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ORIGINAL PAPER

Geological and geophysical study of salt diapirs for hazardous waste disposal

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Abstract Solving the problem of waste is one of the central tasks of environmental protection. It is becoming increasingly difficult to find suitable sites that are acceptable to the public. Salt and salt formations have relevant properties to be utilizing as a repository for each kind of waste. The favourable properties of salt make rock salt highly suitable as a host rock, in particular for non-radioactive and radioactive wastes. Tehran and suburb as an industrial state require a waste reservoir. The Great Kavir (the largest salt desert in Iran) with more than 50 diapirs has surrounded the eastern and southern part of Tehran Province. The Qom and Garmsar basins are the nearest salt diapirs to Tehran province, and there are suitable repository for waste disposal. Great Kavir diapirs have been investigated as a case study based on surface and subsurface studies for its suitability to host a repository for various types of waste. The procedure should be based on field work for surface investigation and also include geophysical studies for subsurface investigations. This research work is presented in regard to site selection in the Central Iran Salt Basins for deposition of only certain types of waste. Results of this study will indicate if the Central Iran Salt Basins are appropriate place to deposit industrial wastes in the deep bedded salt.

Keywords Central Iran salt diapirs · Hazardous wastes · Rock salt · Geophysics

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Introduction

Iran is a member of the Developing 8 or D8, as stated by the D8 facts and figures publication: 'The objectives of D-8 are to improve developing countries' positions in the world economy, including energy, environment, and provide better standards of living, also many other factors. Industrial development is often accompanied by environment hazards naturally, therefore locating a place or reservoir for disposing of industrial wastes is necessary. Salt domes could be the answer to many waste disposal problems. Storage of both liquids and gases in salt caverns was reportedly first conceived in Canada in the early 1940s, during World War II (Bays 1963). Examples include geologic repositories in salt in Germany for chemically hazardous waste, e.g., Herfa (since 1972) (Boraiko 1985), Heilbronn (since 1992), and Zielitz (since 1995) compiling a successful operating record of several decades Salt formation is extremely strong, impermeable and non-reactive. This impermeability is due to the tightness of the structure and the absence of open natural joints and fissures known from many other types of rocks. Moreover, the high plastic deformability of rock salt hinders the development and the maintenance of open artificial fissures where liquids and gases could leak out.

Another advantage to salt formation storage is that the formation itself is not subject to changes due to environmental changes outside of the formation structure. As the salt passed upward through the overlying sediments, long, finger-like projections developed. The depth of the intruded salt (sedimentary piercements) can be greater than 10,000 ft (Whiting 1981), and the top width of the salt domes ranges from about 0.5–2.5 miles (Chilingarian et al. 1989). Salt is easy to mine, virtually impermeable, and contains very little fluid. Salt reacts to differential stress by

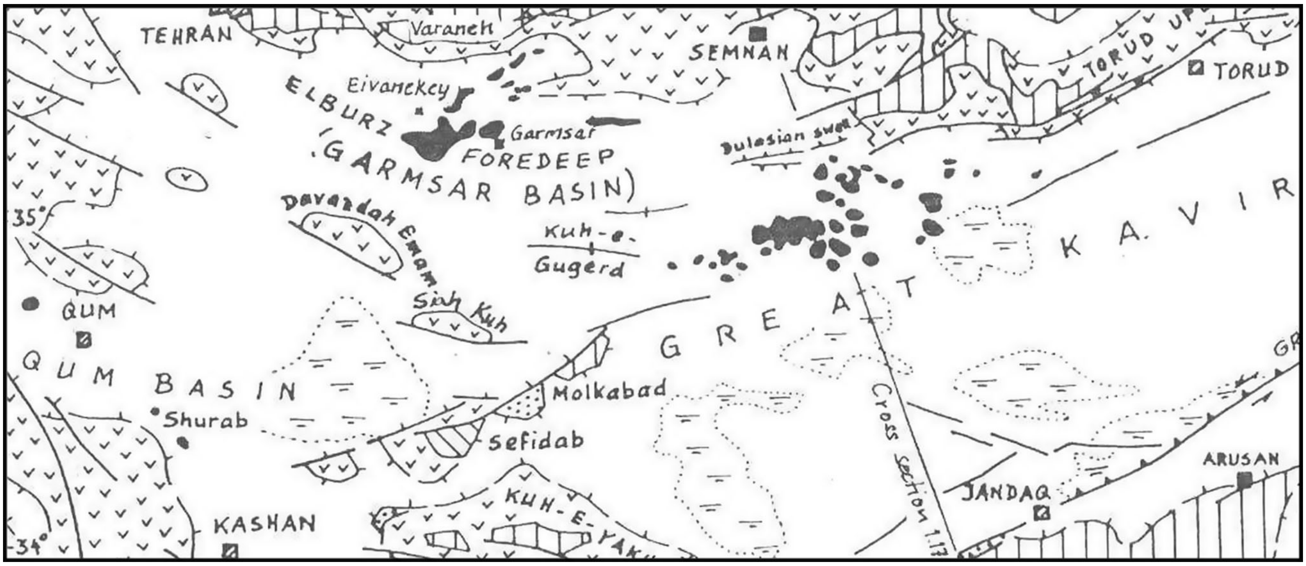

Fig. 1 Simplified geological setting of Cenozoic evaporites at surface in the Great Kavir basins (Jackson et al. 1990)

viscoplastic deformation, closing and healing voids and fractures. In that respect, it behaves similar to ice in glaciers. Massive deep salt deposits are common and widespread. Salt has been mined for hundreds of years, and the behaviour of the mined openings has been studied and documented extensively.

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A further advantage to salt formation storage is that the disposal of hazardous waste in salt formations offers excellent security. Security can be analysed in two aspects: one, surficial security, to secure the site from unauthorized intruders and exposure of hazardous toxic waste to surrounding residences or landowners; and two, subsurface security and the ability to contain a toxic and hazardous waste without exposure to environment.

This research was carried out in the department of Environment and Energy, Science and research branch Islamic Azad University, Iran and it spans between February 2015 and December 2016.

Minimum requirements and criteria for repository sites

The factors that determine whether or not a reservoir or salt cavern storage facility will make a suitable storage facility are both geological and geographical.

The first site selection is made on the basis of geological maps, an evaluation of archival material, particularly geophysics data, seismic data, and field trip studies.

Geographically, potential sites would be relatively close to the consuming regions or industry. They must also be close to transport infrastructure, including main and trunk pipelines and distribution systems.

Resulting from the inhomogeneity of salt structures the demanded safety of a permanent repository for wastes can be demonstrated only by a specific site analysis in which the entire individual system, "the geological situation, the repository, and the form and amount of the wastes" and their interrelationships are taken into consideration (Langer 1991).

Moreover, recommendations for geoscientific studies of the site are to be made on the basis of the available data. In the following investigation of the site, all parameters relevant to the project must be evaluated for the final assessment of the technical feasibility and long-term safety of the repository.

The following tasks of the site study are given:

- Provide information about the cover rock and the presence and quality of salt down to a depth of 2000 m.
- Determine the structural position and verify the seismic results,
- Investigate the depth, thickness, bedding, the structural features of the potential host rock for the construction of caverns, i.e. the salt body
- Perform detailed investigations of the salt in order to gain results for solution mining and rock mechanical assessments relevant for design and operation of the cavern field.
- Hydrogeological inventory (e.g. nature of the aquifer, its division into various levels, cover layers).

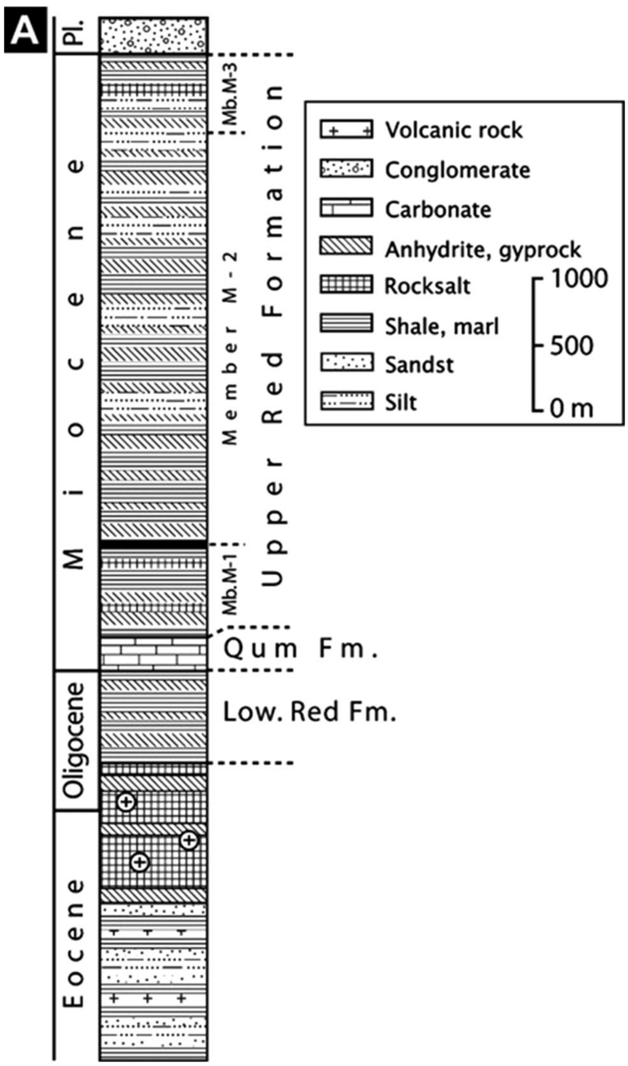

Fig. 2 Lithostratigraphy of Qom basin (after Jackson et al. 1990). The Eocene to Oligocene rock salt is the main source for the extrusions of Shurab salt

Geological setting

The Alborz Mountains represent a composite orogenic belt consisting of salt-bearing Neogen sediments that underwent shortening and uplift during the Cenozoic (Alavi 1996).

The deserts of Iran are suitable natural labratories for studying hundreds of subaerial salt extrusions that are usually submarine or subsurface elsewhere (Talbot 1998). In central Iran Tertiary, salt reaches the surface in many places. The most voluminous salt outcrops can be found in the Great Kavir basin and in its peripheral sub-basins (Qom , Garmsar and Damghan basins). The Tertiary, which lies unconformably on folded Mesozoic strata, starts with marine, Eocene sediments, associated with volcanic rocks (Jackson et al. 1990). Several authors (Gansser 1960b; Jackson et al. 1990; Talbot and Aftabi 2004) proposed that all the salt structures in central Iran involve the same two salt sequences: a relatively pure, upper Eocene—lower Oligocene salt (base of lower Oligocene Lower Red Formation) and a variegated, impure lower Miocene salt sequence (lower Miocene Upper Red Formation) (Fig. 1).

Sediments older than Miocene are not exposed at Great Kavir, Central Iran. Exploration drilling may have touched the top of the Eocene sediments. The lower part of the Eocene rocks consists of a variegated sequence made of sandstone, shale, marl and volcanics. The upper part consists of rock salt and anhydrite/gyprock which reflects regression (Fig. 2). This evaporate sequence continues into the Oligocene (Fig. 2). In the Kavir, hills consist of large diapiric bodies of salt and gyprock with inclusions of mafic volcanic rocks. Major parts of the rock salt are white and fine grained with a tight subhorizontal mylonitic foliation (Schleder and Urai 2006).

The upper part of the Oligocene sequence, the Lower Red Formation, is made of gyprock, sandy shale and some volcanics. A similar sequence, referred to as Upper Red Formation, was deposited in the Miocene. Between the Lower and Upper Red Formation, there is a sequence of limestone, marl, shale and sandstone which is called the Qom Formation (Fig. 2). The age of the latter is upper Oligocene to lower Miocene.

The present surface of the study area is covered by several metres of barren residual insoluble soils after dissolution of the salt by rain. Most of these soils are light green to pale brown gypsite with subordinate marl and calcareous marl.

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Materials and methods

A repository is an engineered structure in geology that requires interdisciplinary cooperation. Geoscientific and technical studies are necessary for each case to work out a concept in which site, deposition methods, properties of the host rock, and geological situation are so coordinated that natural and artificial barriers are used to protect man and environment.

A geological suitable place for sitting of waste disposal shall determine based on:

(A) An analysis of the structural and stratigraphic geology, the hydrogeology, and the seismicity of the region;
(B) A characterization of the salt dome to establish the geologic suitability of the location.

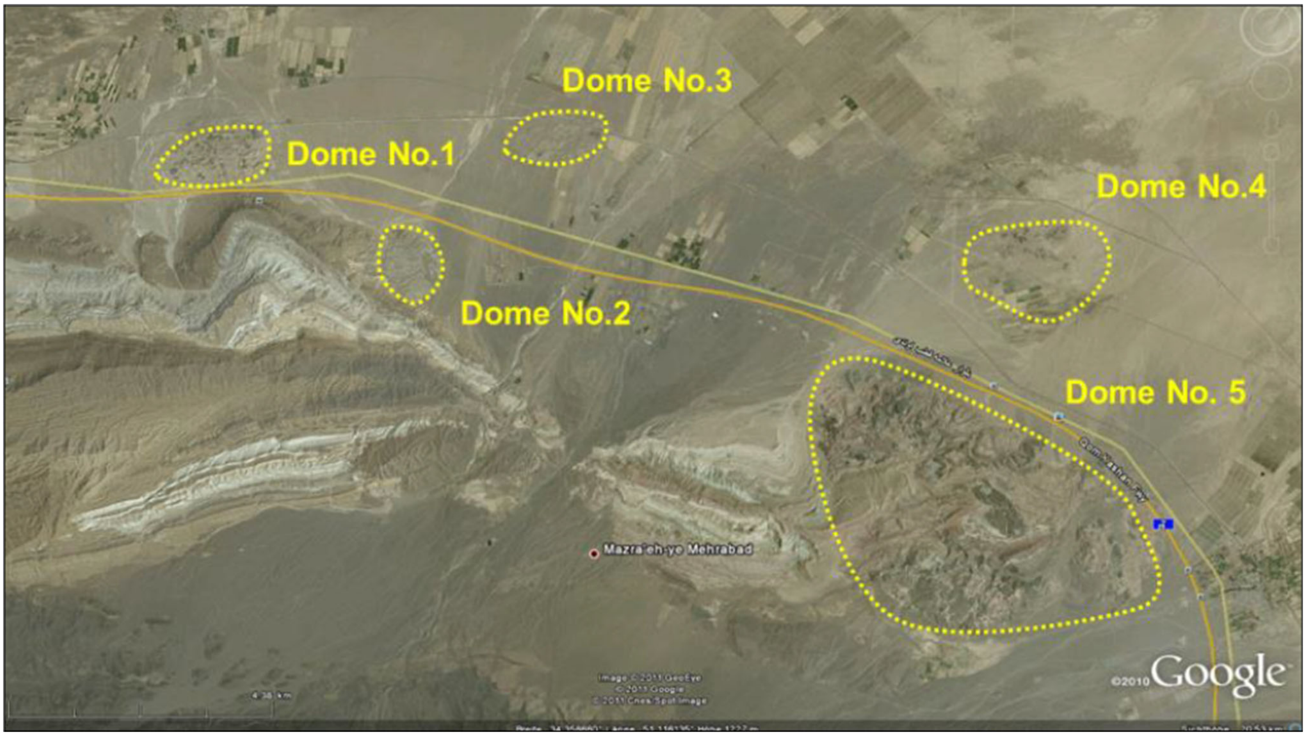

Fig. 3 Shurab salt diapirs. Focus of exploration is on dome no. 4. Dome no. 5 is prominent due to its size and elevation. Here, the existence of salt is proven

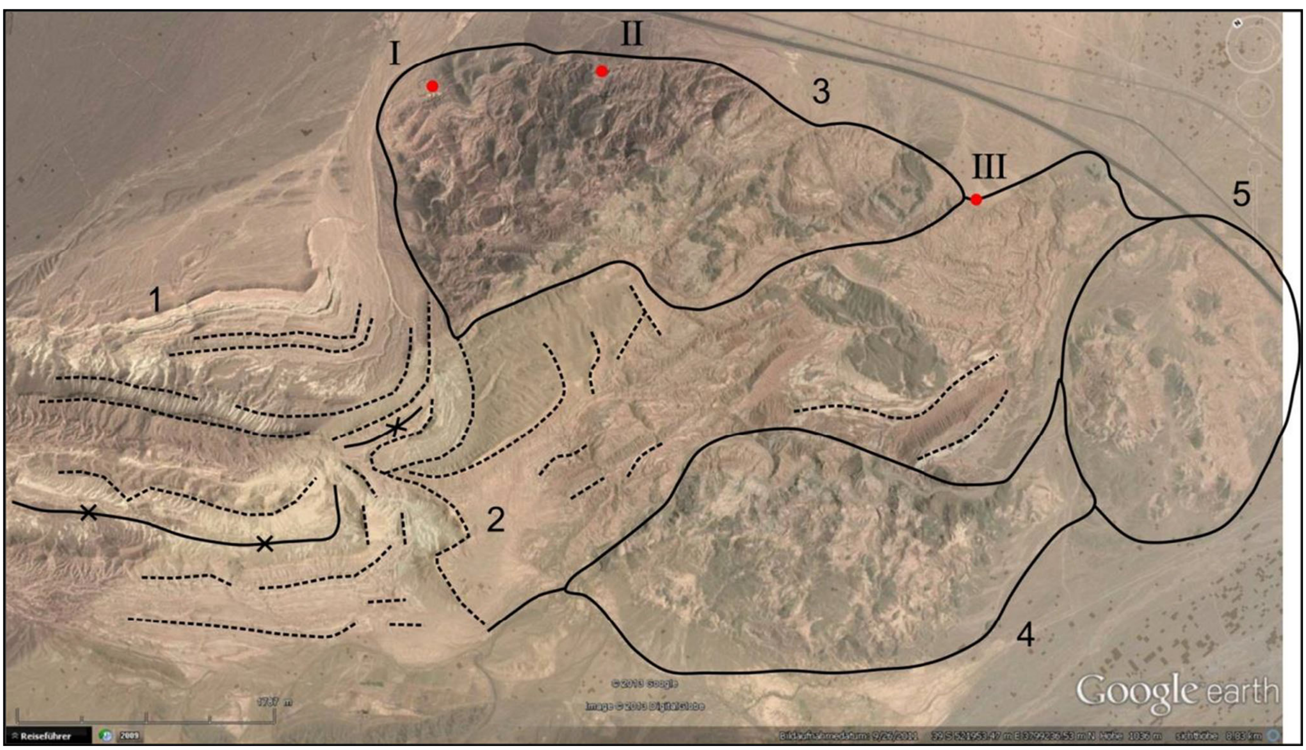

Fig. 4 Partitioning of dome no. 5. Compartment 3, 4 and 5 are strongly uplifted and most probably related to salt movement. This view is supported by gravity maps. Locations I–II (III) have proven salt in manmade outcrops

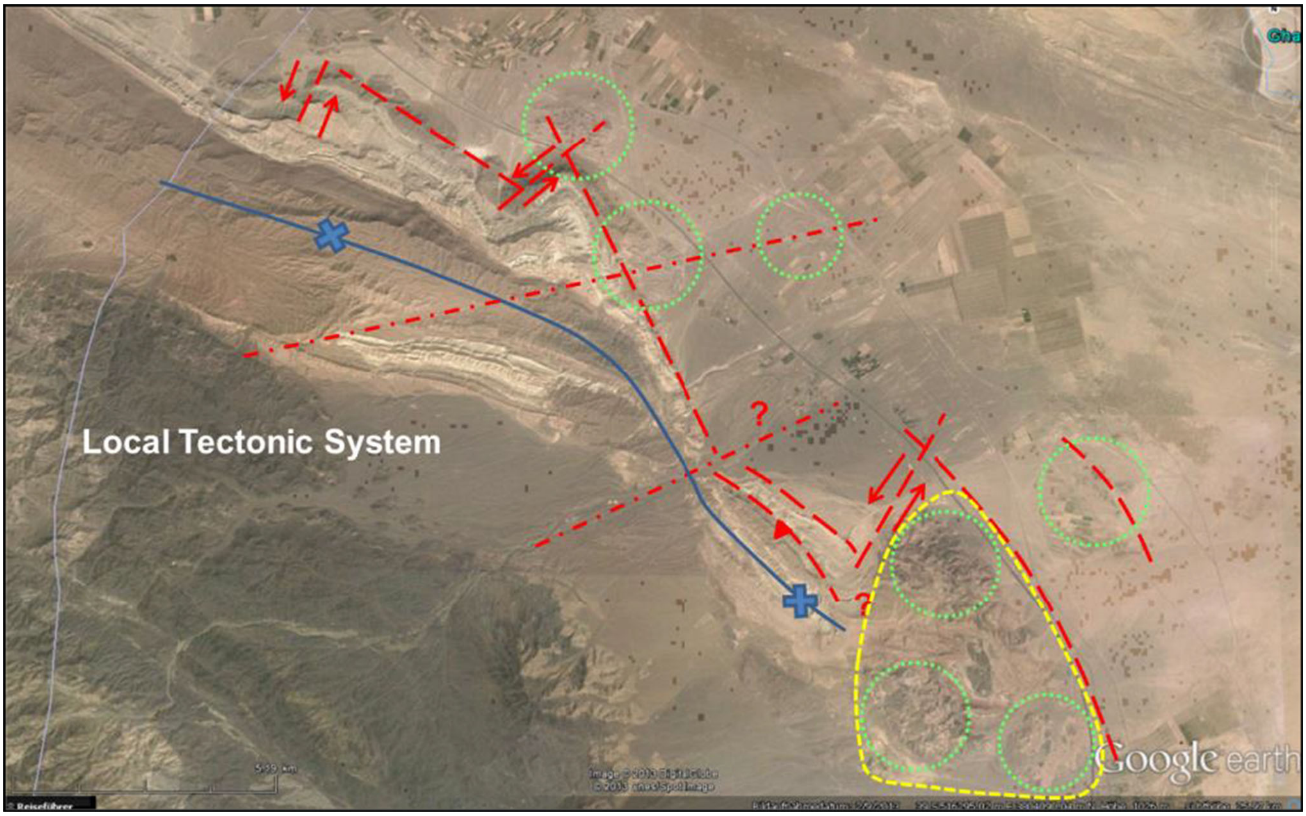

Fig. 5 Fault indications (*red*) and visible direction of movement (*arrows*). The tectonic system is responsible for the salt diapirism. A right-lateral displacement is indicated. Diapirs are marked *green*, Dome no. 5—most probably consisting of separate sections is marked *yellow*. In *blue* the synclinal axis is highlighted

(C) Using geophysical data and interpretation of them (such as seismic surveys, and gravity surveys) to define:

1. The geometry of the salt dome, including all edges and dimensions.
2. The structures are related to salt stock;

(D) Consideration of mine activities such as: sulphur mining, salt mining, brine reduction, oil and gas activity, and any other activity which may adversely affect or be affected by waste disposal in a salt cavern.

Results and discussion

The site analysis has two essential tasks:

Surface studies

Geology at surface

In this chapter the geological features at the surface are being discussed. This comprises the encountered lithology with focus on salt occurrences, their preliminary stratigraphic position as well as the indications on their genesis which is strongly dependent on tectonic faulting but also on structural deformation. It is planned to have a more detailed inspection of specific locations.

Structural elements

Since dome no. 5 has reference character in this area due to its proven salt occurrences and the immediate vicinity of the exploration focus (dome no. 4), this structure is considered first in order to get an understanding on what might have happened in the underground (Fig. 3).

This structure comprises locations (I–III) of outcropping salt in quarries (I & II) and at the slope of a road (III, not yet confirmed). Apparently located at a syncline (1), the dome appears to be composed of different structural elements (2–5). Three of those compartments (3, 4, 5) show similarities. Compartment 3 has the best indications for a diapiric genesis caused by salt movement (Fig. 4).

Tectonic features

The tectonic system which is most probably responsible for the development of this group of salt diapirs is a dextral

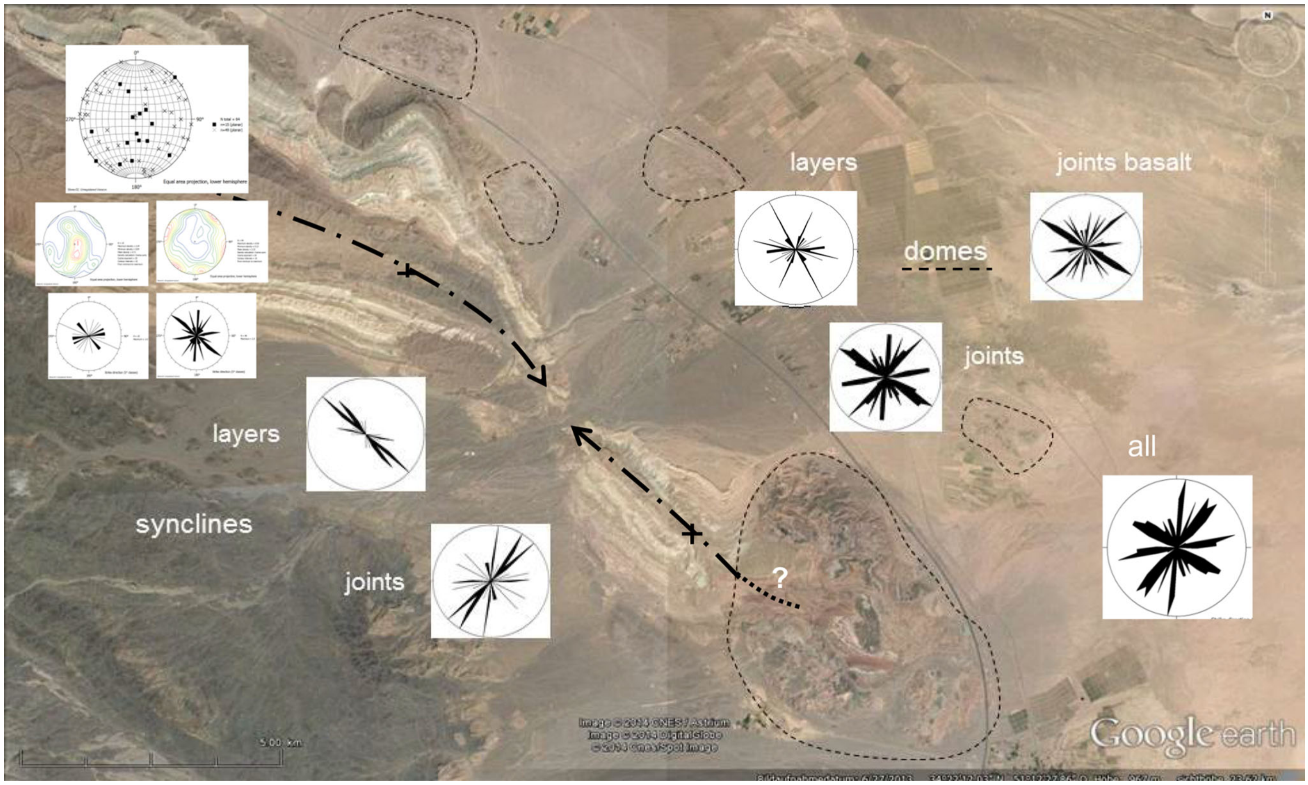

Fig. 6 Distribution of structural elements related to synclines to the *left-hand side*, related to domal structures to the *right hand side*, synclinal axes are marked with *dashed-dotted lines*

strike—slip fault system forming pull apart extensional structures, where the salt uprise could take place. Additionally a vertical displacement component at the fault was effective.

With respect to the Shurab diapirs, it is common for a number of structures that they follow two synclines (Fig. 5) comprising of Lower Red Formation (LRF), Qom Formation (QF) and in parts Upper Red Formation (URF) sediments. The thickness of this sequence appears to be less than in the Qum basin at Kuh-e-Namak but may be more beyond the main fault east of dome no. 5 for instance.

The diapiric structures may be linked, on the one hand, to the sequence encountered in the synclines, on the other hand, to the fault system (described above) dividing the mountainous area in the west and the great plain in the east.

Besides, the dextral horizontal displacement along the main fault is assumed to be right-lateral. A vertical component must also be postulated. Whether it represents overthrusting or normal faulting is, with a restricted view to this area, not obvious. However, the tendency of all different interpretations gives rise to assume overthrusting.

A combination of both, structural relationship of the Shurab diapirs with the adjacent syncline(s) as well as with salt strata in the basin has to be considered (Fig. 6).

The fault system is mainly responsible for the development of the salt diapirs. The pull apart structures were already mentioned with respect to the rise in a local extension zone (Fig. 7). Additionally, a movement along faults or piercing at crossing faults may play a role. Accordingly, the question of the driving forces comes up: Is it squeezing under compressional or rise under extensional conditions?

If we compare with Kuh-e-Namak, the extensional phase caused the first movements, whereas the compressional phase followed. However, the latter force seems to have a comparably bigger influence on Kuh-e-Namak than on the Shurab structures. There is no glacier like movement with huge overhangs recognizable at the current stage of exploration as well as no natural exposure of the salt (Folle et al. 2014).

Since salt seems to be not naturally exposed at any of the diapirs this is taken as indication for at least recently slow movement although the basic depositional parameters as depth and thickness of cover rock are comparable with the situation of clearly exposed salt at fast-moving Kuh-e-Namak (Figs. 5, 7, 8).

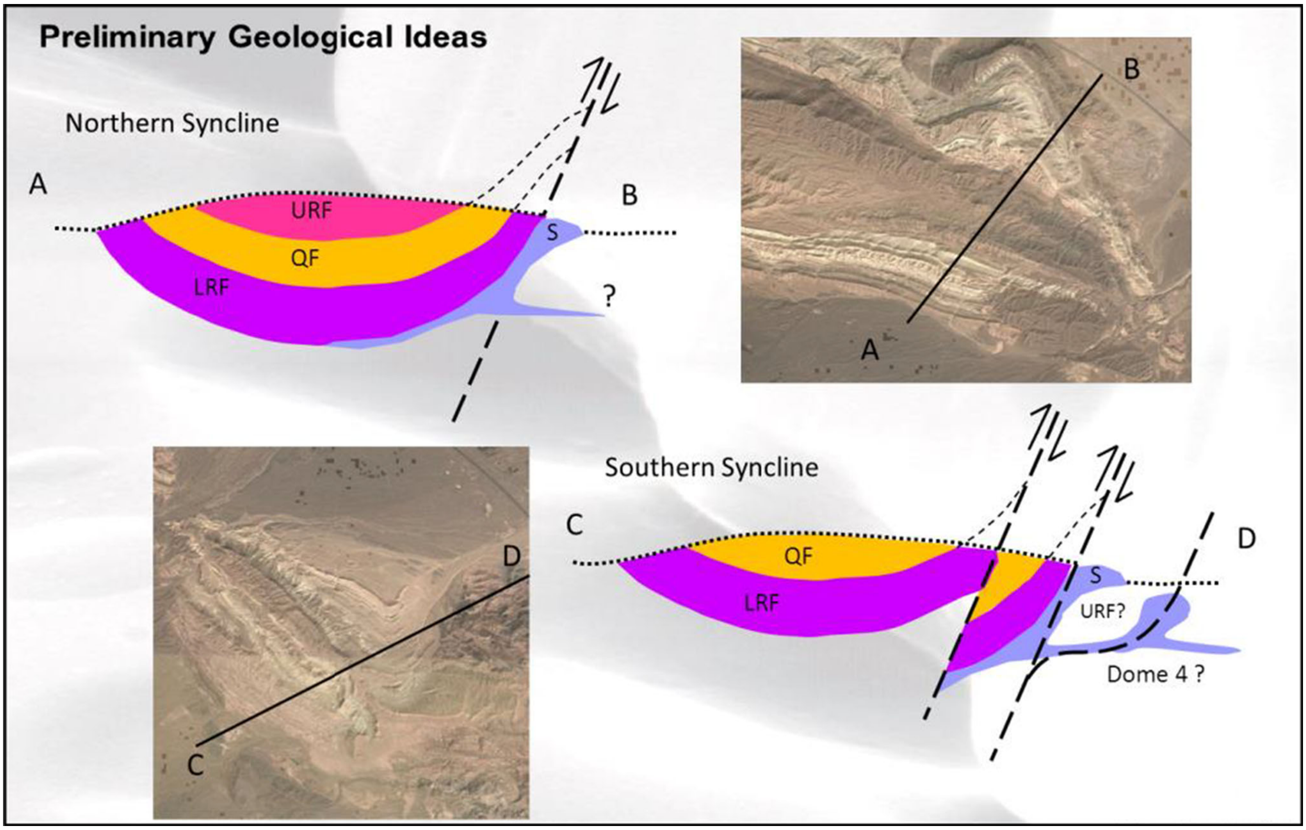

Fig. 7 Northern and southern syncline show diapiric structures at their flanks following the stratigraphic continuity. Additionally, dextral strike–slip faults dominate the structural development and may favour the gliding and uprise of salt masses (S)

Outcropping salt

In order to assess the quality and nature of the salt expected to occur at depth, valuable sources of insight are two quarries at the north-western, respectively, northern boundary of dome no. 5, exactly in compartment 3 (Fig. 3).

The appearance of the salt in both quarries is different. In both cases, it is massive with hints on internal stratifications. The layers are made visible by different concentrations of dispersed iron minerals (northern quarry) or dispersed clay minerals (north-eastern quarry) (Figs. 9, 10).

Even if larger solids (cm-dimension) occur within the salt, they do not worsen the quality for solution mining. However, one has to bear in mind that volcanic blocks of some tens of metres size may occasionally be encountered at depth. Such features can be observed at the Kuh-e-Namak salt glacier where such volcanic blocks are transported by the moving salt (Folle et al. 2013).

One additional salt occurrence (location III) appears to exist in the eastern most part of this structural unit (section "Results and discussion") and has to be confirmed (or rejected) during further geological evaluation.

In general it has to be stated that the quality of the outcropping salt meets the requirements for solution mining.

Subsurface studies

Geophysical interpretations

Magnetotellurics anomalies in the field area Processed MT data were interpreted in order to match a reasonable geological model. The results of this work is shown and discussed in the following (order of profile display from north to south).

In all resistivity sections, there is a distinct conductive (i.e. low resistive) layer in the eastern part (blue colour) with a thickness of some 1.5–2.0 km. Resistivity values are almost below 1 Ωm, which is typically related to saturation with salt water (See Figs. 11, 12, 13, 14, 15). There appears some internal structure (i.e. layering) within this conductive part that might be caused by changes in porosity. The very conductive zone can be considered as caused by salt water saturation either in the downstream of a salt structure or an indication of a rim syncline.

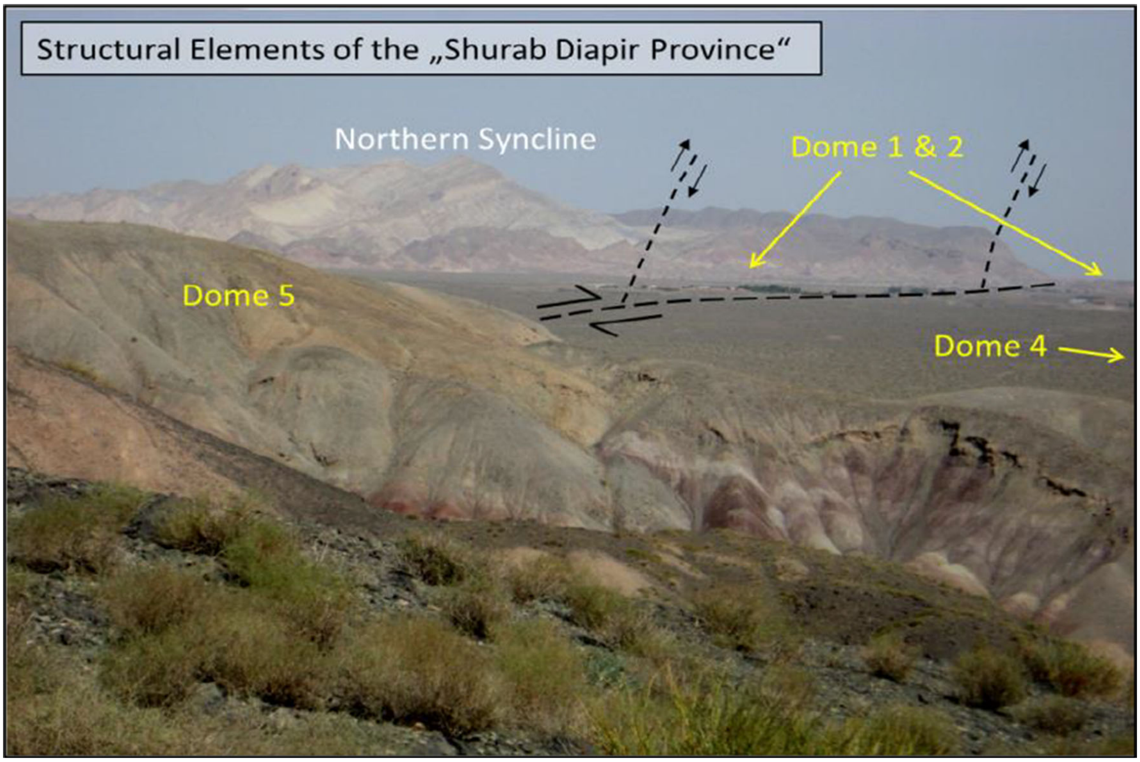

Fig. 8 Dextral strike slip fault with vertical component most probably overthrust and linked to the southern Ab Shirin fault followed by diapirs 1, 2 and 5. The northern syncline with LRF at its visible base is immediately adjacent to domes no. 1 and 2, which are part of it and/or linked to the fault system

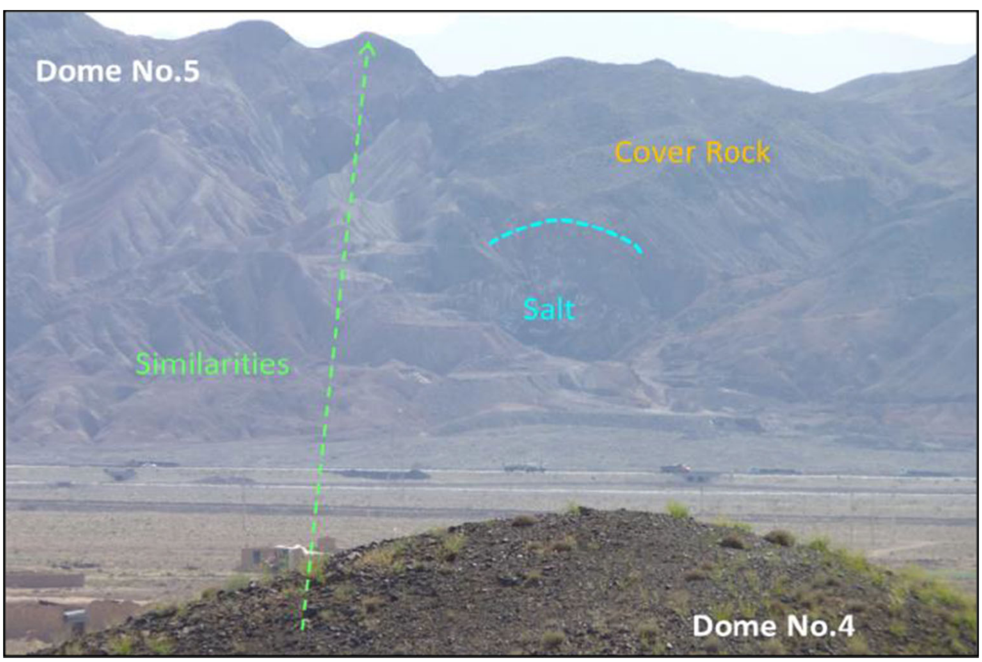

Fig. 9 View (*green arrow*) from the blocky remnants (*hillocks*) of the eroded cover rock of dome no. 4 directed to dome no. 5 with similar features at its *top*. Whereas the maximum elevation of the dome is approx. 1050 m, the plain in front is approx. 850 m above sea level. The visible top of salt (*blue*) is estimated to be at >900 m

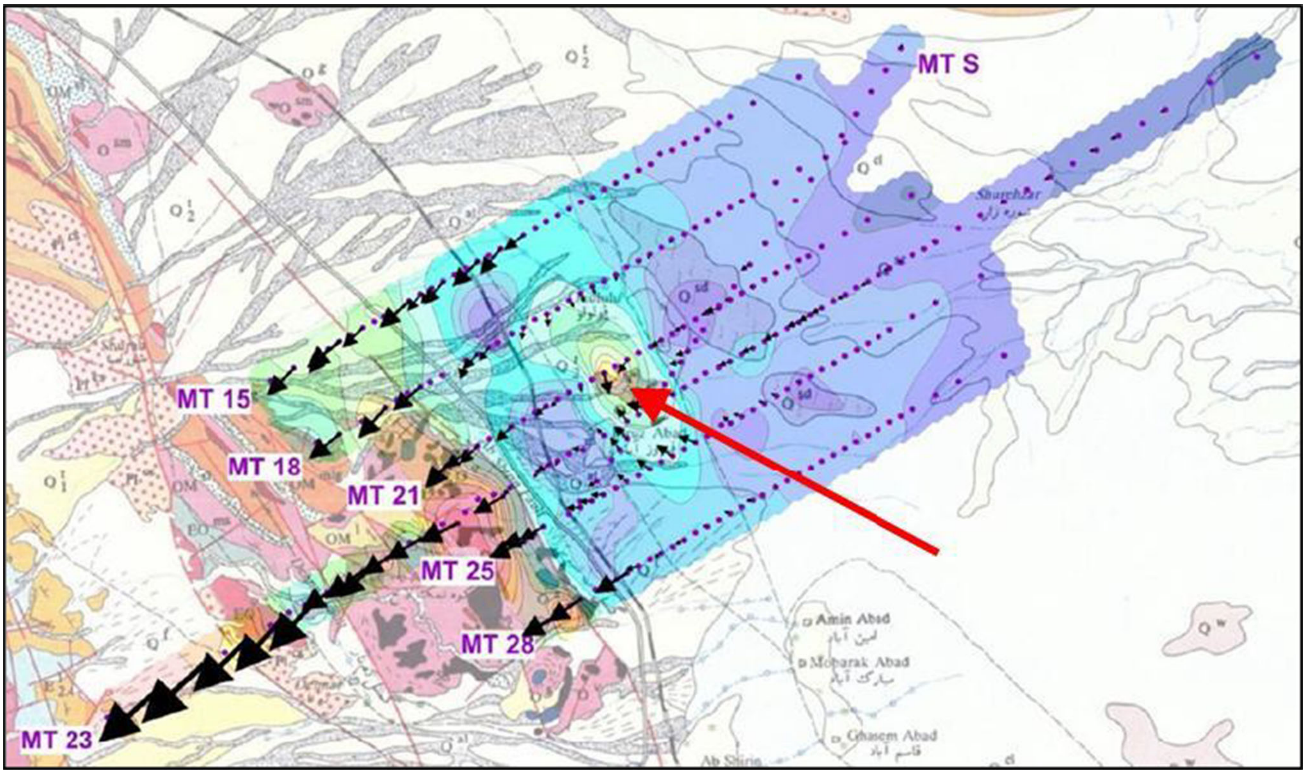

Fig. 10 Map of apparent resistivities (one frequency). The anomaly in the hillock area (*arrow*) is clearly visible prior to inversion. All profiles apart from MT 15 & MT 28 are cutting this feature. Profile MT 18 is additionally cutting the northern boundary of dome no. 5 with its high resistive sediments (salt) as well as the conductive sediments bordering the synclinal structure in the southwest. In particular profile no. 23 shows apparently ambiguous results. Besides two resistive highs at dome no. 4 as well as dome no. 5, an intercalated low was determined in the western mountainous area at depth, which would contradict the presence of salt here. Beyond until the south-western endpoint, high resistivity may be caused by massive volcanic rocks

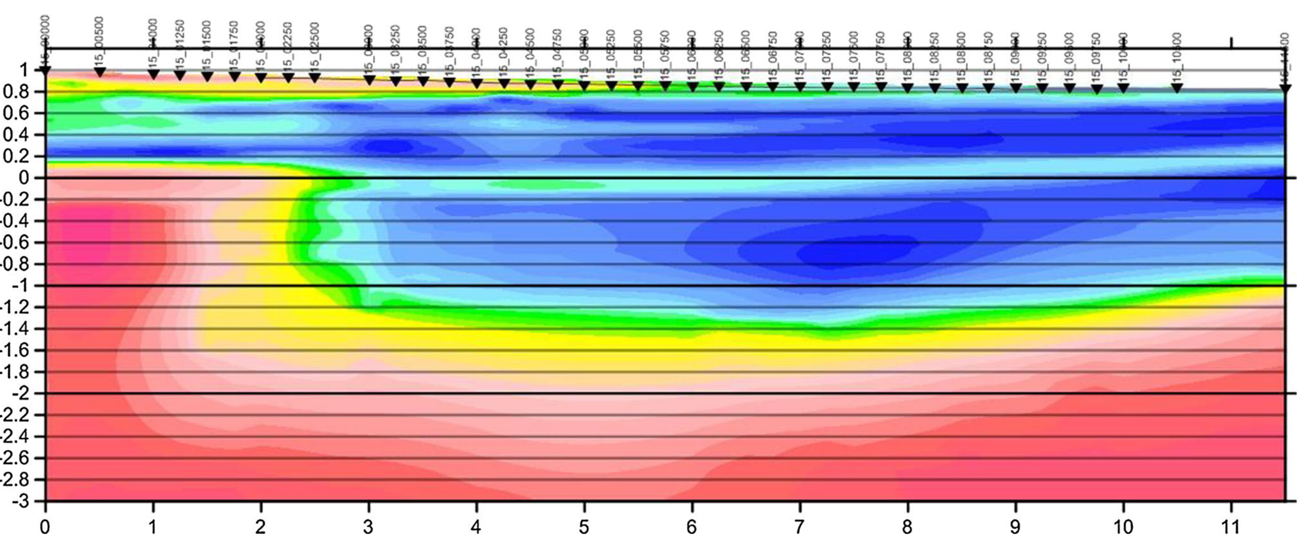

Fig. 11 2D inversion of MT data on profile 15. No indication of dome no. 4

It can be expected that the lower boundary of this conductive layer is not representing a true geologic boundary (i.e. a change in lithology), as this contrast is mainly caused by saturation with saline water and therefore primary a saturation boundary. The dip of the boundary is partly in contradiction to the indicated

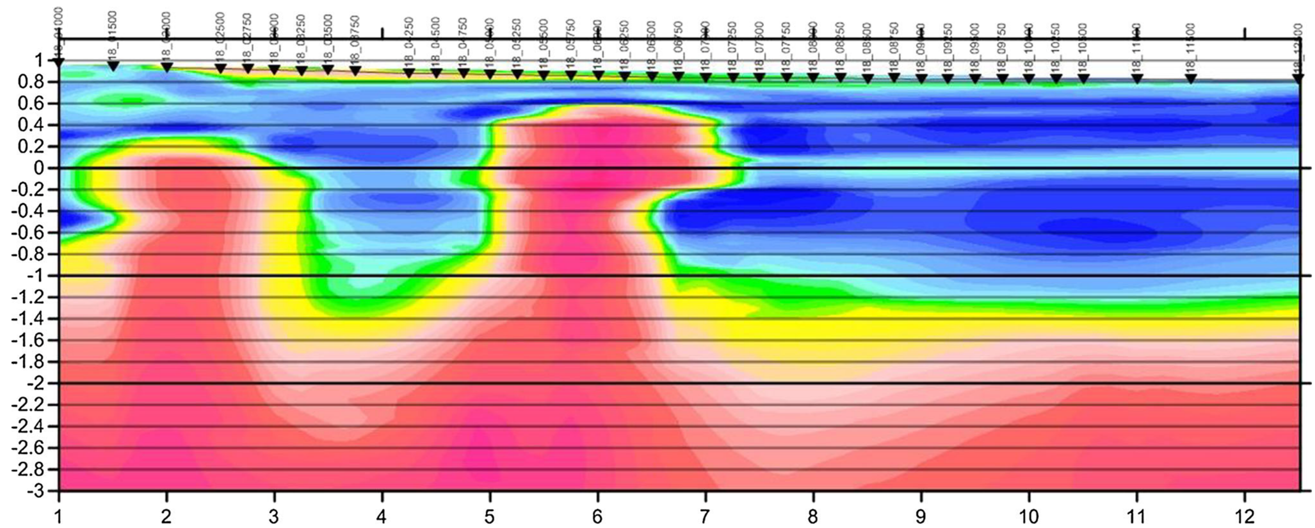

Fig. 12 2D inversion of MT data on profile 18. Dome no. 4 in the centre of the profile is indicating a root zone as well as an overhang situation directed to north-east. The resistive structure in the left-hand side may be related to dome no. 5

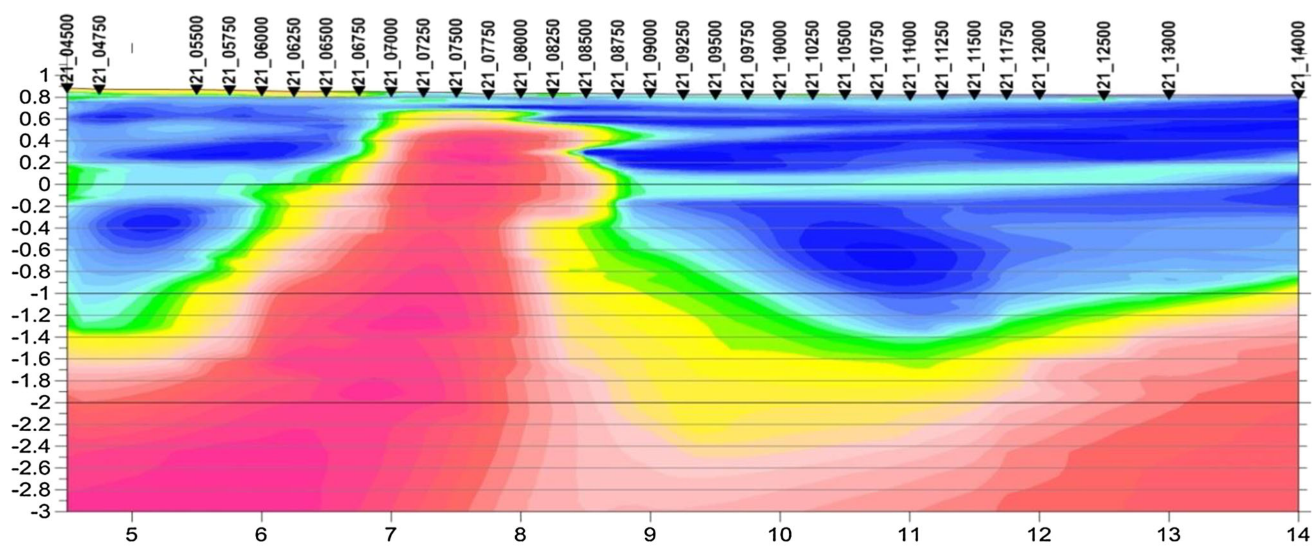

Fig. 13 2D inversion of MT data on profile 21. The appearance of dome no. 4 remains similar

stratification visible on the existing seismic section (Fig. 16).

Within the low resistivity zone, there is a distinct dome-shaped anomaly of increased resistivity (red) in profiles 18–25. On the regional and seismic profiles, this anomaly (resistive body) is located in the hillock area and therefore together with the gravity low, it can be related to rock salt (See Figs. 11, 12, 13, 14, 15).

Location and shape of the resistive anomaly on the "seismic profile" is strikingly corresponding to the structure visible in existing seismic sections (Fig. 16). It has to be stressed that the lower boundary of the resistive body has some uncertainty due to ambiguity of inversion. The width of the resistive (salt) body on MT lines is <2 km.

Taking into account the difficulties from conductive overburden (skin effect), the resulting images are quite impressive, especially regarding the expected salt structure in the hillock area. Considering the range of ambiguity that resistivity models can have, one could ask whether the inversion was manually constrained to get an indication for salt body by a priori knowledge from other sources (gravity, 2D seismic). Also, one could suspect that some features are just artefacts of inversion process.

However, the resistive zone in the hillock area is evident even in apparent resistivity data. Thus, the derived inversion images can be treated as reliable in respect to the observed salt diapir anomaly. On the sections there is an indication for the salt diapir no. 4 to have a connection to

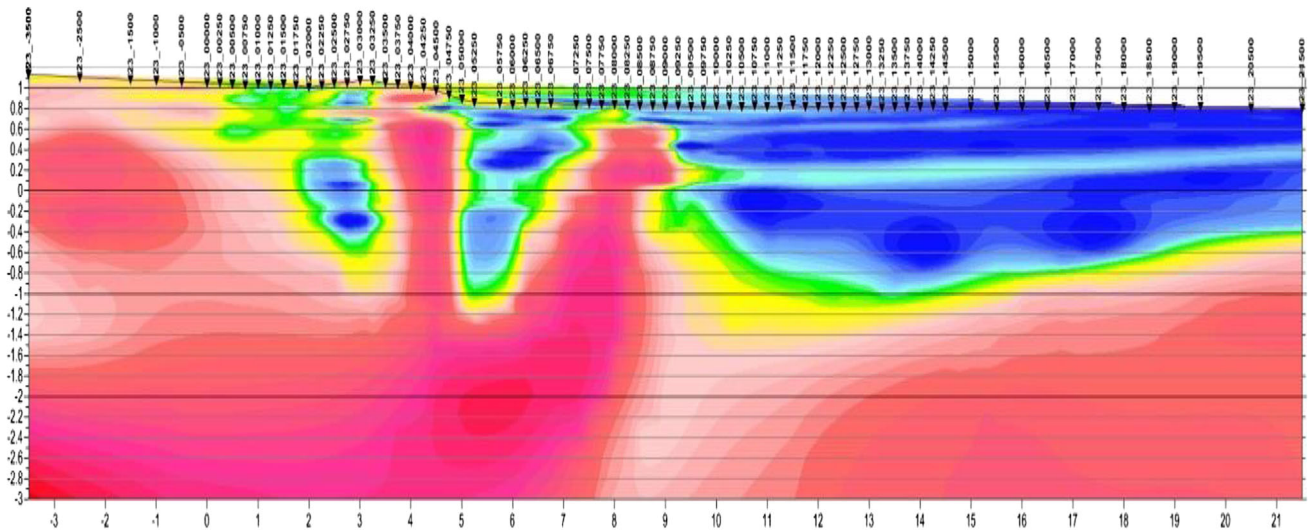

Fig. 14 2D inversion of MT data on regional profile 23 (horizontal scale different to other profiles!)

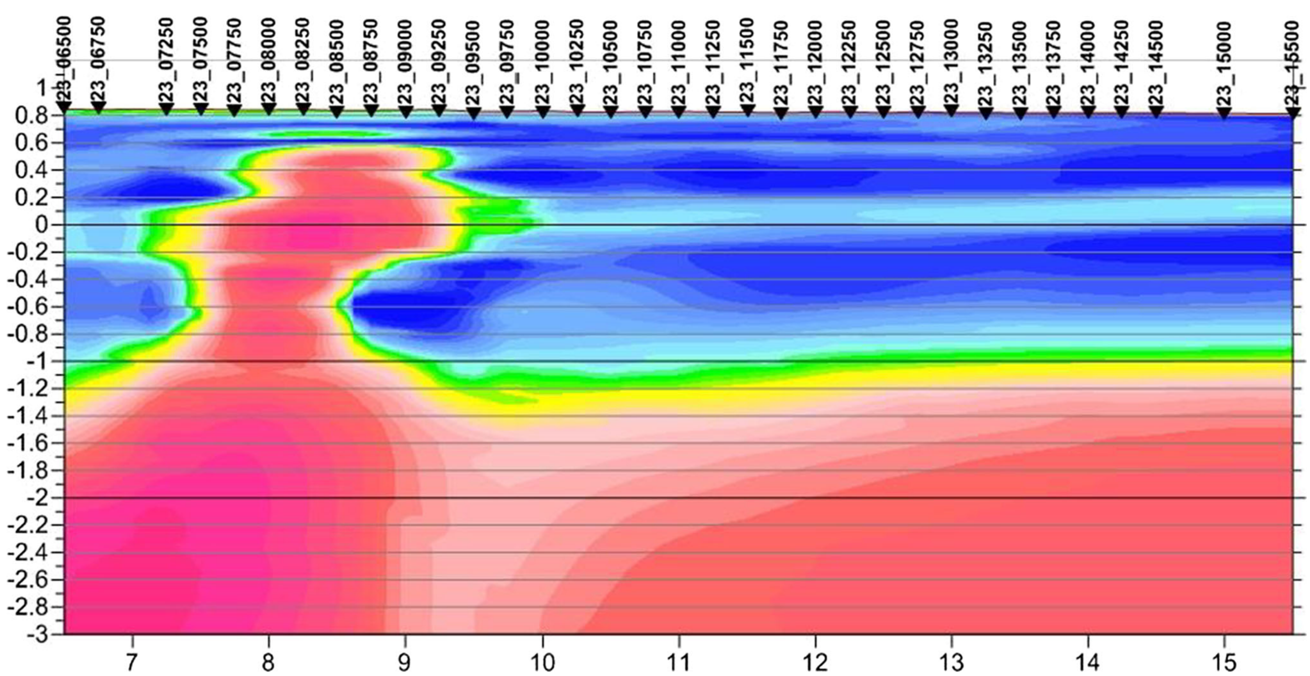

Fig. 15 2D inversion of MT data: Profile 25

its root in the western part; directed to the Ab Shirin fault and the mountainous area.

In contrast to the satisfactory imaging of the isolated salt diapir, the situation especially in the western part of the mountain area is much more difficult to interpret. The mountainous area appears to be divided in an eastern structure of high resistivity and a western one of high conductivity. Beneath a shallow resistive layer, there is a conductive zone that cannot be interpreted uniquely at the moment. One explanation is the partitioning of the mountainous area as indicated by airborne photos (Palshin et al. 2013a, 2013b).

Gravimetry anomalies in the field area The general distribution of Bouguer gravity is dominated by a smooth NE–SW-trending gravity gradient in the north-eastern part of the survey area. In the south-western corner, there is a distinct gravity high. Between the gravity highs in opposite corners, there is a general zone of low gravity. In the south of the investigation area, there is a strong gradient between the gravity high in the west and the gravity low zone in the southeast. This gradient is in coincidence with the Ab Shirin fault almost striking north–south, south of Ab Shirin village. At the Ab Shirin fault, one can expect a great

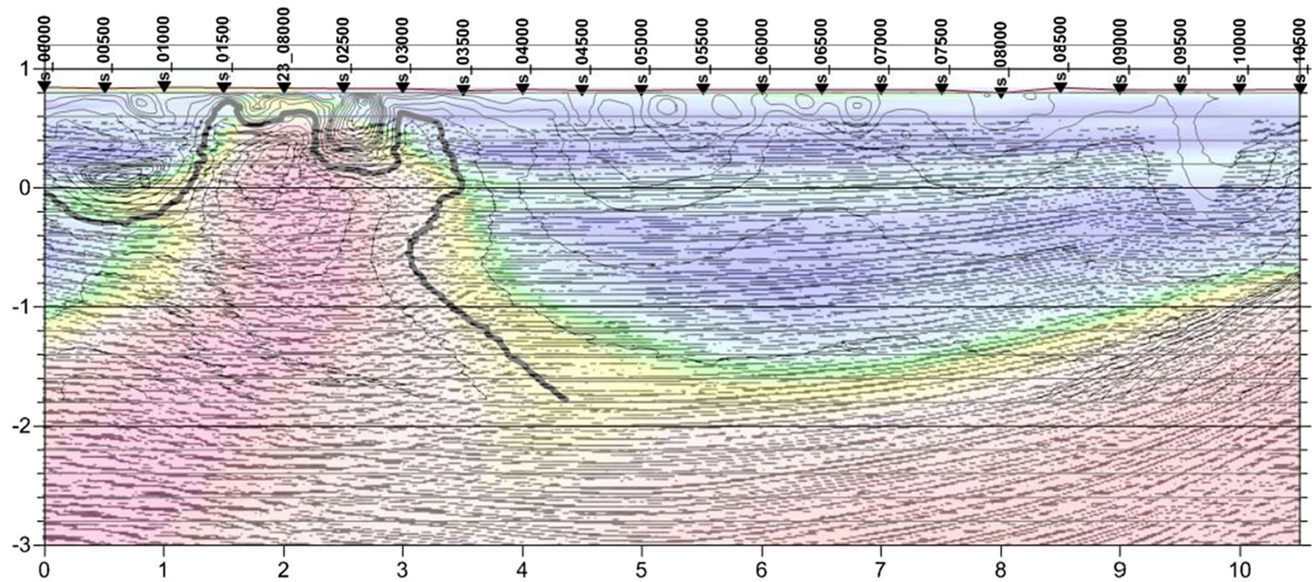

Fig. 16 Overlay of MT resistivity section with seismic depth section of Line Sarajeh-76427 (elevations and distances in km)

displacement between elevated rocks on the western side and the sediment basin on the eastern side of the fault. Therefore, the general (e.g. regional) distribution of gravity can be explained as the effect of fundamental changes in lithology along both sides of the main fault (Fig. 17).

The general arrangement of the gravity anomalies discussed above can be seen even better after removing regional trends from the data, for example by means of a high-pass filter (Fig. 18). In this type of display, local anomalies are enhanced greatly. Strong anomalies at the borders should be considered partly as edge effects (Palshin et al. 2013a, 2013b).

A combined assessment of gravity anomalies and geologic information is also an instructive means to assign gravity features to known geologic elements. Especially in the mountain area, there is great correspondence between the extend of Oligocene material (Lower Red Formation) and the distinct gravity low. Even inside this negative anomaly, there is a small gravity high that could be assigned to occurrences of dense volcanic material (Fig. 19).

Seismics Two old 2D seismic lines are cutting dome no. 4. It is indicated by the interruption of seismic reflections. Since reflectors are dragged upwards at the eastern flank, it must be taken into account that those layers are further dragged to a steeper position which cannot reflect the signals properly and cause random patterns, which could be misinterpreted as being part of the salt dome (Fig. 20). This fits quite well in the picture drawn by the non-seismic investigations indicating an eastward tendency in movement of the uprising salt mass, developing an overhang at least at the eastern edge.

The old 2D seismic investigation delineates a salt structure which is most probably assessed too optimistically. Responsible for that may be steeply dragged strata mainly at the (north) eastern structural boundary. This assumption is supported by the newly performed non-seismic techniques.

Additionally, an overhang situation is expected to be developed at this eastern edge. The assumption of a driving force directed (north) east responsible for these feature is supported by the appearance of the hillocks which are positioned east of the structural centre indicated by gravimetry and MT (Fig. 21). The western edge is rather precisely marked by both MT and old seismics. This boundary is supported by the results from gravimetry which is additionally influenced most probably by deeper and adjacent salt masses. The area where all three methods indicate salt appears to be sufficient in size for a cavern field.

The more exact a structural boundary can be delineated the more precisely the safety zone between outer caverns and salt boundary can be defined. As a consequence, the storage volume would be optimized.

The pre-drilling exploration of the salt dome must be completed by the 3D seismic survey in order to more accurately delineate the shape and dimensions of the salt body. It must also be stated that the existence of a massive salt body is not in question, since the distinct MT and gravity anomalies cannot be explained by a model of several thin salt layers or salt wedges invading the non-salt sedimentary structure. Additionally, one would expect in such a case no interruption of reflectors which in contrast were determined in the old 2D seismic profiles.

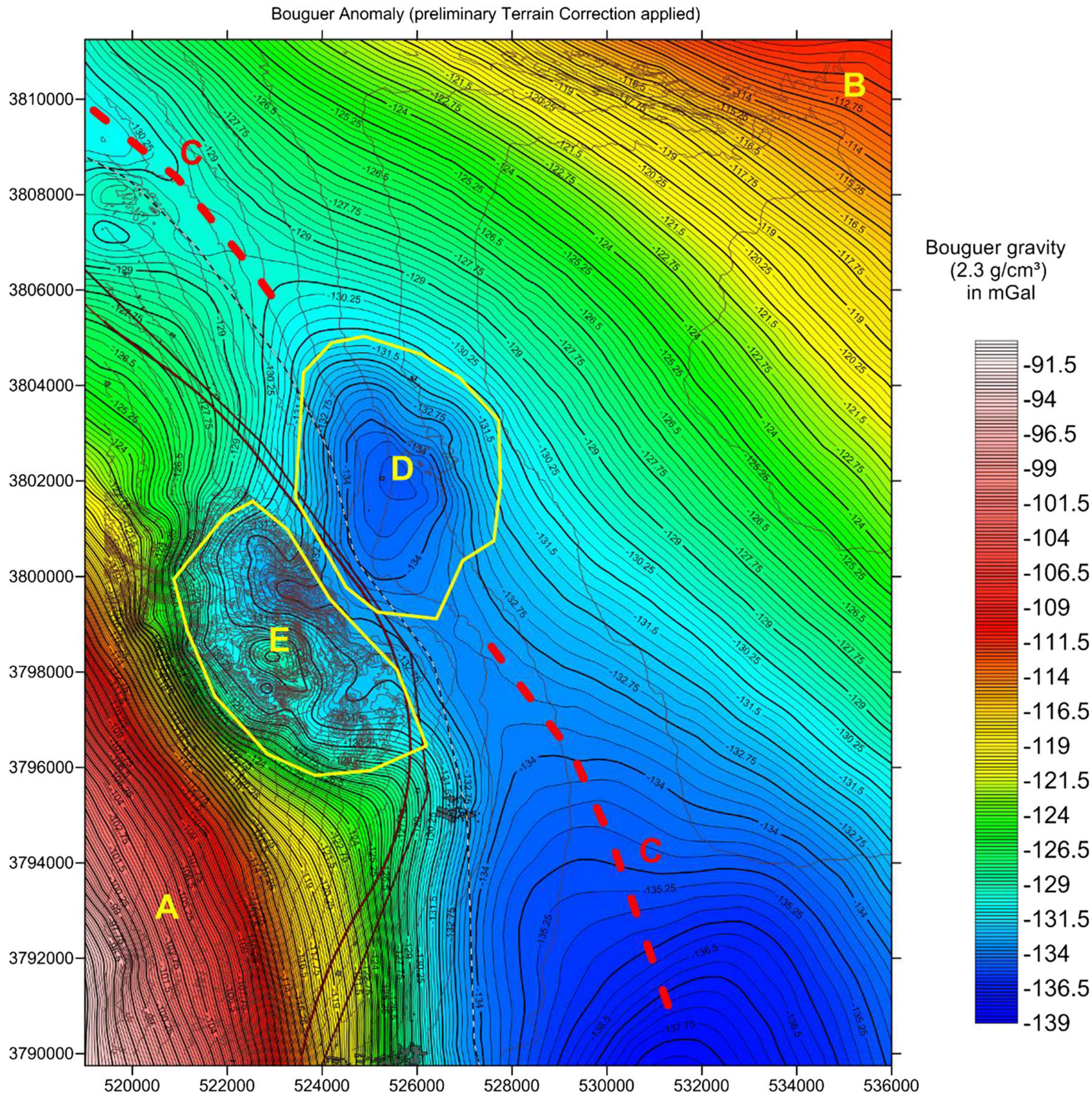

Fig. 17 Bouguer map of the investigated area. *Letters* indicate main features of the gravity distribution

The quality of the salt is expected in dome no. 4 to be similar to the one encountered in the salt quarries nearby, which is considered to be sufficient for reasonable solution mining. However, during drilling or solution mining, it cannot be excluded that e.g. volcanic blocks are being encountered. Normally there is enough flexibility by shifting the originally planned position of a cavern after the well has reached final depth. However, abandonment of a single well after facing an unsuitable situation cannot be excluded. Such a risk is considered to be low.

The risk in this project is more related to the outer boundary of the salt structure which may be diminished during further exploration. This would cause reduction of the originally planned size of a cavern field accordingly.

Combing the outline of the salt dome by seismics with those deducted from gravimetry and magnetotellurics (MT) gives rise to reasonable planning of new 3D seismics as discussed in the following (Fig. 22).

The new 3D seismic investigation, which main task is to precisely delineate the salt body in order to design the cavern field properly (Figs. 23, 24), delivered 2 time slices at 800 ms (twt) and 1300 ms (Fig. 25), based on migrated data each and representing a potential cavern depth interval. Whereas the delineation of the outer salt dome boundary is still in progress, the midpoint of the structure can already be fixed.

As assumed from gravimetry as well as magnetotellurics, the salt structure (dome no. 4) appears to have risen from the southwest coming from the direction of dome no.

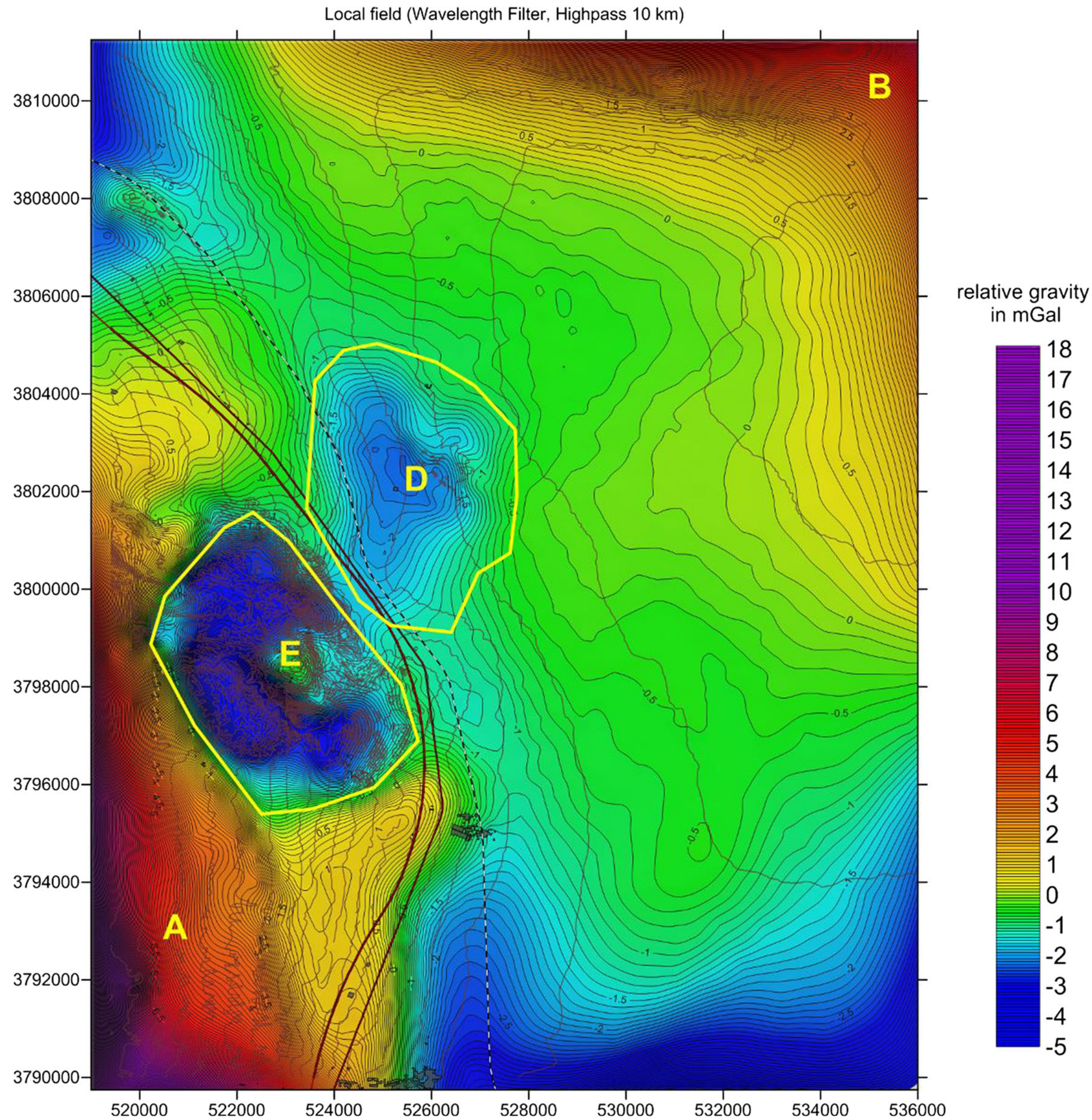

Fig. 18 Local field (high-pass filter 10 km) of Bouguer gravity. Local anomalies are enhanced in this type of display. Strong anomalies at the borders should be considered as edge effects

5. This trend is also indicated by the 2 time slices from the new 3D seismics (Fig. 25).

The apparent discrepancy concerning the identification of the diapir between gravimetry and seismics remains. The centre of the gravimetric negative anomaly and that of the seismic structure at the chosen levels are approximately 800 m apart (Fig. 26).

Three formations in this basin have been studied including Lower Red Formation, Qom Formation and Upper Red Formation. On 2D data altogether 14 interpretable reflectors have been selected and interpreted. All of these horizons belong to the Upper Red, Qom and Lower Red Formations. Identification at deepest levels (such as from Top evaporate to Décollement) has been selected uniquely by 2D seismic data. It should be reminded that no specific tracking strategy has been used in 2D interpretation data. It is worth noting that in this study six 2D seismic lines with total length of about 111 km have been interpreted.

All the interpretable horizons within Upper Red Formation have been transported from 2D lines to 3D seismic data volume. These are phantom horizons in the Upper Red Formation surrounding diapir No. 4 (Figs. 23, 24). High amplitude and good quality of reflectors along with evenly vertical distribution are the main criteria for selection of phantom reflectors. The vertical distance

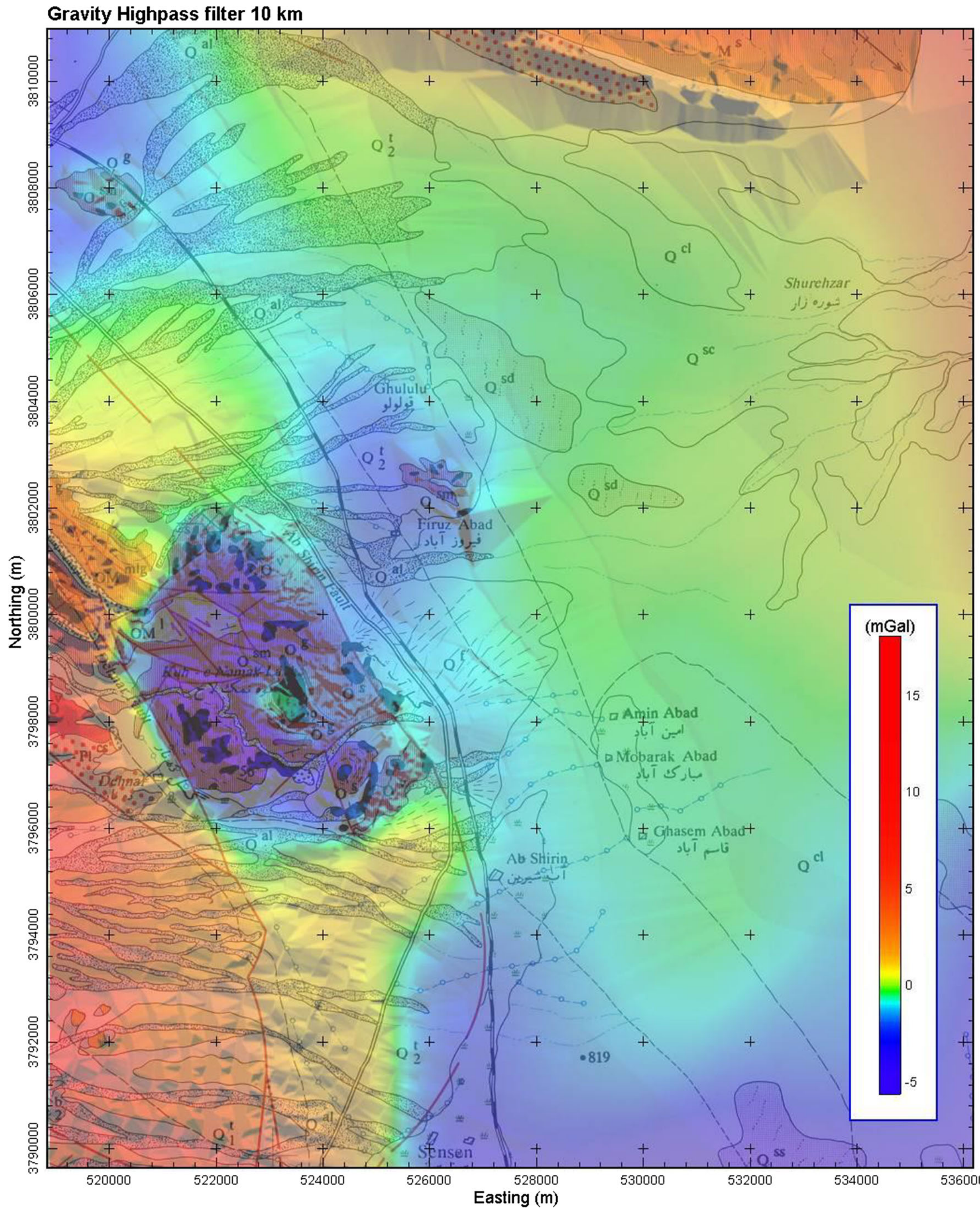

Fig. 19 Overlay of local gravity field (High pass 10 km), ARAN map of geology and terrain shading. Main tectonic features can be found and stated even more precisely on the basis of gravity results. The *hillocks* assumed to be the most uplifted part of dome no. 4 are located at the eastern edge of the structure—a further indication of a southwest-northeast tendency of salt movement

between horizons in the shallow part is smaller than that of the deeper part.

Based on the quality and continuity of the selected reflectors, the tracking strategy has been determined. In good quality portion of 3D seismic data which is usually limited to the east and north-eastern part of the data, tracking was thoroughly successful. In difficult areas, we selected manual interpretation. At first, 2D-guided auto-tracker in Petrel Schlumberger Software was used for interpreting horizons with every 10 inline and xline, and then the interpreted part was used as seed point for applying 3D autotrack. 3D autotrack has been constrained

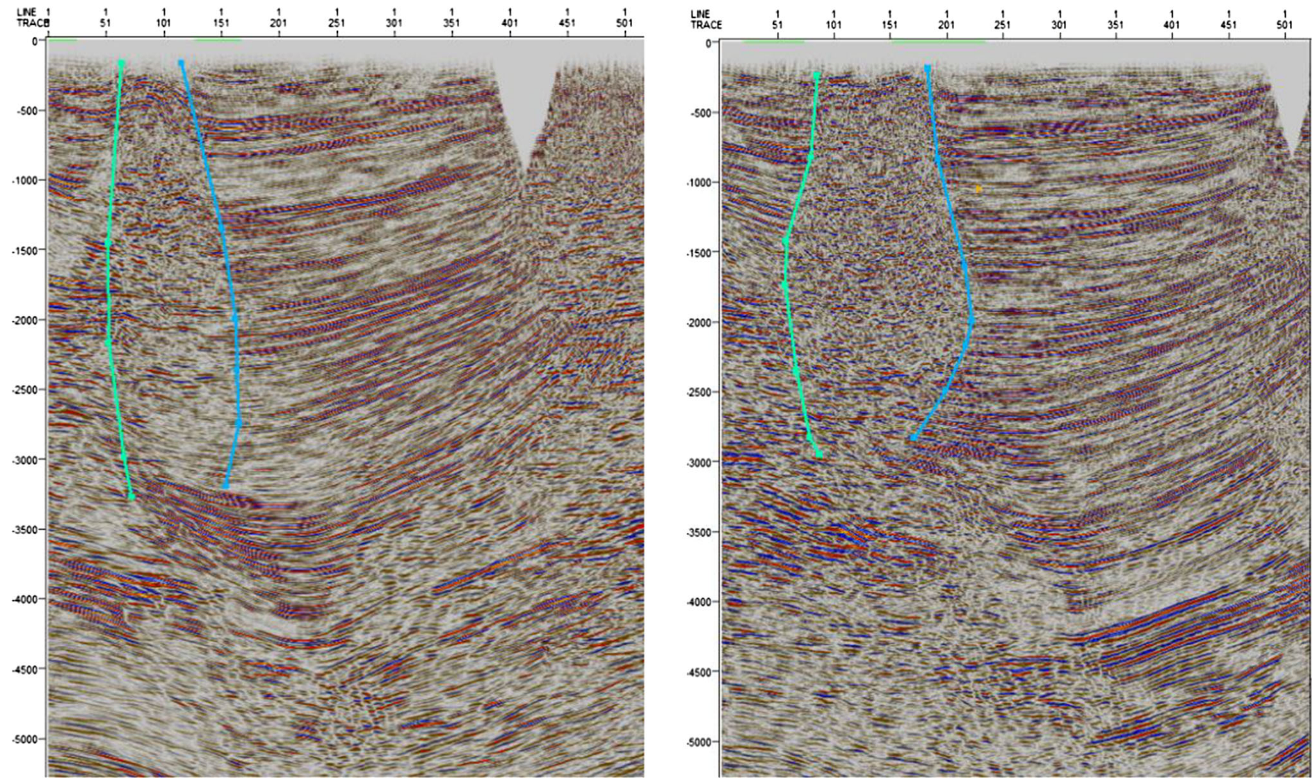

Fig. 20 2D seismic lines Sarajeh 76426 (*left*) and Sarajeh 76427 are crossing the structure. The assumption—supported by non-seismic results is that layers at the eastern edge (*right hand side*) are such steep that reflections are interrupted. Consequently, the structure would have to be expected slimmer

by wavelet correlation in specified window associated with maximum allowable time shift consideration. These two constraints provide better result of 3D auto tracking. The 3D auto tracking has been bounded to area of good quality seismic data by defining polygon.

Hydrogeology

The study area is oriented in northwest–southeast direction with about 75 km in length and a width of 20 km from Kashan city to the Qom plains in the north. The mean elevation is about 950 m above sea level. Faulting and fracturing have increased the capacity of rocks despite the low porosity and permeability of these formations. In cretaceous and oligo-miocene carbonate formations karst systems have caused higher permeability in brittle rocks.

The main karstic forming formations belong to the Qom carbonate formation and cretaceous carbonate rocks. Eight carbonate zones were estimated as areas with high underground water bearing potential. The water exploitation limit of these zones was determined at about 5.8 million m^3.

Some wells use the karstic formations as water supply. The yield varies from 15 to 200 lit/s. Additional withdrawal of water from the karstic formations or the springs of main rivers would decrease the volume of water entering the plains and promote the invasion of salt water as well as a drop in water table.

As result of analysis of geophysical and drilling data as well as exploration drilling and piezometric studies, the material of the main aquifer is composed of clay, sands, cobbles and pebbles. The size of grains decreases towards the east of the plain and the salt lake. The level of underground water is constant according to piezometric studies.

The aquifer is composed of Quaternary deposits with:

- Gravel at the foothills to the south and west of the plains
- Alluvial cones of coarse sand and pebbles, deposited during floods
- Clay top layer in north and north-western parts of the plains, transported over long distances by water from the western and southern mountains and by wind (loess)
- Eolian sands in the north and northeast of the plains, probably transported from the northern desert.

In part of the Kashan plains, the aquifer is divided into different parts by impervious layers. The aquifer is situated in a depression with a northwest–southeast-oriented axis.

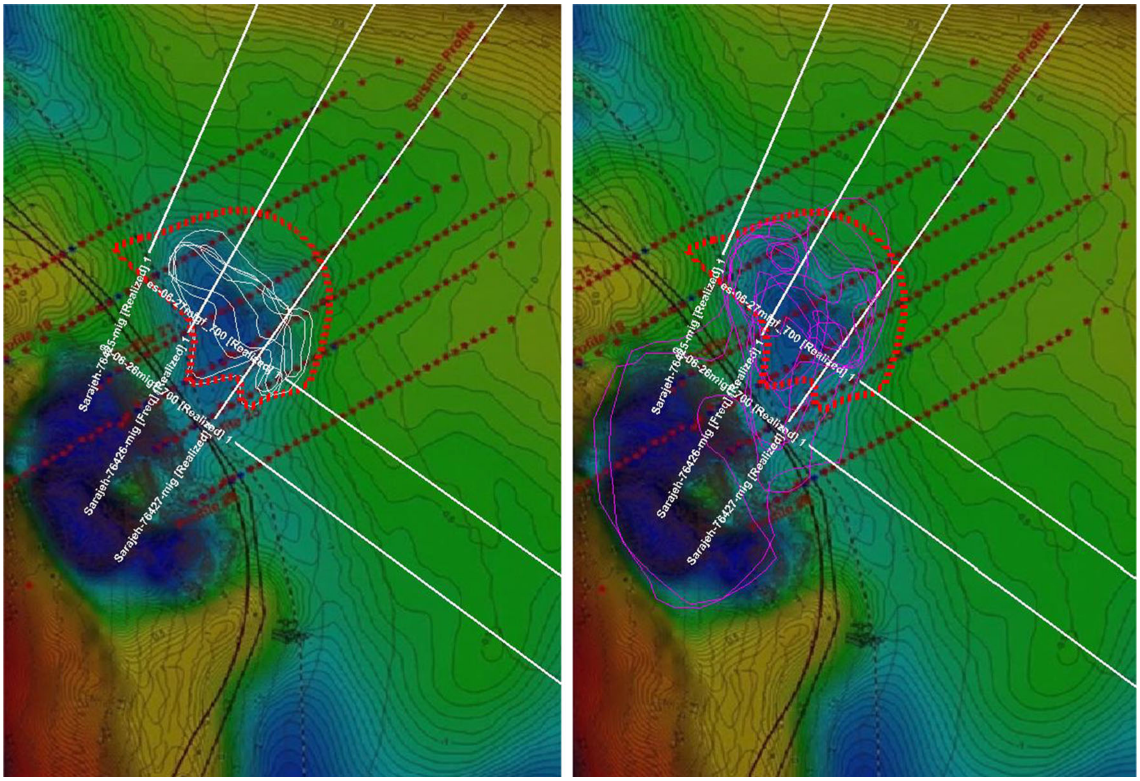

Fig. 21 Synoptical presentation of approaches to substantiate the focus of investigation. To the left-hand side (**a**), the area of further investigation (3D seismics) is defined by MT (*white isolines*) and seismics. To the *right hand side*, this area is compared to the gravity field/calculated density isolines, which show a good but not perfect correlation

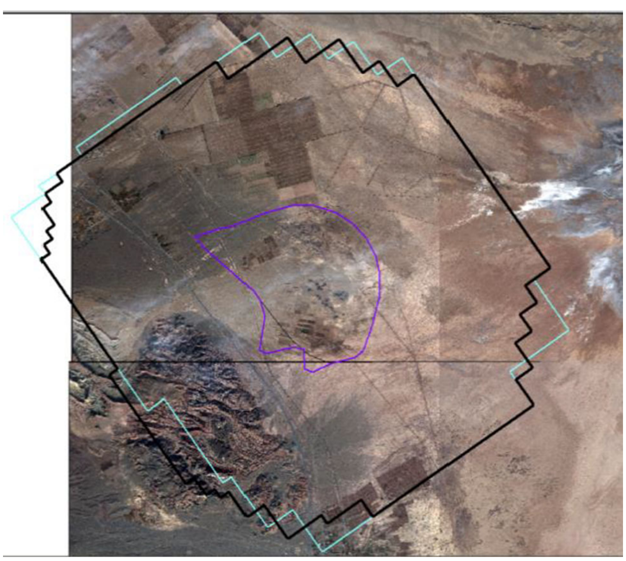

Fig. 22 3D seismic investigation area based on 2D seismic profiles and magnetotelluric results, supported by the encountered (local) gravity field

The maximum thickness of the aquifer is in the western part near the village of Ab Shirin, the minimum thickness was determined in the northeast of Mehdiabad. The data of 53 observation wells were checked for investigation of underground water level fluctuations. As a result, the general flow direction was determined from the mountainous areas in southwest and west towards the centre and northern directions. Recharge zones are located in the west and southwest of the area.

A change of flow direction in recent years was determined as a probable result of increased water production from water wells.

In the central part and along the main axis of the aquifer increased water production and changes of the slope of the impermeable bed(s) may be the reason of a decreasing hydraulic gradient. The hydraulic gradient was determined with 0.009–0.01 in the east and west of the plains and a minimum of 0.001 in the northwest. The direction of groundwater flow is from the mountainous areas and partly from the salt lakes to a centre south/southeast of the salt dome area. Detailed information about the influence of the salt lakes is not available due to lack of observation or measuring stations in that area. A declining groundwater level was determined for the Kashan plain causing a decrease of water yield of the wells as well as land subsidence with damage to buildings.

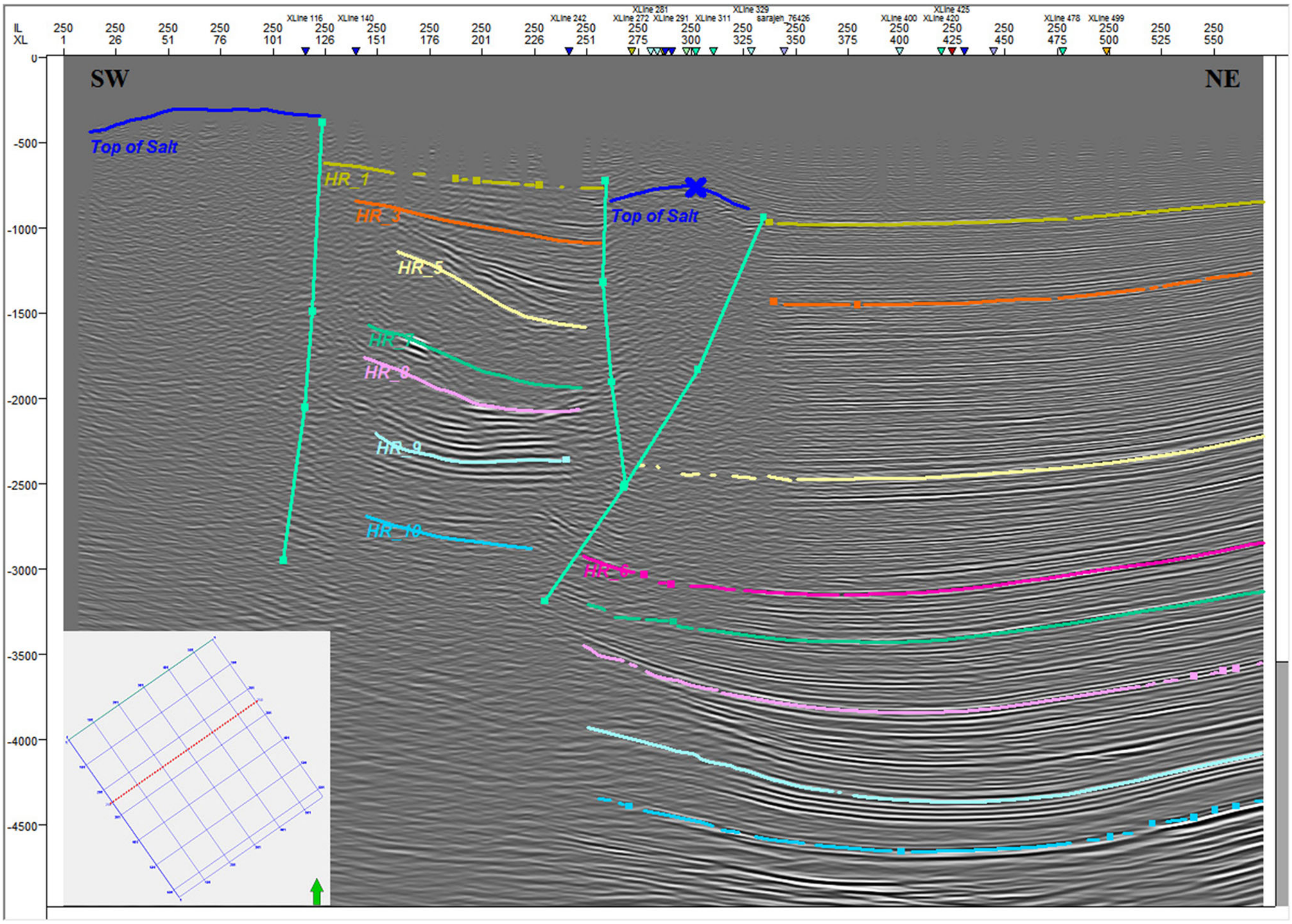

Fig. 23 3D seismic line with interpretable phantom horizons in the *Upper Red* Formation surrounding diapir no. 4

Conclusion and recommendation

The present database of the Salt basin suggests that chemotoxic and radiotoxic waste might be safely and permanently be disposed in the deep salt layers. Positive aspects that could make the deep salt layers of this study basin as a favourable site for waste disposal are:

- No or only slow ground water movement at repository level.
- Low tendency to build new pathways in salt layers.
- Situation which allows a good spatial characterization of the salt rock formation.
- Situation which allow a reliable prediction of the long-term stability of the favourable conditions of the salt rock formation.
- Good compatibility of the salt layers with temperature changes.

Some geoscientific scenarios have been identified as negative aspects in deep repository areas:

- Geological or tectonic events, e.g. seismic activities in earthquake zones.
- Active disturbance zones.
- Geophysical basement faults treatments.
- Human life risks and environmental problems.

Intracrystalline inclusions and intercrystalline pockets in undisturbed rock salt contain saturated brines, each with a different chemical composition, a unique isotopic ratio, and a distinct and specific pressure. These discrete brine occurrences constitute convincing evidence for the tightness of the salt: what little formation fluid it contains has not become homogenized by internal or external force and has therefore remained isolated for tens to hundreds of millions of years (Stein and Krumhansl 1984).

From the geological field work it is assumed, that a changing stress field with SW–NE-directed compression caused a northeast directed fracture system including the conjugating shears in Post-Qum Formation times. This was responsible for overthrusting at the edge of the basin and for the final piercement of salt, forming an overhang in salt dome no. 4.

Both methods (gravimetry and MT) give good indications for a salt diapir in the hillock area.

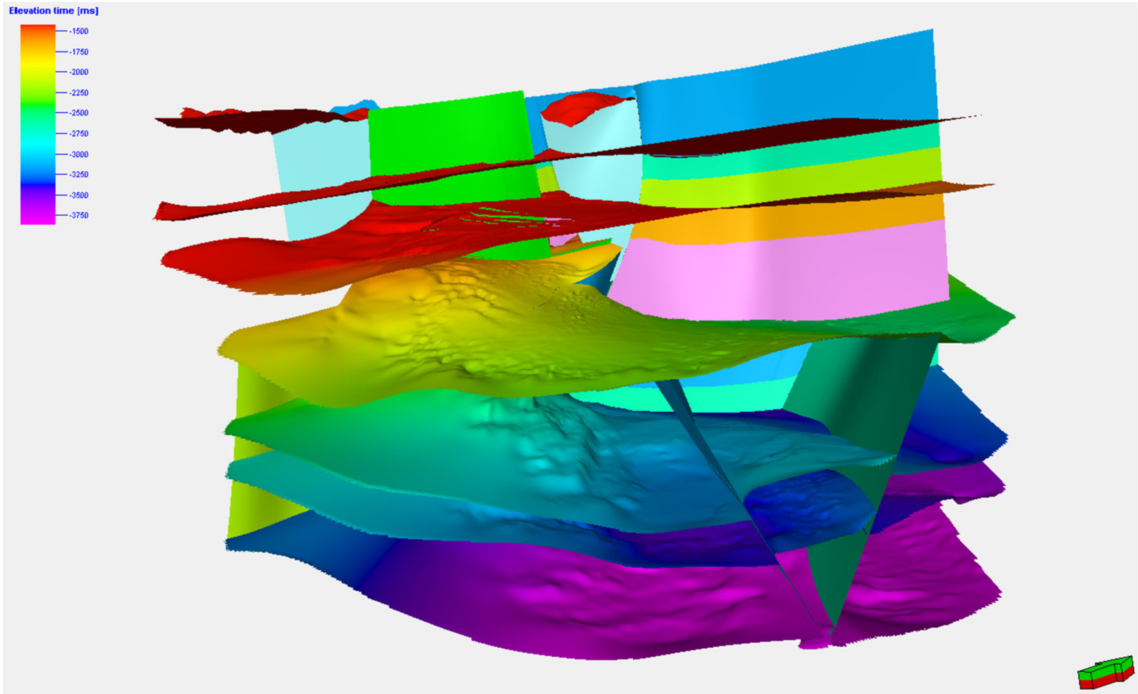

Fig. 24 3D geological model with interpretable phantom horizons in the *Upper Red* Formation surrounding diapir no. 4

Looking at the shape of anomalies in detail, there is a great correspondence between boundaries derived from MT and the observed gravity low.

Obviously the gravity low is not caused by the outcropping/visible structures alone. Parts of the gravity low might be caused also by deeper sources such as the zone between the mountain area and the hillocks. Additionally, there is the fault zone which might be a source for negative anomalies of the gravity field. Considering the gravity field in this area as a complex superposition of different sources, evaluation of extent, respectively, shape of the salt diapir by means of gravity alone appears not to be feasible.

The following conclusions and recommendations are given:

- Based on preliminary results available up to now, both methods show good indications for a salt diapir proposed in the wider hillock area with western tendency of extension.
- Gravity results show a distinct gravity low in the hillock area, but this anomaly is expected to be superimposed by effects from other sources (fault zone, regional trends).
- Thus, the main conclusion from MT and gravity results at this project stage is that there is a separated resistivity structure in the hillock area that is corresponding with a gravity low. Therefore, there is an indication for a salt dome at the expected location. This is also in compliance with known geologic features and results in former 2D seismic profiles. This coincidence is a fundamental precondition to continue the detailed exploration with 3D seismic focusing on this structure.
- The depth to the top of salt is assessed to be at approximately 350–400 m.
- The structure appears to be linked to a root zone. An overhang most probably is developed mainly towards east.
- In the mountainous area, there is no clear indication for a deep-reaching salt structure as a whole from both methods. This area is expected to be partitioned. Some compartments are considered worthwhile to be further investigated.

The relative density was derived by unconstrained inversion, a rather mathematical approach to determine density values from gravity data. For the estimation of the shape of the salt body, resistivity data following a coinciding 2D seismic profile were used to assess the border of the salt body.

This method is acceptable and correct. Due to the lack of well data for calibration, this is probably the most plausible way of interpretation. However, it should be stated clearly that on the MT and gravity profiles and depth slices physical parameters are displayed, which do not necessarily show the geological structure. These parameters are determined with reasonable accuracy at the top and shallow layers, but the accuracy decreases with increasing depth. Therefore, the determined shape and dimensions of the salt body can only be estimations.

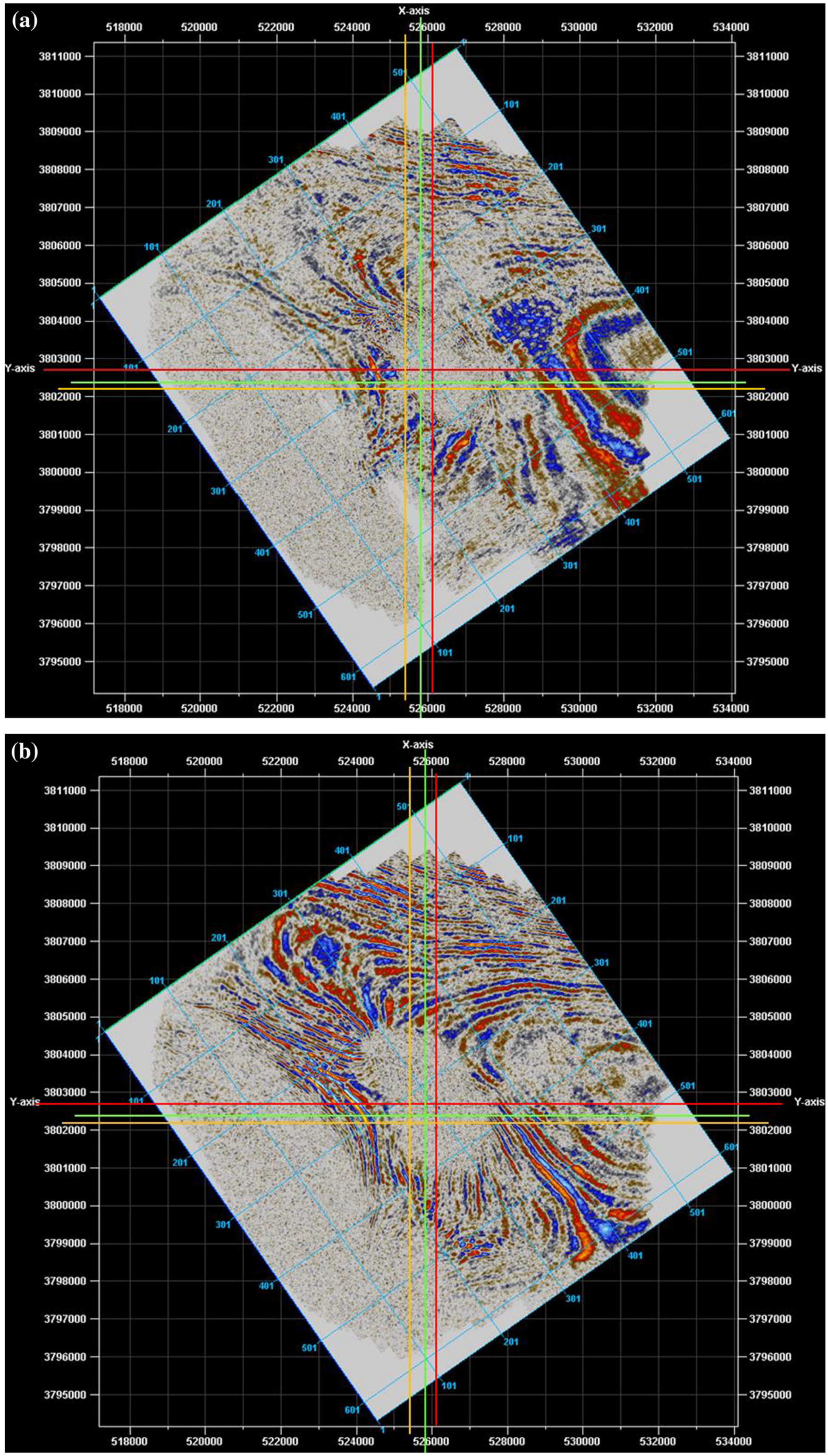

Fig. 25 800 ms (**a**) and 1300 ms (**b**)—time slices(twt)of migrated 3D seismic data. The reference level is above ground level. The centre of the *orange* crosshairs indicates the approximate maximum of the negative gravity anomaly, the one of the *red* crosshairs represents the approximate centre of the assumed salt body derived from 3D seismics and the centre of the *green* crosshairs illustrates the selected drilling location

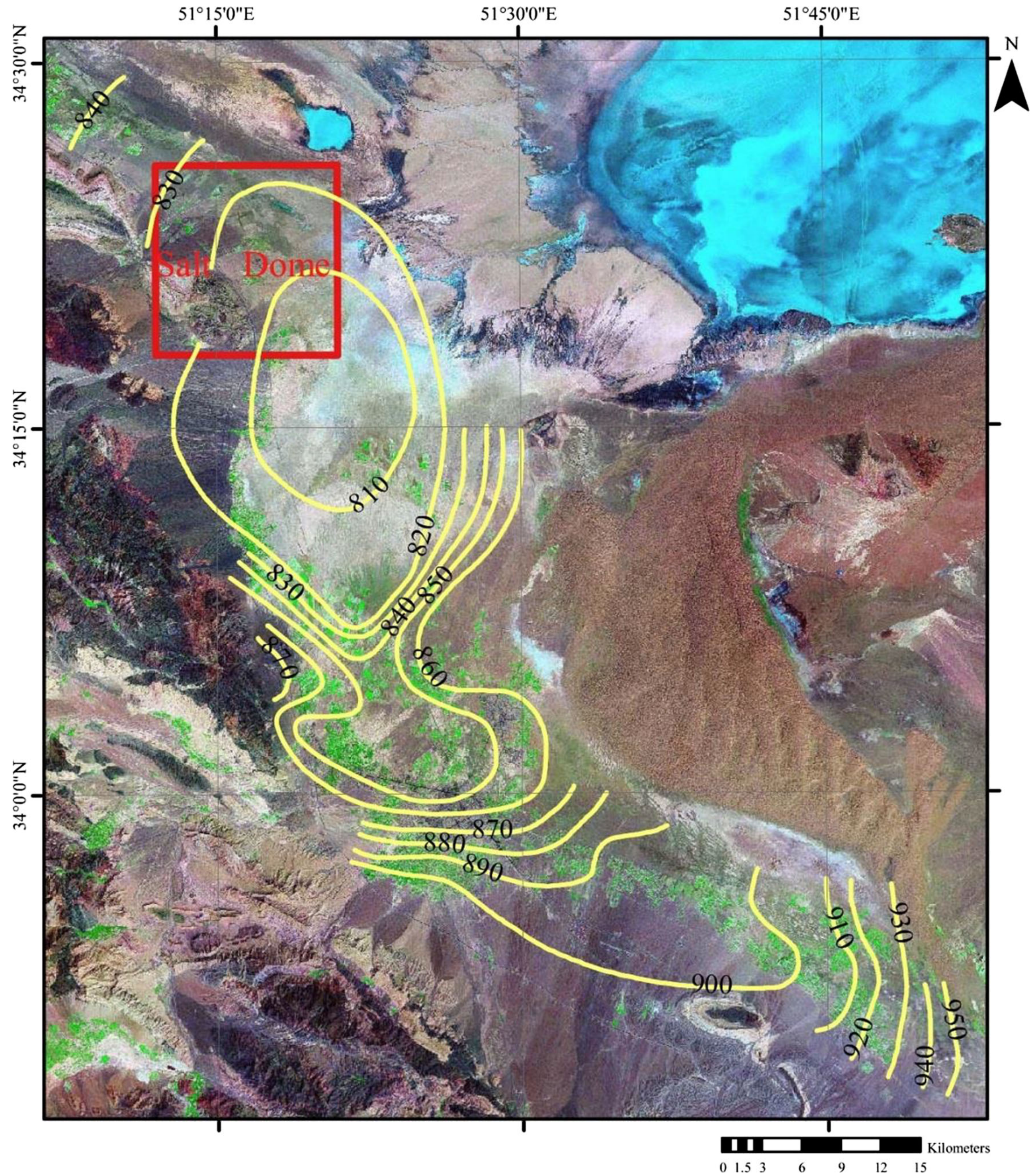

Fig. 26 Kashan aquifer contour values in metre relative to the sea level, ZAPCE (2013)

The approach to define the structural outline by different methods gives already at this stage a good impression of the structure as it could look like. This comprises a significant overhang situation in the northeast, a clear but limited overhang in the northwest and a slight one to the southeast.

From a geophysical point of view the combined MT and gravity surveys have been successful because "the existence of the proposed salt structure was confirmed". However, the displayed shape and dimension of the salt body bear considerable uncertainties.

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