery, like petals of a flower. A similar pattern occurs on the eastern side of the Lisan. It appears similar to the regional pattern of sinkhole distribution around the main doming zone in the south–central Lisan.

**Fig. 12** **a** Example of a narrow cavern; **b** the roof is very thin and the cavern will slowly evolve to a ~4 m-deep trench. One can see the circular trace of a stromatolite near the gap indicated by an arrow; **c** the surface above the cavern. Two parallel fractures are conduits for water to extend caves and caverns. Pictures **b** and **c** indicate that walking or driving in the peninsula can be dangerous, particularly near the lineament (Closson 2005a, b)



**Fig. 13** **a** An example of draperies. **b** A spring high on a cliff (Closson 2005a, b)

Evidence of reactivation of former conduits can be found, for example, in the extension of former caves, toward the sea. Figure 14c shows an example of a small sinkhole near the entrance to a cave along saltpan 19. This feature is associated with soil piping or water leaking from a natural-drainage structure. This can create a void beneath the conduit. It may increase in size to the extent that the soil has insufficient strength

to support itself, with subsequent failure leading to the formation of a steep-sided collapse sinkhole.

Figure 14b, d show an interesting case illustrating the geotechnical problems encountered by engineers in building infrastructures in a dynamic environment. Since the beginning of the 1990s, sinkholes affected saltpan 18 more frequently than solar evaporation pond 19 (Fig. 15). Therefore, it is deduced that more unsaturated water circulates under the bottom layers and in its vicinity. At the first glance, water comes from two directions:

- from the Wadi Araba, owing to the truce-line flood channel, as attested by a kilometre sinkhole alignment very close to saltpan 18;
- from the Lisan peninsula, probably owing to the Lisan diapir's radial-faults system.

Arab Potash Company's engineers emphasize the role of the underground brackish water coming from the Lisan. Several springs exist along the foreshore bounding saltpan 18, and Arab Potash Company's divers mentioned an underwater sulphur spring (Fig. 6) close to the new brine intake station, between solar evaporation ponds 18 and 19 (Arab Potash Company, personal communication during a field survey in 2004). This suggests that under saltpan 18 the sea-water–fresh-water interface is pushed away beneath sea level because the ground water flows under a high hydraulic gradient generated in the provenance area. From topographical maps, aerial photographs, or various satellite images, linear kilometric narrow canyons dissecting the Lisan Peninsula can be delineated. The analysis of an InSAR digital elevation model computed with the ERS



**Fig. 14** **a** Vegetation is extremely rare in the Lisan due to the repulsive edaphic conditions. Depressions caused by local subsidence or collapse concentrate runoff water during rains. In the deepest part of the sag, the remaining water evaporates slowly, concentrating salt, and creating a repulsive salt crust for the plants. They are thus confined to the periphery of the depression. To live, however, plants have to develop roots to reach the upper part of the fresh-water lens beneath the peninsula. Therefore, the study of fossil roots would be a nice indicator of water fluctuation. **b** Sinkholes developed in saltpan

18. In 1999, this site was affected by decametric sinkholes, and saltpan 18 started to empty. Dead Sea brine remains 2 years in a pond before it can be used for mineral extraction. The loss of water is thus an important loss of money. Engineers created a rapidly improvised jetty to clog the foothold ( $L > 100$  m,  $l = 40$  m,  $h = 10$ – $15$  m). In 2005, a new feature appeared proving that geological mechanisms are always at work and that filling a hole can start a sinkhole. **c** “Recent” open sinkhole at the entrance of a cavern system. **d** “Recent” open sinkhole affecting the dike of saltpan 19 (Closson 2005a, b)

tandem pair of December 15–16 1995 (Fig. 4), and the geological sketch map of Sunna (1986), show that canyons extend along lineaments diverging from the Lisan diapir main dome. Such faults and fractures affect both the Lisan Peninsula and the recently emerged platform. The most affected areas are in the extension of the main canyons, suggesting that the WNW-striking linear weakness zones cross through solar evaporation pond 18 and are used as ground-water conduits.

Ben-Avraham (1997) and Bartov et al. (2002) mapped two fault zones, striking NNE through the Lynch Strait and bounding the Lisan’s western margin, respectively.

Places located at the intersections of these fault networks and the Lisan diapir radial-fault system (Fig. 16) are more hazardous, because they concentrate the groundwater coming from the Lisan highlands and the Wadi Araba. The distribution of the collapses recorded during the last 12 years support this statement (Closson 2005b).

#### Salt collapse: the birkat el haj area

Salt dissolution and collapse structures are prominent features of the Lisan Peninsula. An example is the Birkat el Haj area “salt collapse” (Fig. 17). It corresponds with the removal of salt at depth. When the salt is removed, two things happen: lithified sediments slump into the resulting cavity, and a basin is formed at the surface. The basin fills with sediments during basin formation from slump. In an area characterized by oil prospecting, it is worth noting that salt collapses can create reservoirs. Collapse chimneys and basin sediments may have been cemented and rendered impermeable, providing seals for fractured and leached reservoirs along the downdip side of a collapse basin.

Birkat el Haj could have resulted from a “catastrophic” event (i.e. formed during one instantaneous collapse) or an “incremental” event (i.e. salt removed gradually over time). From the interpretation of field data (Fig. 17), it seems that Birkat el Haj is a multi-stage or incremental structure. The salt flat area of

**Fig. 15** **a** Subset of an ERS amplitude image (August 05, 1993) showing the location of saltpan 18. Slant range projection; **b** differential interferogram (same area) realised with a pair of ERS images spanning from June 11, 1992 to August 05, 1993. Displacements are measured in the line of sight of the satellite. The *square* focuses on a wide part of saltpan 18; **c** the *line* (across **a** and **b**) helps in the understanding of the displacement fields. Two areas of subsidence have affected the bottom of saltpan 18 already in 1992–1993. The southern *arrow* indicates a particular distribution of sinkholes similar to a “flower” pattern—a main central collapsed zone with several smaller features around

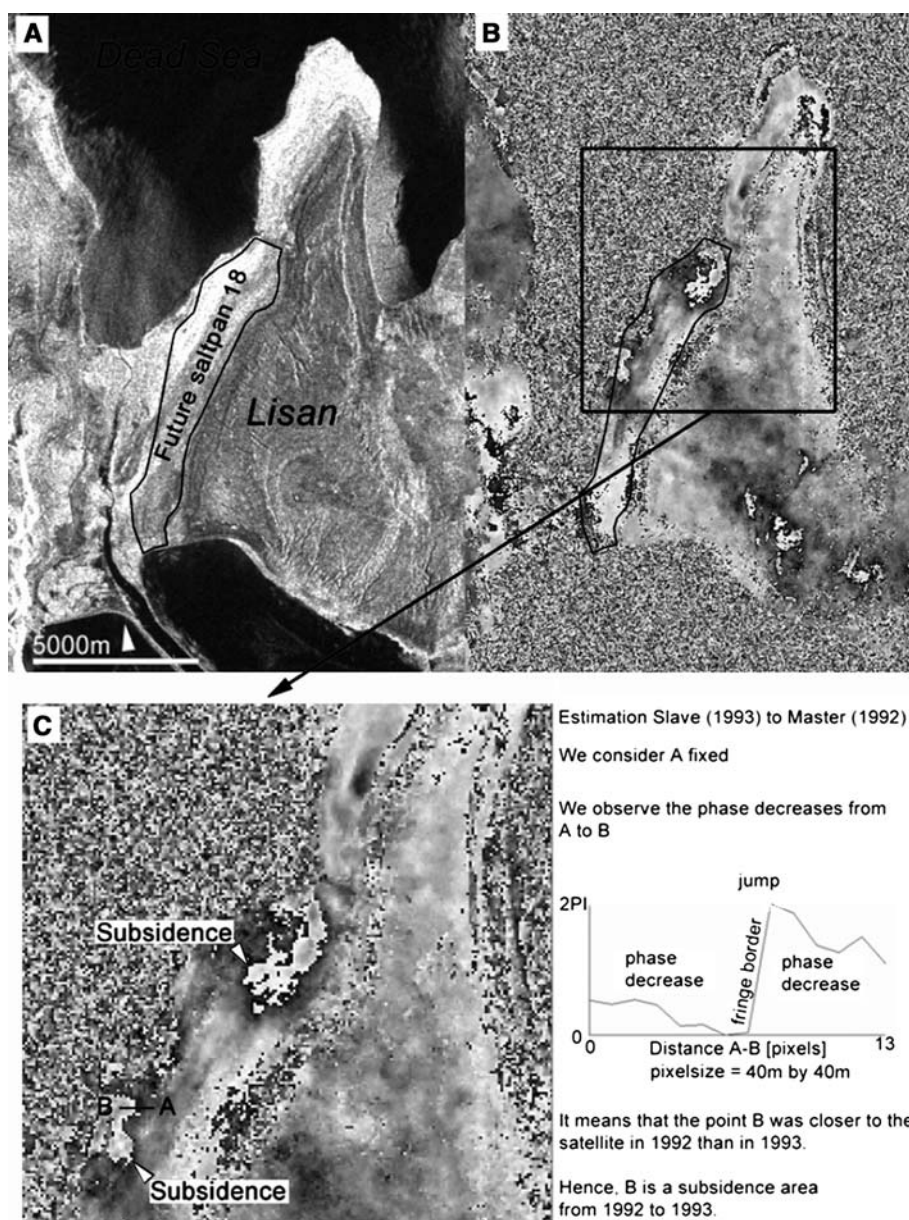


Fig. 17 acts as a local base level. If the depression lowers, then the position of groundwater and springs will move downward to reach the new elevation of the salt flat. Figure 17 focuses on a seepage underlined by living vegetation. Two lines of dead vegetation exist above the present seepage. We interpreted these features as two former positions of the seepage zone, now abandoned, due to the incremental lowering of the salt flat (base-level). The area of Fig. 17 is only a part of the Birkat el Haj structural feature (Fig. 3c).

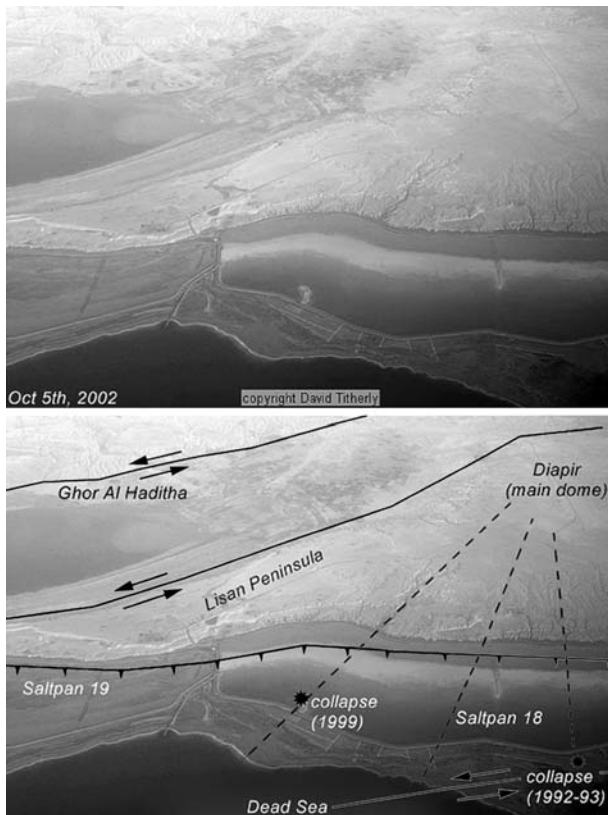
### Discussion on karst dynamics

The karst system of the Lisan peninsula is born from three basic components:

(1) soluble rocks: the main components of the different members of the Lisan formation are salt, gypsum, aragonite, calcite,  $MgFe(CO_3)$  and lithogenic detritus. They are highly soluble rocks with high porosity. Gypsum dissolves rapidly in running water, faster than limestone (Table 1).

(2) Unsaturated water, with respect to salt coming from:

- rainfall: there are 70 mm of rain per year that fall over the Lisan. Only the events of more than 4mm per 10 minutes are able to produce surface streams (Hallot 1999).
- groundwater from the nearby Moab Plateau and/or Judean Hills and, since the 1980s, from the wadi Araba. Groundwater follows the main faults of the



**Fig. 16** Oblique aerial photograph (*above*), and another view of the same photograph (*below*) showing saltpan 18 in 2002 (photograph © David Titherly). The land-filled sinkhole's area of 1999 is inside a zone of subsidence detected with interferometric techniques (Fig. 15c). This is an extension of a kilometre-sized canyon related to the uplift of the Lisan diapir southern dome. *Lines* are major faults; *dashed lines* are fractures emanating from the main dome of the Lisan diapir; *two stars* indicate subsidence and sinkholes sites. Their location correlated with the geological structure

Dead Sea pull-apart basin and the radial set of fractures that are the consequence of the Lisan's diapir rising.

**Fig. 17** Birkat el Haj is a complex structure, resulting from multiple episodes of salt dissolution and collapse



**Table 1** Solubility of evaporites in comparison with calcite (Ek 1993)

Halite	NaCl	360 g/l at 20°C
Sylvite	KCl	340 g/l at 20°C
Gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	2.53 g/l at 20°C
Calcite	CaCO <sub>3</sub>	0.014 g/l at 25°C

The major contribution of unsaturated water feeding the Lisan's water lens (Fig. 8) comes from the east side rather than the west side. This is supported by the elevation of the tectonic block corresponding to the Lynch strait being slightly below the Mazra'a–Ghor al Haditha (Fig. 5), which is a very fertile zone on the Lisan's eastern margin.

Since the building of the truce-line flood channel in the 1980s, the delta of Wadi Araba is now at the northern part of the dried up Lynch Strait. In consequence, a new source of unsaturated water with respect to salt can feed the Lisan's water lens from the southwest. This happens especially when floods occur, as in the winter 1991–1992. This needs more investigation.

With the gradient of salinity inside the Lisan's water lens (Fig. 8), this could be a key element to explain the location of the Antic's hermitages; a contribution to the way the hermits were able to live in a so hostile environment, as well as the presence of vegetation in confined places (Fig. 14a).

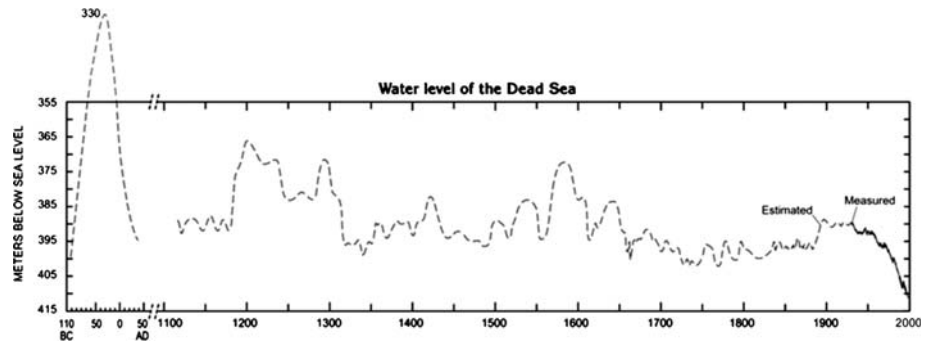
(3) Energy to dissolve, erode, and evacuate salt materials

Here, we consider three possibilities:

- Karst features may develop if the base level fluctuates. Of course, this is the case with the Dead Sea (Fig. 18).

If the lowering is rapid, then the groundwater level has to adapt to the new base level. However, as the water lens level does not react in the same proportion as the base level lowering (because of the ground

**Fig. 18** Historical water-level records of the Dead Sea have been reconstructed for a period of over 1,000 years, including the very large rise and fall in water level around the first century B.C. (Source Klein 1985; USGS 1999)



permeability), it results in an increase of the potential energy of the ground water. At the periphery of the fresh-water lens, water starts moving toward the sea, and, progressively, the disequilibrium propagates toward the centre of the lens. This movement acts as a pump and, little by little, induces more and more water from the surroundings. When moving toward the base level, a drop of water will convert its potential energy to kinetic energy. Part of this energy will be released due to resistance forces, and another to transportation of particles and dissolution. A karst system is thus activated or reactivated.

- Another way to increase the potential energy could be a rise in the water table on a regional scale. This exists where the Lisan diapir finds its way towards the surface. It is the case essentially in the south and central parts of the Peninsula.
- An earthquake is a third possible way, able to uplift the water table or lower the base level. Faults can provoke locally or regionally vertical displacements that will increase the potential energy. Figure 19

can be considered as an illustration of such a case. The “spade” cavern is characterized by its flat bottom where remaining tracks of running water are present and a relatively deep and narrow channel incises the floor. This feature explains a very rapid local base level lowering at the entrance of the cavern caused, for example, by an earthquake that lowers the local topography. Within 100 m, an old hermitage was completely destroyed in the fifth century AD, by a strong earthquake.

The Lisan karst feature can be considered as a relatively rare case at the Earth’s surface because we have a conjunction of three factors that can contribute to the energy needed to create a karst system.

**Conclusion**

The following recommendations provide guidelines for builders wishing to develop industrial or tourism activities in the Lisan or along the Dead Sea coast.

**Fig. 19** The flat bottom of the “spade” cavern (left) is characterized by old meanders. Its elevation corresponds to a former local base level. Due to the lowering of the downstream part caused by an earthquake, rejuvenation process occurred and vertical erosion took place, creating a narrow channel (right) at the bottom of the cavern (Closson 2005a, b)





**Fig. 20** Parts of the Lisan are currently becoming the garbage dump of the Jordanian southern Dead Sea urbanised area (Closson 2005a, b)

Attention to other elements for land management or archaeology is included.

- Hazards

Suitable foundations must be chosen and piling must be done carefully. To prevent infrastructures falling into sinkholes, a type of foundation known as “linked foundations” can be used. Preventing damage to buildings, as well as services such as water and electricity, must be considered. Flexible pipes can be used to prevent cracking.

Roads, bridges, and dikes must be planned carefully when subsidence features are present as they are a serious hazard to motorists (Milanovic 1981; Newton 1987). There is a method that could be adopted involving geogrid being layered into the embankment of the road or the dike. If a subsidence feature does develop the material will sink but not collapse.

Water extraction must be planned carefully as the dissolution of gypsum and/or salt occurs due to the water within it.

Dissolution of gypsum and/or salt presents a serious geological hazard; however, it can be mitigated with the use of careful planning and management on several different scales. On a national scale, it is important to help the public recognize that areas prone to gypsum and/or salt dissolution are potentially dangerous. On a local scale, it is important to understand the recharge patterns within the gypsum and/or salt karst.

- Pollution and water extraction (Fig. 20)

Like all karst-water systems, gypsum and/or salt karst can rapidly transmit pollutants. It is sensitive to both industrial and agricultural pollution, and requires careful exploitation and protection.

The complexity of hydrogeologic systems, in gypsum and/or salt karst terrains, mandates thorough hydrogeologic studies to determine whether a specific

**Table 2** Important characteristics for characterization of karst terrain (LaMoreaux et al. 1989)

Stratigraphy (regional and local)	Geologic structure (regional and local)	Geomorphology (regional and local)
Stratigraphic column	Nearly horizontal bedding	Relief-slopes
Thickness of each carbonate/salt/gypsum unit	Tilted beds	Density of drainage
Network	–	–
Thickness of non-carbonate/salt/gypsum interbeds	Homoclines	Characteristics of streams
Type of bedding	Monoclines	Drainage pattern(s)
Thin	Folded beds	Dendritic
Medium	Anticlines	Trellis
Thick	Synclines	Rectangular
Purity of each carbonate/salt/gypsum unit	Monoclines	Other
Limestone or dolomite	Domes	Perennial
Pure	Basins	Intermittent
Sandy	Other	Terraces
Silty	Fractures	Springs and/or seeps
Clayey	Lineaments	Lakes and ponds
Siliceous	Locations	Flood plains and wetlands
Interbeds	Relationship with geomorphic features	Karst features, active, historic
Overburden	Karst features	Karst plains
(Soils and sub-soils)	stratigraphy	poljes
Distribution	Structural features	Dry valleys, blind
Origin	Joint system	Valleys, sinking creeks
Transported	Joint sets	Depressions and general
Glacial	Orientation	Subsidence
Alluvial	Spacing	Subsidence cones, in
Colluvial	Continuity	Overburden
Residual	Open	Sinkholes
Other characteristics	Closed	Roof collapse

site is, or can be rendered, suitable for a facility. Important components of hydrogeologic studies are: field mapping of structural and stratigraphic units; interpretation of sequential aerial photographs; test drilling and geophysical analyses; fracture analyses; seasonal variation in water-levels; spatial variation of hydraulic characteristics of the aquifer and aquiclude; velocity and direction of movement of ground water within aquifers; determination of control for recharge, discharge, and local base level; and evaluation of the effects of man's activities, such as pumping, dewatering and construction (LaMoreaux 1991; LaMoreaux et al. 1989).

Table 2 lists the generic categories of information that should be considered during evaluation of a potential site (LaMoreaux et al. 1989).

- Archaeology

Additional investigations regarding the salt gradient of the Lisan's water lens would provide new concepts for archaeological prospecting.

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