SOLUTION MINING RESEARCH INSTITUTE
105 Apple Valley Circle
Clarks Summit, PA 18411, USA

Telephone: +1 570-585-8092
Fax: +1 570-585-8091
www.solutionmining.org

Technical Conference Paper

Presentation of Salt Structures and Considerations about their Genesis as a Basis for the Evaluation of their Economical Use

Stefan Folle, StorConsult, Hannover, Germany

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PRESENTATION OF SALT STRUCTURES AND CONSIDERATIONS ABOUT THEIR GENESIS AS A BASIS FOR THE EVALUATION OF THEIR ECONOMICAL USE

Stefan Folle

STORCONSULT, Hannover, Germany, folle@storconsult.de

Abstract

The complexity of many salt structures means that evaluating their economic potential is associated with a high level of uncertainty. This is especially true when access is restricted by the presence of buildings on the surface or natural inaccessibility.

On the basis of satellite pictures, models and field observations, some typical well preserved structures in the deserts of the Middle East will be presented which can undoubtedly be used to draw valid conclusions about buried, diapiric salt deposits in humid climates.

In all of the examples described here, strong tectonic regimes are responsible for continuing diapirism, with glacier-like movement in part on the non-evaporite land surface. Despite the arid climate, the exposed salt is karstified in many cases, making it even more difficult to carry out exploration and site selection.

The clarification of overhang situations as well as the assessment of recent tectonic movements with respect to the associated fracturing are essential for project realisation.

Key words

Middle East, salt dome, salt glacier, salt uplift, tectonics, karst, Dead Sea, Central Iran

Introduction

There is a need for storage space even in some of the gas-producing countries from which some of the examples shown here are derived. This is due to the usually strongly growing populations and increasing industrialisation. In addition, these countries have entered into supply contracts which can jeopardize supplies to their own inhabitants during peak periods.

The knowledge acquired here can also be extrapolated to most of the covered structures in the – now – humid climates, which were also exposed to similar conditions in the past. This visualisation of the structural possibilities should help understand the risks, and evaluate them more precisely when new projects are begun or when existing projects are to be expanded close to their limits.

The more realistic the geological models, the more reliable one can define the boundaries of the cavern fields. This helps optimise the storages by reducing the conservative stipulation of the pressure range and the total volume. It also constrains the risks of contractual penalties if it is not possible to realise the leasing options.

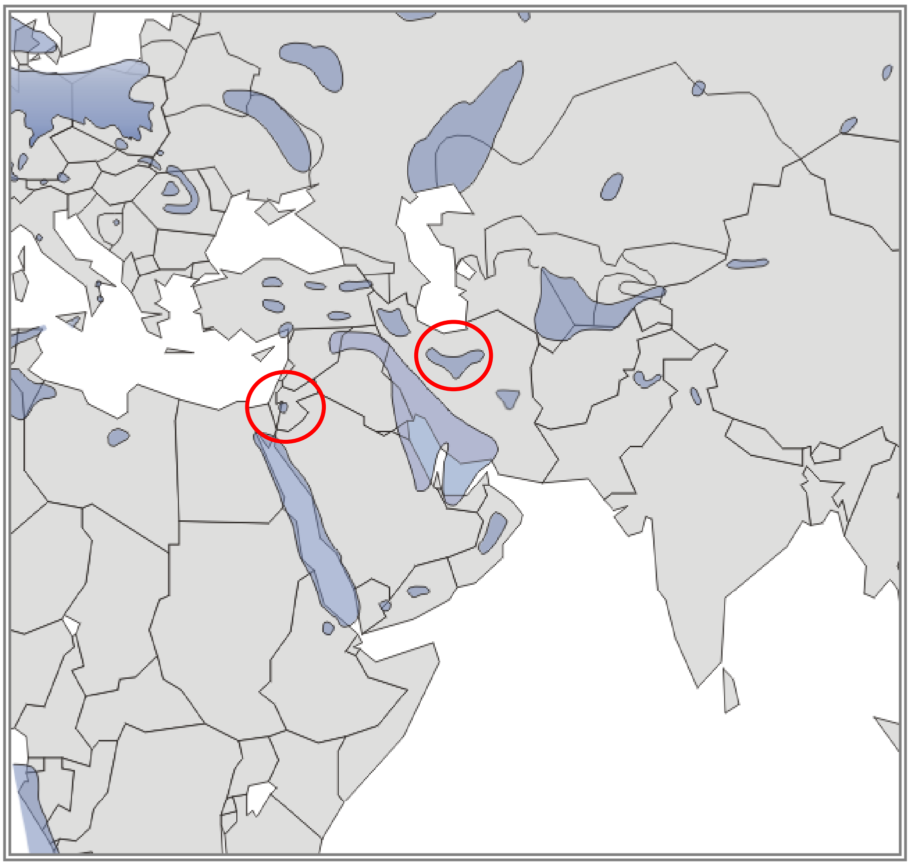

Fig. 1: Locations of the salt structures presented here (modified after Folle, 2006)

Example 1: Salt structures in the Great Kavir Desert (Dasht-e-Kavir)

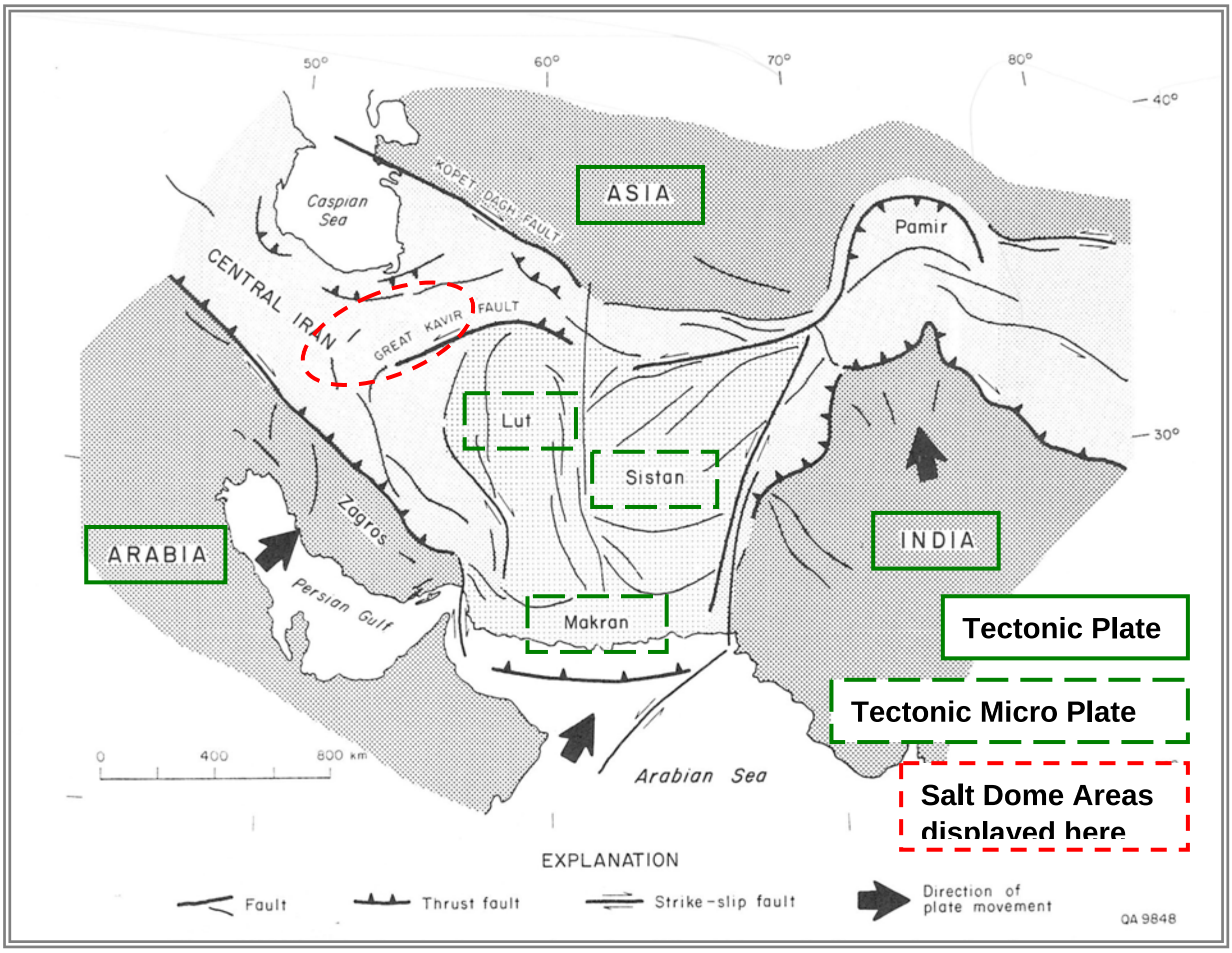

Fig. 2: Plate tectonic overview (modified after Jackson et al., 1990)

The salt domes in the Great Kavir Desert as well as the structures lying further to the west described in Chapter 2 are located in an extremely active tectonic zone. This tectonic zone forms the boundary between the colliding Arabian, Indian and Asian plates. Smaller units are squeezed in between which also move relative to one another. The current nature of the movement is evidenced by frequent, in some cases, devastating earthquakes.

In addition to fracture tectonism, this region is also marked by the uplift of the marginal orogens, subsidence of the foreland, and associated strong sedimentation within the basin.

The Tertiary salt deposits in Central Iran described here have risen up through a faulted cover rock sequence characterised at least in part by significant transverse movements and associated pull apart structures. The salt initially moved upwards through this faulted cover rock under the force of gravity. In addition, the lateral tectonic pressure also gave rise to strong upward movements and even surface lateral movements with glacier-like flow.

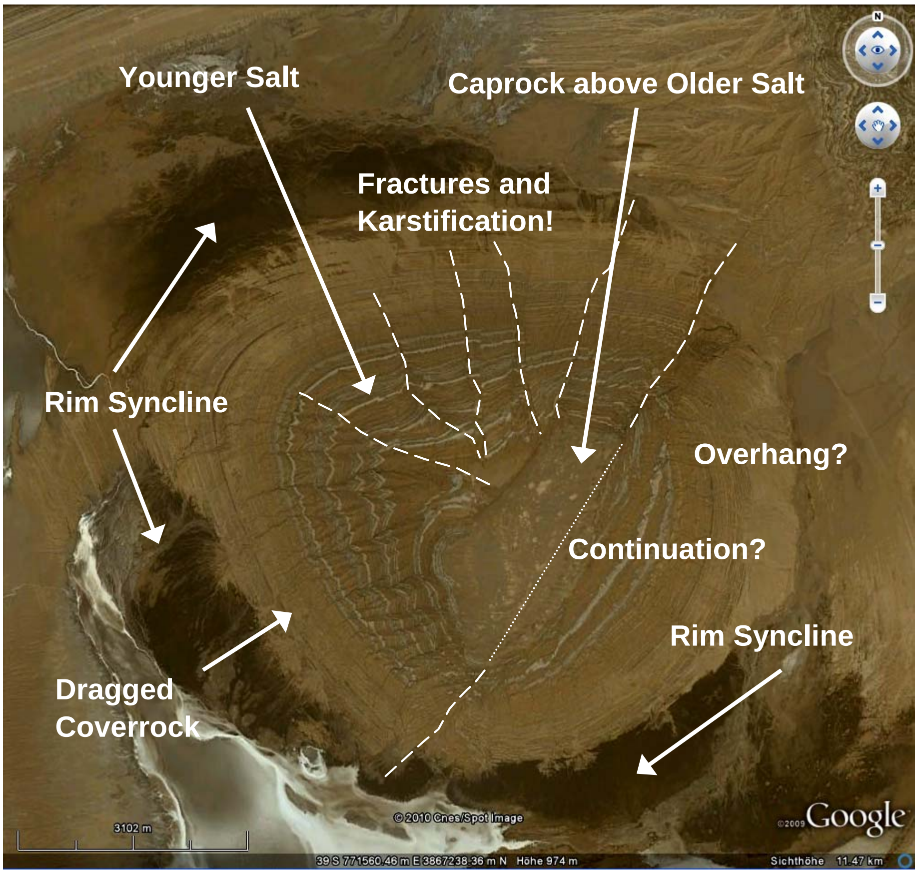

Fig. 3: Salt dome with relatively uniform comparatively slow upward movement. The centre consisting of older salt (Eocene) is covered by a cap rock. The younger salt is characterised by uniform bedding and extremely minor amounts of folding – primarily very minor echelon folding. On the outer margins, the cover rock is visibly dragged upwards. The continuous movement is highlighted by rim synclines filled with dark clay or light salt.

The salt domes in the Great Kavir Desert (Dasht-e-Kavir) are constrained by wedge-shaped fault zones which converge on one another. The closer the fault zones to one another the stronger the salt appears to be deformed, in part with the formation of salt canopies in which the individual salt domes merge together towards the top. The wider the wedge between the faults, the fewer structures appear at the surface. They are therefore no longer at the surface in the east because erosion is stronger than the vertical uplift.

The examples presented here show on the one hand a diapir which rose at a relatively slow speed (Fig. 3), as well as one which is interpreted to have involved stronger movements (Fig. 4).

The gradual upward movement is demonstrated by more simple folding. The cap rock was able to develop. The cover rock lies relatively undisturbed at the margins and is not displaced laterally by the formation of sub-vertical fold axes. Continuous upward movement can be assumed if the secondary rim synclines are preserved and have not yet been completely filled with sediments.

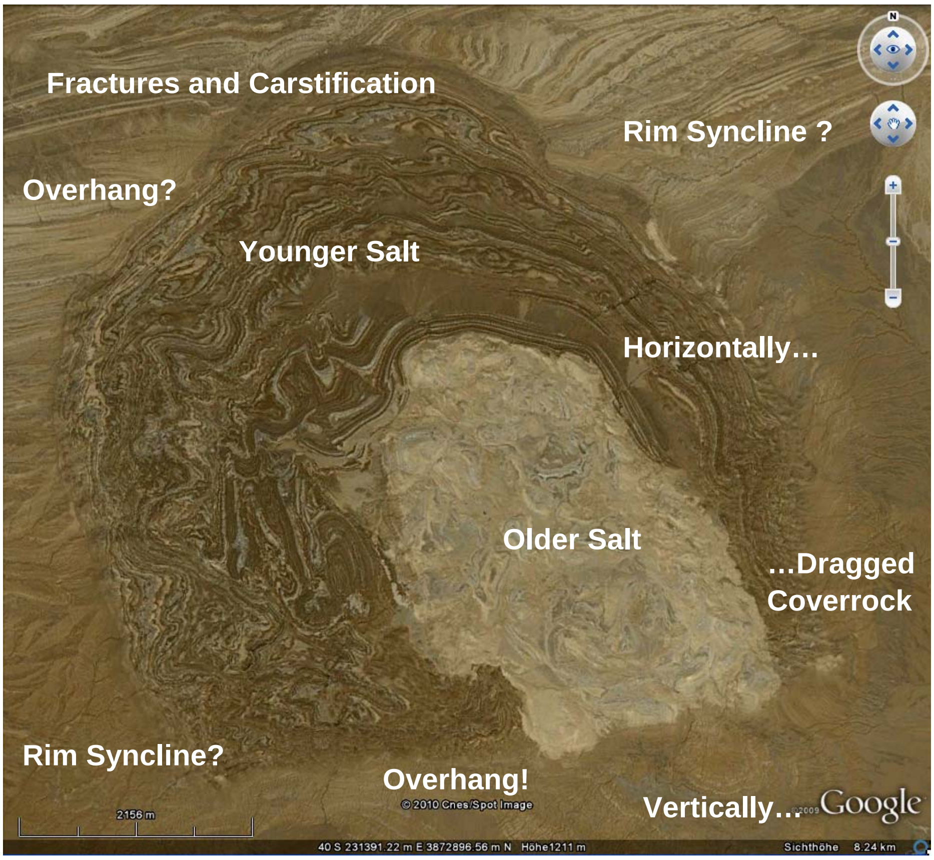

Fig. 4: Salt dome with rapid upward salt movement which proceeded step-by-step and created echelon folds in the younger salt. The old salt in the centre has a blocky appearance. The enormous force is also documented by the compensatory movements of the salt leading to the formation of a glacier, which overlaps the younger salt to the south. The neighbouring cover rock is clearly deformed and only lies on the structure to a minor amount

Fast moving diapirs have echelon-type folds (sub-vertical fold axes), particularly when the upward movement took place in pulses. This applies particularly to areas where the material was very ductile, such as in the argillaceous younger salt (Miocene) of the Dasht-e-Kavir group. The more brittle older salt (Eocene) is contaminated with less fine clastic material, tends to contain sulphates, forms blocks, and appears to have less structural organisation. The enormous upward movement of salt gave rise to isostatic compensation in the form of glacier formation. Vertical movement in this case was transformed into horizontal movement. This reduced the load of the diapiric zone which enabled more material to move upwards. Movement of this kind is favoured when the sliding surface is at an angle. In Figure 4 for instance, the surface dips to the south on the flank of an anticline and controls the direction of movement of the glacier.

If no rim synclines are identifiable despite intensive salt movement, this strongly indicates that movement has come to a stop. Alternatively, as is the case in Figure 4, the source of the salt is not directly within the diapiric aureole, but instead, for instance, comes from the core of a salt-bearing anticline which may itself still be moving as a result of tectonic compression.

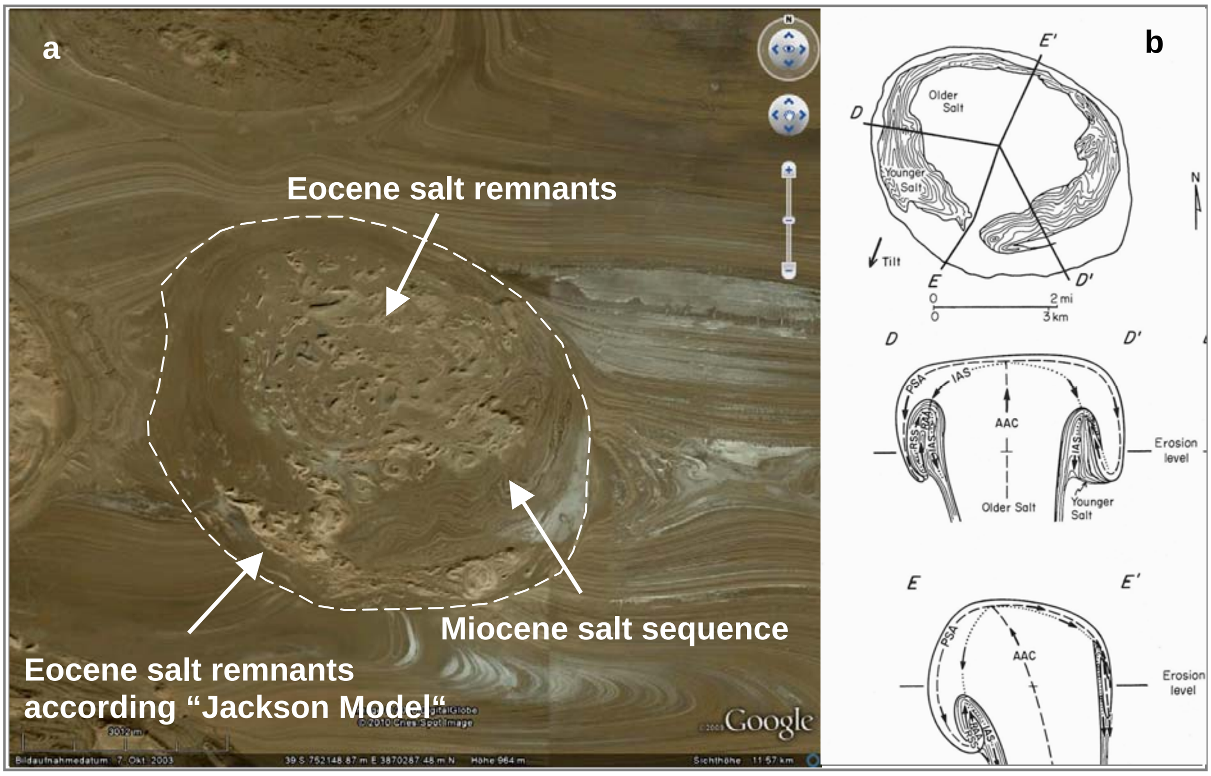

Fig. 5 a+b: This diapir is a structure which seems to have come to a stop. Originally, there must have been considerable upward movement of the salt which was responsible for the folding. The Eocene salt has moved to the south over the top of the younger salt. Exposures have now been considerably eroded, but further upward movement of the salt no longer compensates for this erosion. According to the modelling by Jackson et al. (1990), the older (central) salt folded in younger salt in a south-verging mushroom diapir and has now been eroded down to the level of this folding in. The vergence may have been assisted by the neighbouring anticline to the north. Rim synclines are no longer identifiable. The neighbouring tectonic syncline accommodates the salty water.

The main feature indicative of slightly active diapirs is that erosion overprints the movement of the salt. Sometimes this gives rise to unique structures with a lateral sequence of old – young – old (compare Fig. 5).

According to modelling by Jackson et al. (1990), such a diapir developed in the form of a mushroom with a minor constriction. In this way, the younger salt appearing at the margin was folded in by the older salt which rose up in the centre and flowed over the younger salt so that older salt appears in outer positions. This could also be described by a roller-like lateral movement. When erosion then takes place so strongly that it removes the connection between the old salt in the centre and on the margins, the outer old salt becomes isolated in a position where one would normally expect young salt to be.

In the Gorleben salt dome in Germany, which is being explored to assess its suitability for a geologic repository for nuclear waste, a similar phenomenon is observed, even though the shape is more like that of a salt wall.

With respect to exploration and thus the assessment of the feasibility of constructing a facility, e.g. cavern fields, one can say that when a salt dome has a history of fast permanent uplift this is not only attributable to an increase in load respectively thickness of the overburden, but also to lateral constriction by tectonic stress. In extreme cases, this gives rise to large overhangs which significantly restrict the width of the usable area underground. It is therefore advantageous if the structures are associated with more moderate rates of salt uplift which should be associated with the formation of a protective cap rock or the preservation of the cover rock. Low physical height and a protective cover to prevent the influence of weathering avoid or minimise karstification and thus makes it possible to exploit the structures from a central location.

Example 2: Salt structures in Central Iran

In the vicinity of the Zagros Thrust Belt, transverse thrusting and strong tectonic pulses give rise to salt structures with enormous rates of upward movement, which form glaciers and are marked by intensive folding which is itself frequently overprinted by younger folding. The transverse thrusting gives rise to pull apart structures as shown in Figure 6. This diapiric chimney shows the centre of the structure (pull apart spreading). If the movements are gravitational at the beginning, the laterally applied stress plays another important role.

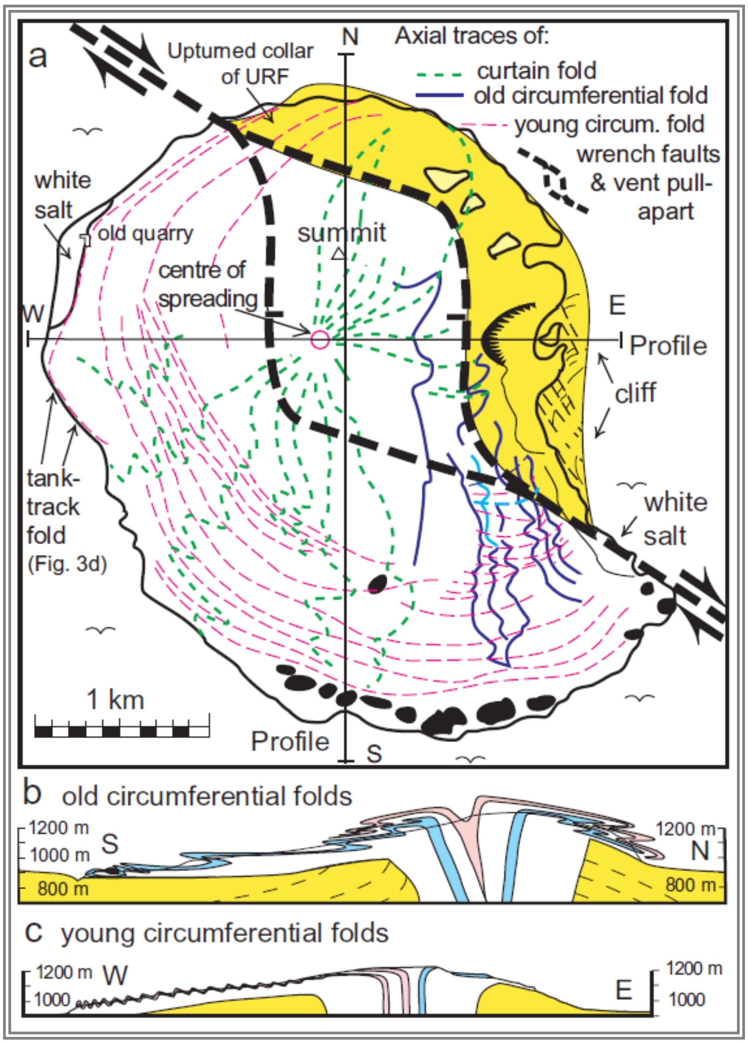

Fig. 6 a-c: Structural history of Kuh-e-Namak (Farsi, Salt Mountain) shows different types of folding (Talbot & Aftabi, 2004 [after Folle, 1997, unpublished]). The uprise takes place via a comparably narrow central vent formed by pull apart spreading (a). Whereas to the North the cover rock laps over the salt, a glacier like movement to the South accompanied by intensive folding occurs, e.g. lying tank track folds as well as steep curtain folds (b+c). Periodic salt movements favor the generation of the folds as the surface of the sliding plane does. The structure is located slightly south of the anticlinal top. Volcanic rocks aged early Eocene are transported by the salt and remain at the end of the glacier like moraines.

The vulcanites embedded in the salt were most probably formed at a similar time to the basal older salt. It is considered unlikely for them to appear within the saltdome if their deposition was restricted to the underlying sequence. There is structural evidence that they are of synsedimentary origin. The age of the older rock salt in this area is assumed to be Lower Oligocene/Base Lower Red Formation (Talbot & Aftabi, 2004).

The older salt flows over the younger salt because of the formation of a salt glacier (Miocene, Base Upper Red Formation), and this transported the andesitic vulcanite inclusions to the end of the glacier tongue where they formed a chain of hills after the complete dissolution of the salt. The further upward movement of older salt seems to have stopped because no other vulcanites have been identified in the vicinity of the diapiric zone. The source area here is interpreted to have been isolated at depth or squeezed out. Diapirism still continues but is now restricted to the volumetrically dominant younger salt.

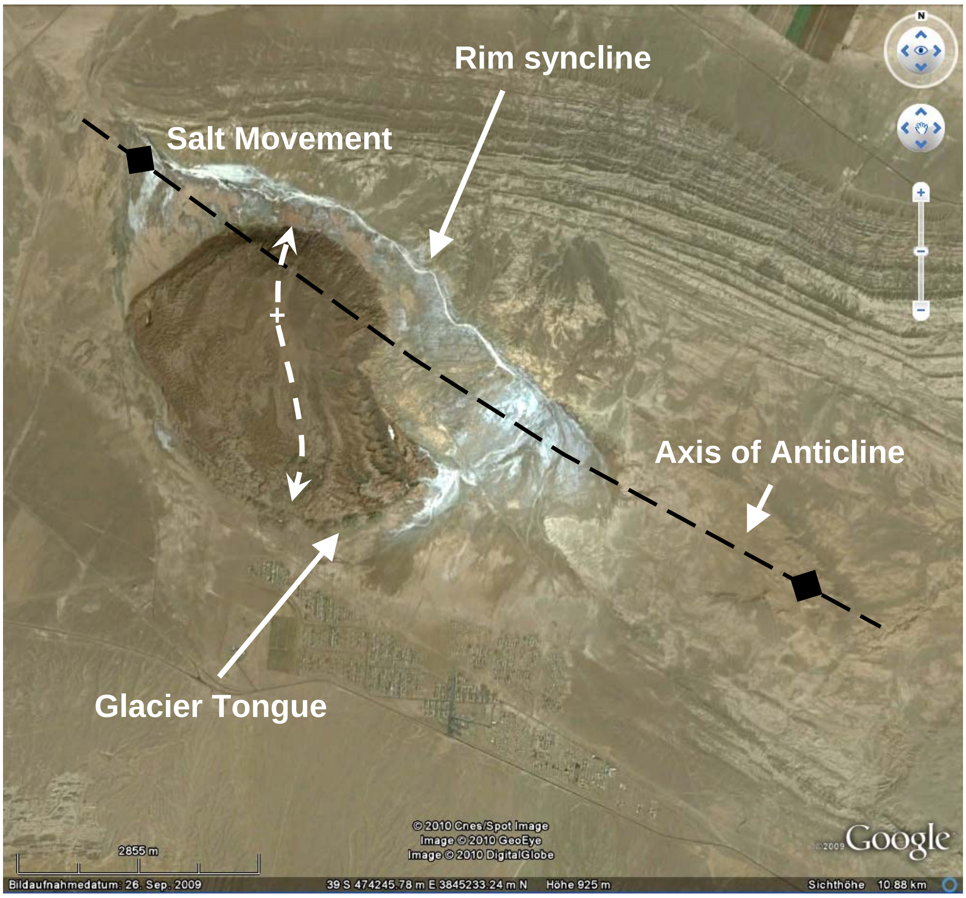

Fig. 7: The Kuh-e-Namak rose up close to the axis of an anticlinal structure, probably in the area of a crestal fault, and began to slide on the inclined surface of the southern flank of the structure after permanent strong salt diapirism. Initially, older more brittle salt flowed over the more ductile younger salt until the source ran out of material and the glacier was then “fed” by younger salt which rose up to the surface and continued to feed the glacier with its masses via isostatic lateral compensation movements.

The salt is supplied from the core of the anticline. The trough generated by the upward movement of the salt runs on the northern margin of the diapir following the anticlinal axis (inversion).

The surface of the structure is strongly karstified. The outlet of the karst system is normally levelled close to the surface (ground water). Because of the continuous strong upward movement of the salt, the openings of the karst caves which feed the outflowing salt streams lie partially above the surrounding surface of the ground.

There was no development of a significant cap rock. The only analogous material lies at the end of the glacier and primarily consists of argillaceous residual rocks forming a type of cover material.

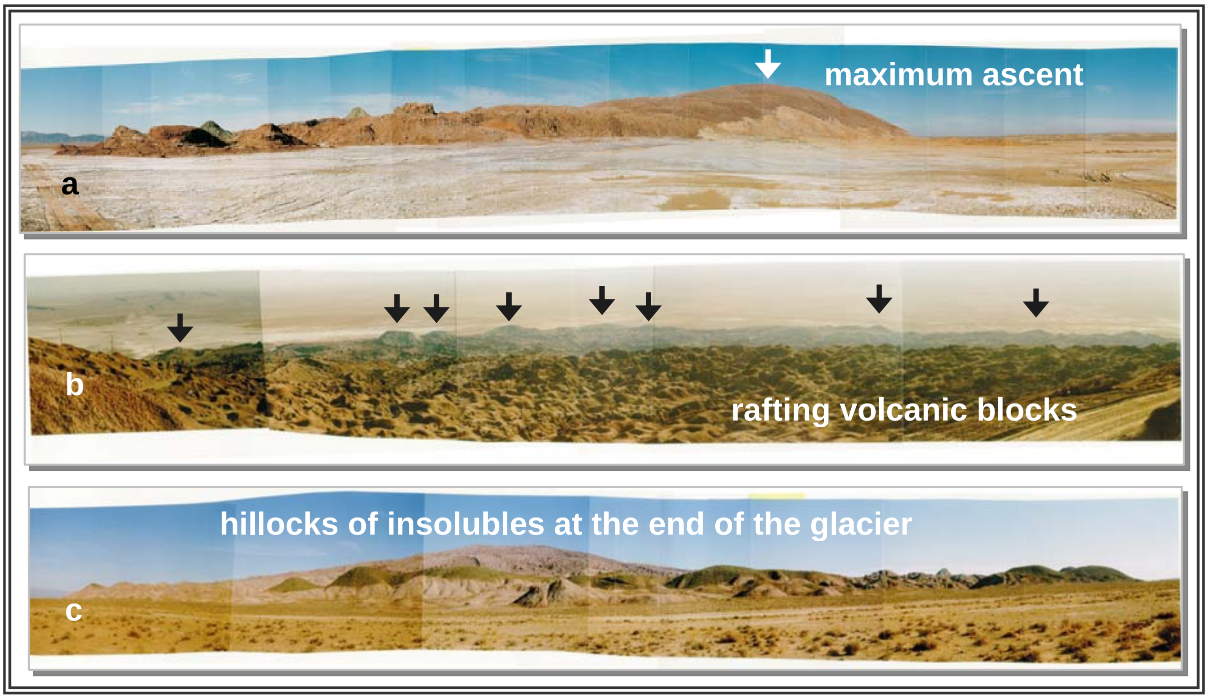

Fig. 8 a-c: View of Kuh-e-Namak structure from the east (a) with its salt-filled trough indicating the origin of the salt from a deep source region (in the foreground) and the diapiric salt zone in the background, from the top (b) looking across the glacier, and from the south (c) with the final ring of residual material (photos by R. Jagsch, 1996).

Exploiting such a salt dome economically would primarily involve opencast mining (potash salt and halite). Exploiting the salt underground in the area of the glacier is not feasible, and even in the northern marginal area where there is still some overlying cover rock, the overhangs are only of minor thickness and are therefore unsuitable for underground mining. The strong continuing movement could also have a negative effect on equipment such as casings. And the salt karst which covers the whole area will also prevent the long-term construction of buildings on the salt dome.

In a similar tectonic situation around 70 km to the south-east, there is another diapir which belongs to the Shurab diapir group. This diapir is also associated with an anticlinal structure. The tectonic fracturing and movement pattern here suggest the presence of a pull apart spreading zone which initiated gravitative salt diapirism, which was then maintained and intensified by tectonic movements.

Unlike the Kuh-e-Namak structure, the cover rock is still preserved here. In addition, there is still residual rock on the paleokarst (Fig. 9a). The salt is exploited in a quarry. It appears to be older salt (Base Lower Red Formation). It is brittle, strongly mylonitised (Fig. 9b) and sulphate-bearing. Protective caps on the sediments are frequently formed by vulcanites and must therefore be younger than the salt (a similar sequence may also initially have been present in Kuh-e-Namak). There is no indication of any recent movement (rim synclines, naturally outcropping salt). In the case of this probably inactive diapir, it is also questionable whether younger halite from the Miocene (Upper Red Formation) is accessible at economic depths, or even whether it was deposited at all.

To the north (Fig. 9a left), the structure stops at a large fault with transverse throw and a considerable vertical component. Beyond the fault, the land is almost completely flat. The question is whether the salt deposit continues here under ideal surface conditions.

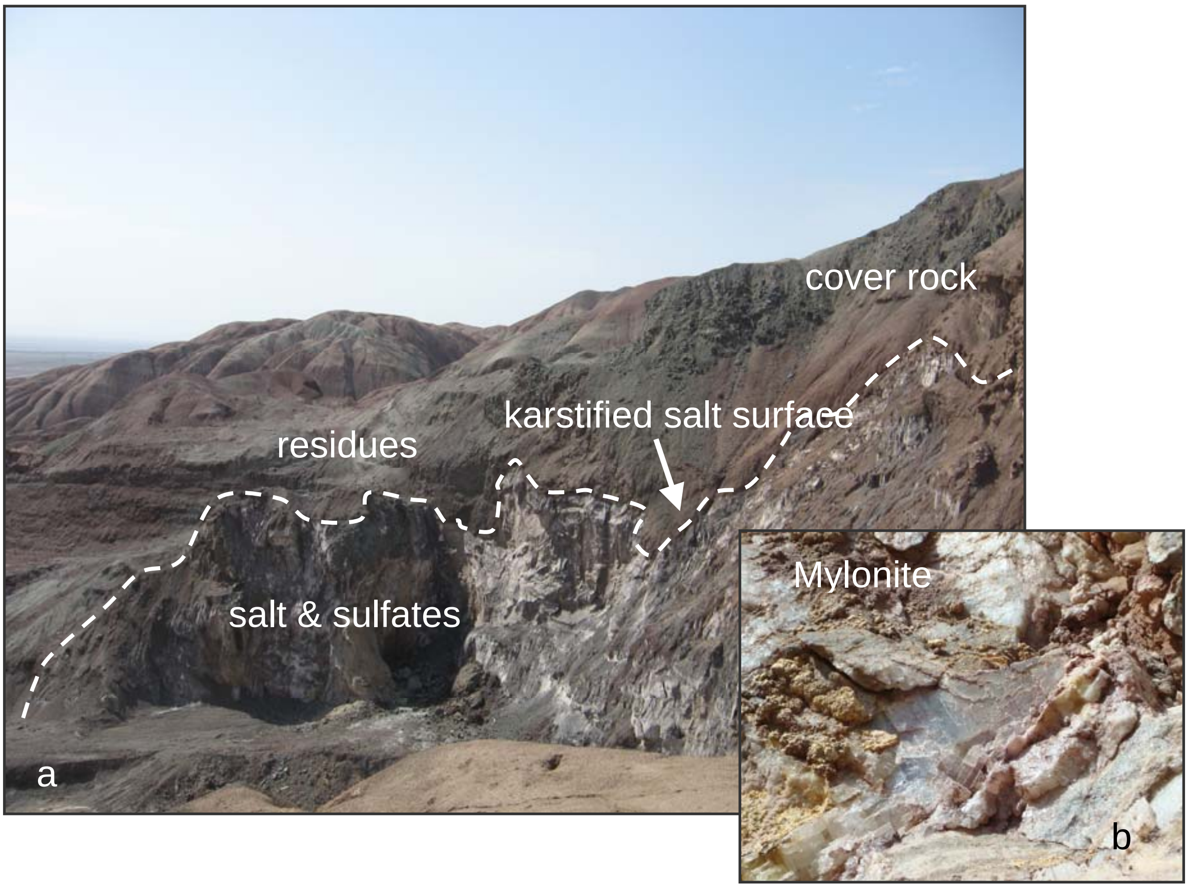

Fig. 9 a+b: The quarry shows a relatively fresh exposure of the Oligocene evaporite (Lower Red Formation). The former presence of strong movements is indicated by the deformed mylonitised fabric of the salt (b, width of the picture approx. 50 cm). The former karst surface is filled with residual rocks and cover rock.

Because the salt has probably not moved far from the original zone of vertical movement, it is possible that a potential deposit lies autochthonously to the north of this fault and is not derived from the area of the surface outcrops.

The relatively minor amount of uplift does not indicate the existence of a large thickness of overburden as in Kuh-e-Namak, which also means that the base of the salt is probably at relatively shallow depth. However, this may also be a result of a minor amount of lateral movement due to the absence of younger salt forming a sliding surface.

A group of hills directly located in this northern region and which resembles the residual deposits at the margins of some Great Kavir diapirs or the southern margin of the Kuh-e-Namak structure, suggests that salt diapirism also took place here and is now either no longer active or only moves to a very minor degree. This is definitely an area worthy of further exploration. A potential salt deposit probably lies at fairly shallow depth.

Fig. 10 a+b: Shurab diapir group – location near Kashan. This view is directed from a salt quarry at the base of a diapiric structure (Fig. 9), looking across a larger fault (dashed line), to the Dasht-e-Kavir plain with a group of hills. These erosion residues may be associated with a salt structure. Good surface conditions and the assumed proximity to salt make this location interesting for storage exploration activities.

Example 3: Salt structures on the Dead Sea

The structure at Mt. Sdom described in the following lies along the boundary between the Arabian and the African continental plates. This boundary is dominated by the Arava Transform Fault which offsets the two plates by > 100 km and where a graben (Dead Sea Graben, Jordan Graben) has developed as a result of an extensional trend, and faults down with a maximum vertical throw of > 10 km.

After more than 6,000 m sediments were deposited in the southern Dead Sea Graben in the Pleistocene (Lower Quaternary) at the latest, building up an overburden above the Pliocene salt, the pressure in the cover rock was released along the western flank of the graben – along the main faults as well as a result of the diagonally running faults – and initiated salt diapirism. This process may also have taken place simultaneously with the deposition of the thick graben sediments.

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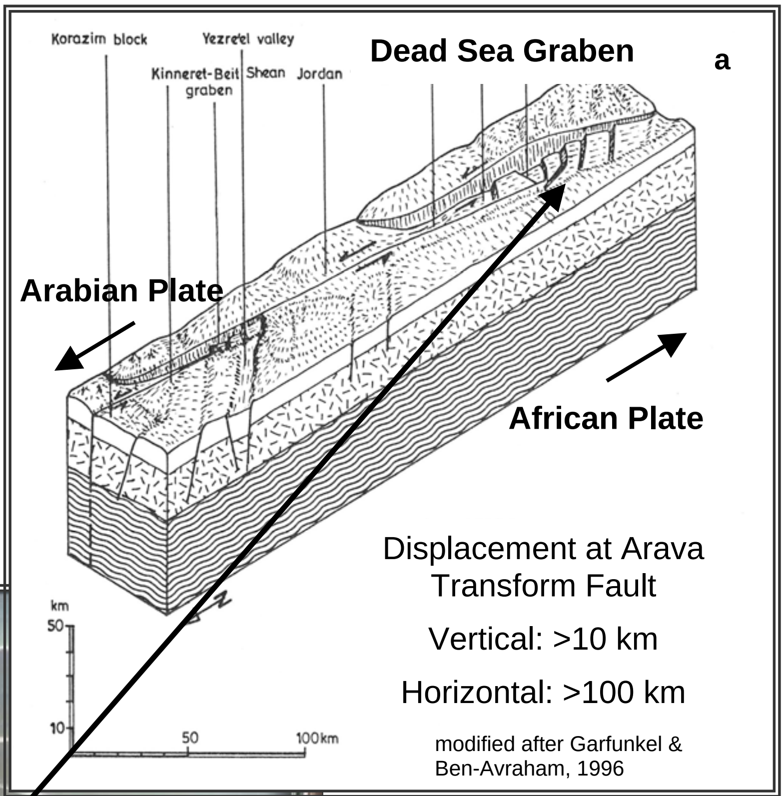
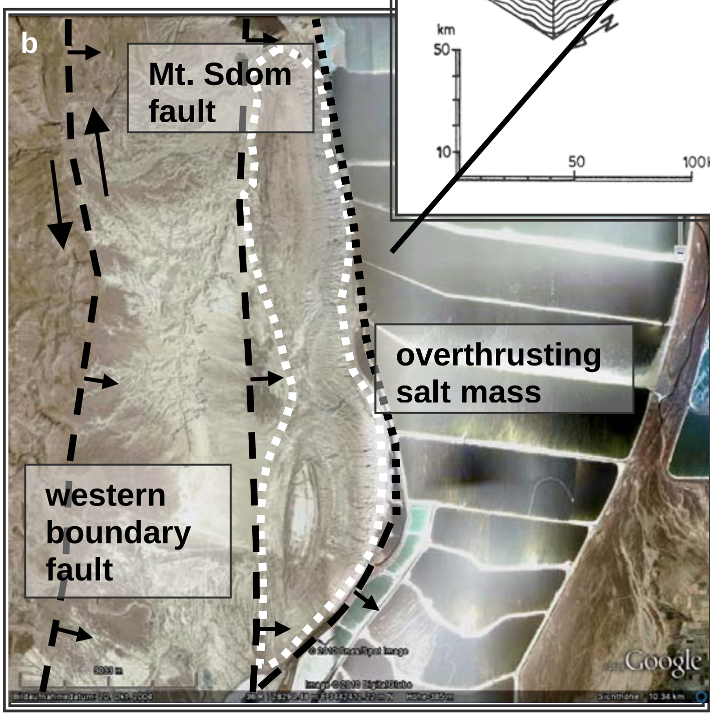


Fig. 11 a+b: General and regional tectonic overview of the locality. The steeply dipping salt body is marked white in 11b. The main faults along the western flank of the graben run to the west of the structure.



The salt thrust over the neighbouring cover rock is in so far an inversion because an originally normal fault locally operates as zone of upward movement.

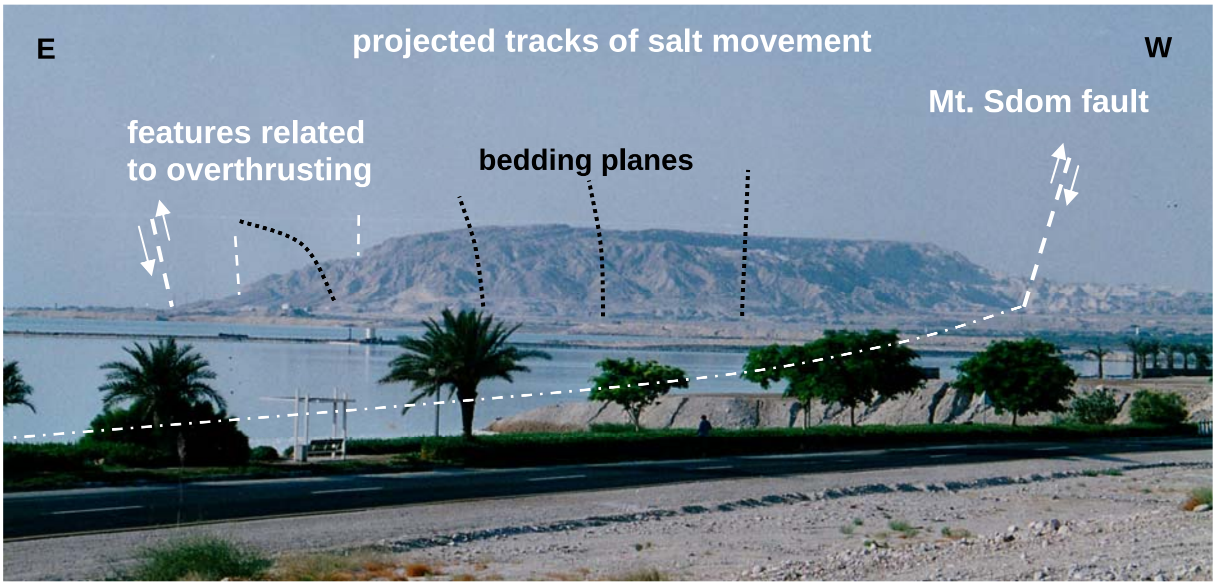


Fig. 12: View from the north towards Mt. Sdom. The relative height above the former water level of the Dead Sea at this location is approx. 200 m, the width approx. 1.5 km. The Mt. Sdom fault is one of the main faults in the graben system. It is originally a normal fault with a significant transverse throw along which the salt rose up since the Late Pleistocene. The water surface seen here is part of the brine extraction ponds and marks the former level of the Dead Sea (- 393 m). The water level has sunk approx. 22 m since then.

Only the Upper Lisan Formation is preserved on the salt dome above the approx. 30 m thick cap rock and was lifted up approx. 100 m above the current level. This corresponds to an uplift in the Holocene of approx. 7 mm/a.

Recent salt movements are difficult to classify. The graben is still tectonically active as indicated by the earthquake activity amongst other things. Although there are some indications, mainly on the east side facing the Dead Sea, of features which are clearly associated with salt movement, there are also other features which could have originated tectonically (Fig. 13 a+b).

There is no doubt though that the eastern side is affected by active movement, which means it would probably not be feasible to erect buildings in this area. These should preferably be constructed on the west side at a certain distance to the Mt. Sdom fault. Collapse associated with faults or salt movement appear to be limited to the margins and not the inner salt structure.

This consists of steeply dipping layers which only overturn towards the centre of the graben in the vicinity of the thrust plane. Halite is intercalated with sulphate horizons which in some cases have higher solubility. This has led to the formation of a karst system (Fig. 14 a+b), with karst chimneys which start at the top and end at the height of the former water level of the Dead Sea. The unaffected salt is below.

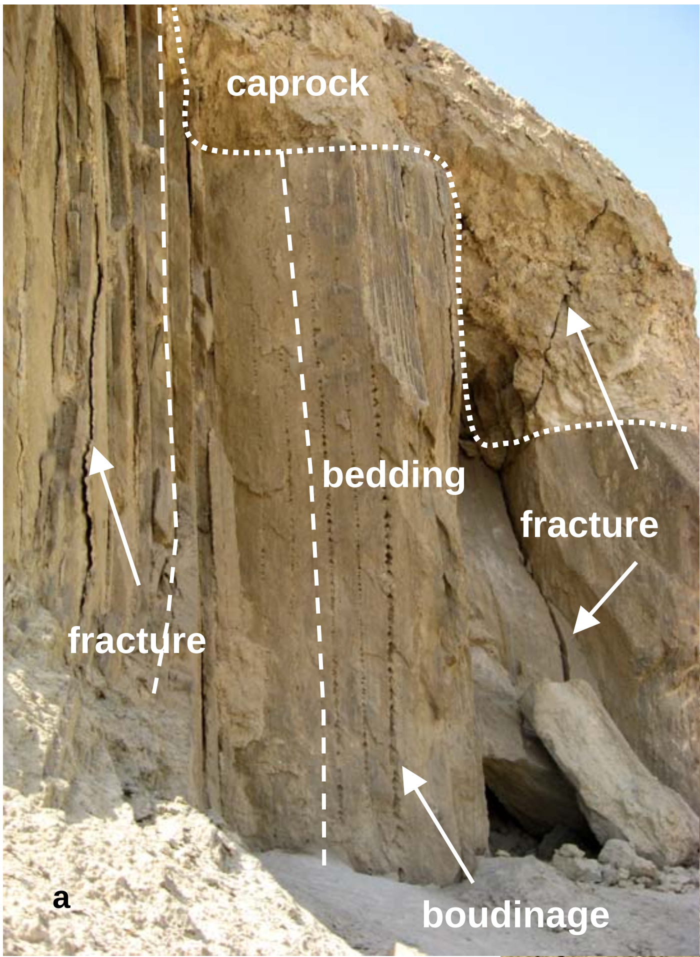
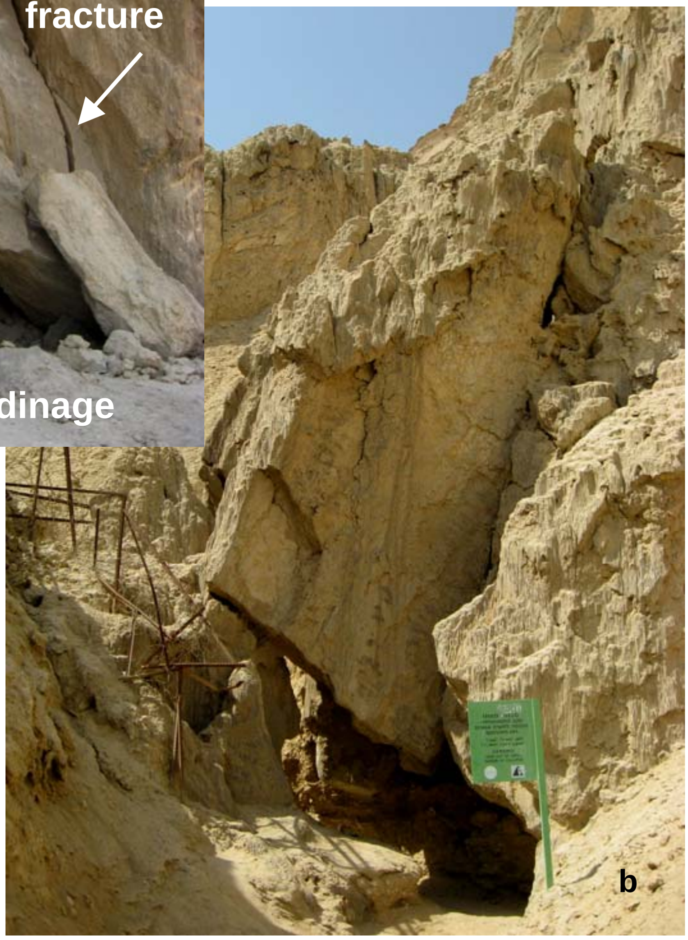


Fig. 13a+b: The eastern marginal zone near the salt overthrust above the younger graben sediments of the Dead Sea. The bedding-parallel boudinage is certainly not a deformation feature which occurred in the recent past: it is more likely to be related to the major overburden or earlier movements. The deformed material was more easily soluble than the salt and therefore completely weathered in exposures.



There are also clear fracture deformations beginning with smaller fractures as shown in Fig. 13a, as well as very dramatic fractures such as in Fig. 13b. Here, the entrance to a karst cavern system has collapsed – most probably related to a tectonic event.

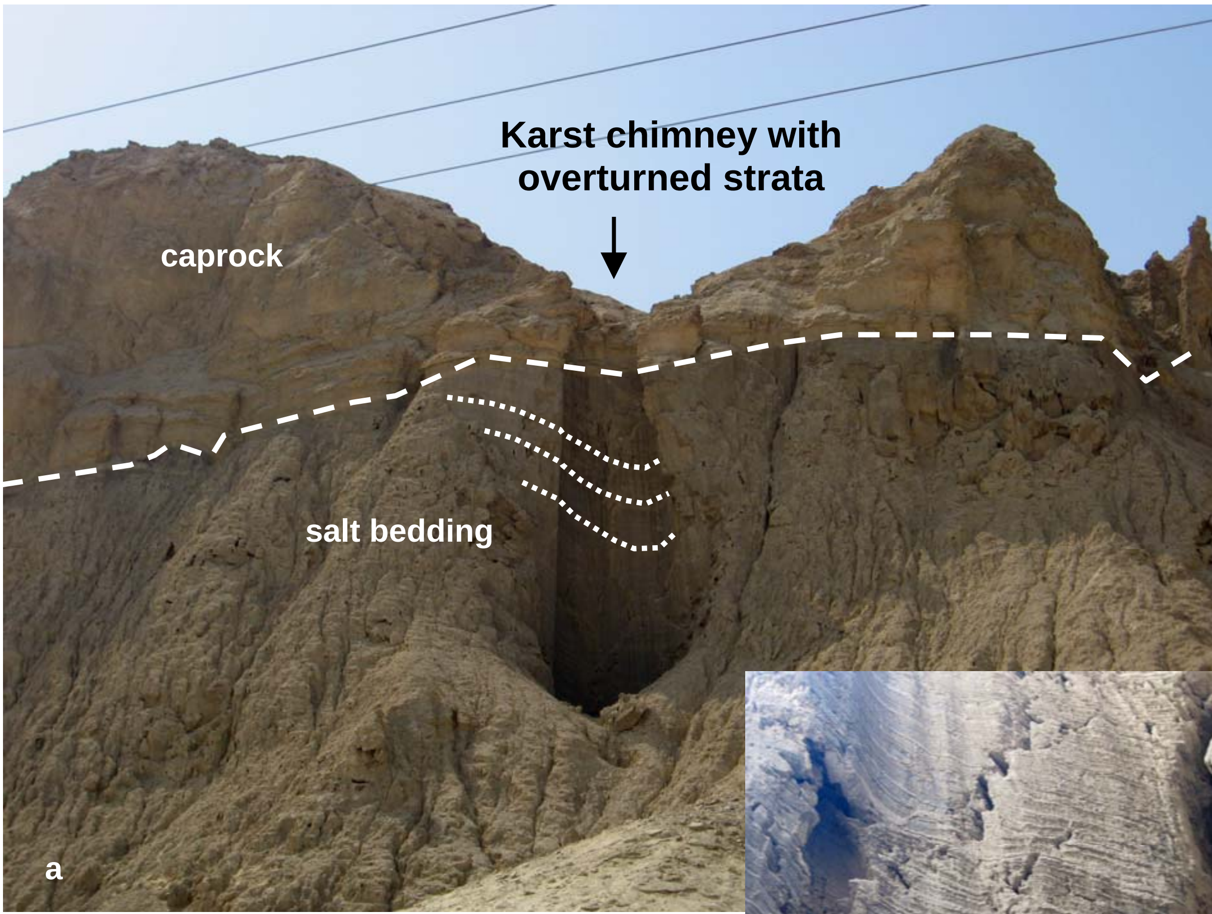


Fig. 14 a+b: On the eastern margin of the salt dome close to the overthrust zone an approx. 70 m high karst chimney has been exposed by collapse and erosion (a). The bedding is strongly overturned and shallow dipping. This is also clearly indicated by the sulphate horizons (b). The joints and fractures are very noticeable, some of which have been expanded further by water. It is difficult to determine whether they are linked to the movement of the salt itself in the overthrust zone or caused by tectonic events. Whatever their origin, these marginal areas of the salt dome should be avoided when selecting building sites.

A second structure lies to the north-east of Mt. Sdom on the Lisan peninsula in a central graben position. This is round rather than elongate. It probably rose up in a pull apart spreading zone. Unlike Mt. Sdom, this salt dome appears to have come to a standstill during the deposition of the Lisan Formation in the Late Pleistocene.

The cover rock above the salt and the at least weaker if not completely dormant movement of the salt make this diapir a better choice for potential underground mining.

This region as a whole has been included in the plans to build pipelines to link the Arabian Peninsula and Egypt to Europe via Jordan and Israel. Since there is a demand for storage space in Israel as well as in Jordan, the locations described are worthwhile to be further considered.

Conclusions

Diapiric salt structures were presented which are in different stages of development. There are also differences in the intensity of the salt movement, which has an impact on the development of mining projects.

Another aspect which was revealed was that construction measures should remain a safe distance away from the margins of the salt structures due to uncertainties in the evaluation of the usable salt mass as well as tightness considerations..

One would expect that these tend to be exceptions because of the strong tectonic activity which affects these regions, but if one considers for instance the Lower Saxony tectogen in North Germany or the salt domes in the Gulf of Mexico, the complexity of these structures is at least comparable if not even more exaggerated.

Finally, these examples from the Middle East are not only good for drawing analogies, but also highly relevant for the current planning work concerning supplies in each of these regions.

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