Discussion


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Jallouli et al. (2005) are to be congratulated on their use of gravity measurements, edge enhancement of Bouger anomalies, and 2.5D forward modelling of geologically realistic profiles to convince us that at least one of the SW–NE trending bodies of Triassic evaporites (mainly salt and gypsum) in the Tunisian Atlas are diapiric walls rather than folded sheets of allochthonous salt. The significant implication of their work is that any hydrocarbons trapped by these structures are likely to be along their flanks rather than beneath their flat crests.

However, the supposition by Jallouli et al. (2005) that their Jebel Debadib body had a flat submarine crest level with the sea bed when it extruded in Late Albian times (p. 223) and their Fig. 9 repeat a common misunderstanding about the relief of emergent salt domes. There are also inconsistencies between their interpretations of the geology (Fig. 7) and its history (Fig. 9). This discussion therefore focuses on the shapes and heights of past salt extrusions and interpreting their histories from the surrounding sediments as both these topics have significant implications concerning sedimentary facies along their flanks (Giles and Lawton, 2002).

As Fig. 9 in Jallouli et al. (2005) illustrates, salt structures change shape as they evolve. Gentle conformable salt pillows that rise very slowly are likely to accelerate when they narrow to reactive piercing diapirs (Jackson et al., 1994). They are likely to accelerate even more when they surface and formerly constrained salt is liberated with its most buoyant geometry (Talbot, 1998). The low relief assumed by Jallouli et al. (2005) for the extruding salt at Jebel Debadib may assume that a high proportion of the salt was dissolved as fast as it extruded. This is unlikely if it extruded into seawater. Calculations by Fletcher et al. (1995) found that dissolution was a relatively minor factor in the growth of a salt diapir extruding into the Gulf of Mexico. Insoluble materials in the dissolving evaporites accumulate as a thin residual cap soil that slows later salt dissolution. Fletcher et al. (1995) estimated that only 10 vol.% of an expanding salt extrusion dissolves at a rate that would...
result in a cap soil 26 m thick after 3 Ma and 48 m thick after 5 Ma.

This discussion assumes that the Triassic evaporites of Tunisia are characterised by the high vol.% of salt that is usual in diapirs of evaporite sequences that range in age from Neoproterozoic (\(\sim\)500 Ma) to Miocene (\(\sim\)5 Ma) worldwide.

1. The shapes and heights of salt extrusions

What happens when salt diapirs reach the surface depends on the environment into which they extrude. Thus extrusions of the same salt have negligible relief on the US Gulf coast but can rise up to 260 m above the bed of the Gulf of Mexico (Wu et al., 1990). Theory (e.g. Lister and Kerr, 1989), experiment (e.g. Talbot and Aftabi, 2004) and observation (e.g. Talbot, 1998) suggest that the shapes of active extrusions of a visco-elastic crystalline fluid like salt are likely to be smooth, round topographic domes on scales \(\geq 1\) km and jagged on scales \(< 100\) m whether they are extruding at \(\sim 1\) m year\(^{-1}\) (Talbot et al., 2000) or nearer \(8\) cm year\(^{-1}\) (Talbot and Aftabi, 2004).

The maximum height of the rounded dome relative to its surroundings (its freeboard) is a function of the velocity at which the salt extrudes and the rate at which it degrades by gravity spreading and climatic erosion. Davison et al. (1996) tabulate the freeboards of modern salt extrusions in 7 basins worldwide as between 45 and 1500 m. The freeboard of steady-state extrusions can be approximated by a simple analytical expression derived by Talbot and Jarvis (1984) that fits the profiles of natural salt fountains in Iran, the Gulf of Mexico and analogue laboratory models surprisingly well (see Talbot, 1993, 1998; Talbot and Aftabi, 2004). Laboratory experiments by Lister and Kerr (1989) also simulate the profiles of natural salt extrusions (but are time-dependant with inappropriate boundary conditions). However, all these models are dynamic and require knowledge of the rate of salt extrusion.

The rate of salt extrusion is easiest to measure where active salt diapirs were planed to flat tops by marine erosion in the past. Such erosion surfaces are particularly useful strain marker because they allow the distinction of rates of tectonic extrusion from rates of climatic degradation. Thus the crest of the ridge of diapiric salt known as Mount Sedom was truncated to a planar top by a precursor to the Dead Sea \(\sim 300,000\) years ago. This flat top is now 200 m above the adjacent Dead Sea as a result of subsequent extrusion at \(\sim 6\) to \(7\) mm year\(^{-1}\) (Pe’erí et al., 2004). Another salt diapir truncated by marine erosion, Namakadram on the island of Qeshm in the Straights of Hormuz (on another boundary to the same plate) also rose at \(\sim 6–7\) mm year\(^{-1}\) from 6 to \(4\) ka BP (Reyss et al., 1998).

It is much more difficult to separate the tectonic and climatic signals for salt extrusions that gravity-spread rounded domes or fountains of salt that have not had simple horizontal time markers etched into, or added to them. The extrusion rates of such active salt bodies have to be modelled, either from their freeboard, or the rates at which markers on their surfaces travel. Thus the \(\sim 8\) cm year\(^{-1}\) extrusion rate estimated for Qum Kuh was based on its freeboard of 315 m above the central plateau of Iran (Talbot and Aftabi, 2004). By comparison, the extrusion rate of between \(1\) and \(2\) m year\(^{-1}\) of Kuh-e-Jahani, the largest salt fountain in the Zagros Mountains (Talbot et al., 2000), was modelled using the rate at which a marker on the edge of the summit domes moved downslope (taken as \(4\) to \(6\) m year\(^{-1}\) and subsequently found to range from \(1\) m in dry years to \(10\) m in wet years).

Past extrusion rates of formerly emergent diapirs can also be constrained by backstripping the surrounding overburden. However, salt extrusion rates constrained in this manner tend to be orders of magnitude lower than measurements of active salt extrusions. Thus Zirngast (1996, Fig. 14) constrained the fastest rate of extrusion of the salt of Gorleben diapir to \(0.11\) mm year\(^{-1}\). The \(1–2\) m year\(^{-1}\) extrusion rate modelled for Kuh-e-Jahani mentioned above was modelled from 3.5 years of measurements (Talbot et al., 2000). Nevertheless, despite their difference of 5 orders of magnitude, both these rates could be correct. Thus Jahani could only sustain its current extrusion rate \(\sim 1\) m year\(^{-1}\) until its deep source layer starves and closes, perhaps after something like 100,000 years of extrusion. The salt of Gorleben diapir might also have extruded at \(>1\) m year\(^{-1}\) for \(\sim 10^5\) years in Campanian times without this being obvious in an extrusion rate that had to be
averaged over the 39 Ma from Cenomanian to Early Paleocene times (Zirngast, 1996).

2. Lessons from Iran

About 150 diapirs of Neoproterozoic to Cambrian salt (>~500 Ma) extrude in the Zagros Mountains and the marine gulf to the south, and perhaps 100 diapirs of Oligocene to Miocene (20–5 Ma) emerge on the central plateau of Iran (Kent, 1970). Independent of the age of their salt, all these extrusions appear to evolve through similar histories and illustrate what happens to salt extrusions in regions where dissolution is slow. A rounded dome of salt rises rapidly (in a few thousand years?) to ~400 m above its vent, whether this is on a plain near sea level or on the crest of an anticlinal ridge >1 km high (Talbot, 1998). Unsupported by surrounding air or water, the extruded salt cannot support its own weight and the lower flanks of the dome gravity spread sheets of allochthonous salt downslope over the surrounding scenery. Young salt extrusions soon establish and maintain the distinct rounded shape of a viscous fountain (Lister and Kerr, 1989). Salt fountains can maintain essentially steady-shapes where tectonic and climatic erosion degrades the salt as fast as it extrudes. A high ratio of extrusion to spreading can raise a summit dome well above the allochthonous salt spreading from its flanks while a slow extrusion may resemble a viscous droplet (Huppert, 1982) from the beginning. A collar of country rocks upturned around the vent can locally hinder gravity spreading and result in a pseudo-fountain (Aftabi, pers. comm., 2003). Eventually, salt withdrawal from depth closes the roof and floor of the source to a primary weld. Salt left in the source layer supports the overburden in a turtleback structure between diapirs. As the ratio of extrusion-to-spreading rate falls, the summit dome sinks into the salt apron and the extrusion assumes the distinctive parabolic profile of a viscous droplet. Unless extrusion is re-invigorated by further burial or lateral tectonics, erosion thereafter outpaces extrusion and the profile of the droplet degrades to conical piles of cap soils growing atop the dissolving salt. Eventually only a hollow lined by residual soils above a breccia chimney marks the site of a former salt extrusion.

3. The static approach to extrusive salt freeboard

As inertia is unlikely to be significant even in salt diapirs extruding at over 1 m year\(^{-1}\) (Talbot and Jarvis, 1984) a simple static approach can be adopted to calculate the potential freeboards of past salt extrusions (Talbot, 1998, Volozh et al., 2003; Talbot and Aftabi, 2004). This approach neglects any lateral tectonic forces, gravity spreading and climatic degradation of the extruded salt and assumes that the extruded salt column is supported by the weight of the surrounding overburden on its source layer. Thus the body force of gravity acting on the overburden loading a horizontal salt source layer \((\rho g h_o)\) can support a diapirc column of salt of equal mass \((\rho g h_s)\), where the subscript \(o\) refers to the overburden and subscript \(s\) refers to salt, \(\rho\) is the density, \(g\) the gravitational acceleration, and \(h\) is the height.

4. The potential height of Jebel Debadib

Table 1 uses measurements and data in Fig. 7 of Jallouli et al. (2005) to list the density of the Triassic evaporites, the average densities of the overburden units and the cumulative thicknesses of the overburden on either side of Jebel Debadib at different times. The height of the salt column (above the top of the adjacent source layer) is calculated by equating \(\rho g h_s = \rho g h_o\) so that \(h_s = \rho g h_o / \rho_s\) and the freeboard of the extruded salt above the adjacent surface or sea floor is \(h_s/h_o\) at the time. Fig. 1 here illustrates the results to the right of a repeat of Fig. 9 from Jallouli et al. (2005).

Fig. 9B shows the salt of Jebel Debadib moving into a pillow and the caption refers to a reactive diapir piercing during Upper Jurassic to Cretaceous regional extension. This is consistent with the gravity model of Jallouli et al. (2005) on their Fig. 7 showing Jurassic carbonates 700 m thicker on the SE side than on the NW side of Jebel Debadib. Presumably the thicker sequence was of syn-rift growth sediments deposited on the hanging wall of a normal fault (Fig. 1). The caption to Fig. 9C refers to reefs late in the Aptian (hachured) and the beginning of active piercement promoted by inversion to lateral compression. However, the reefs, now presumably found on the flanks of the salt structures, may have formed beside an already extruded diapir (as in Mexico: see Giles and Lawton,
that calculations summarised in Table 1 suggest could have had a freeboard of 450 m.

The caption to Fig. 9D and page 223 of Jallouli et al. (2005) refer to a small sheet of allochthonous salt fed by emergent salt with a flat crest extruding onto the seafloor during renewed extension and rapid Albian sedimentation. In fact salt extrusion is more likely to occur during relatively slow deposition (Talbot, 1995) of Albian–Cenomanian marls and black shales; indeed that these are shown thicker on the SE side in Fig. 7 Jallouli et al. (2005) indicate normal faulting of 100 m (shown reactivating the basement fault in Fig. 1). The 3 km length of the end-Cenomanian salt sheet shown in Fig. 1 is by no means exceptional; Cretaceous equivalents in the Pricaspian basin are as long (Volozh et al., 2003) and modern axisymmetric version reach lengths of 10 km in Iran (Wenkert, 1979); these are still short compared to monoclinic salt extrusions in the Gulf of Mexico (Wu et al., 1990). The caption to Fig. 9E refers to continued lateral extension, and that to Fig. 9fF, another inversion to Cenozoic lateral shortening that rejuvenated the diapir so that it develops tertiary withdrawal basins. My equivalent Fig. 1 illustrates that the overburden had the mass to extrude a salt column with a freeboard N 500 m until it was partially overstepped by Oligocene to Neogene sediments.

A very crude estimate of the rate of extrusion of salt likely at Jebel Debadib when the salt was emergent comes from inserting likely values into the expression:

\[ m = \frac{0.084}{\mu} \rho g a^3 \]

from Talbot and Jarvis (1984).

Here \( m \) is salt mass flux (mass/unit time/unit distance in m), \( a \) is the maximum height of the summit, \( \rho \), is the density of the extrusion (2700 kg m\(^{-3}\)), \( g \) the gravitational acceleration (9.8 m s\(^{-2}\)) and \( \mu \), its kinematic viscosity (taken as 10\(^{16}\) m\(^2\) s\(^{-1}\) to reflect the impurities indicated by its relatively high density).

\[ m = 0.084 \times 2700 \times 9.81 \times 400^{3}/10^{16} \]

\[ m = 5.7 \times 10^{-3} \text{ kg s}^{-1} \text{ m}^{-1}. \]

Taking the vent as 4500 m across (see Fig. 9) and following the logic of Talbot and Jarvis (1984) suggests that the rate of extrusion at Jebel Debadib was of the order of 0.016 m year\(^{-1}\) = 16 mm year\(^{-1}\). This rate

<table>
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<tr>
<th>Geological unit or time</th>
<th>Time for unit Ma</th>
<th>Average density of overburden, g cm(^{-3})</th>
<th>Density, g cm(^{-3})</th>
<th>Maximum crest relief over base of overburden, m</th>
<th>Maximum potential freeboard, m</th>
<th>Rate of deposition, m/Ma</th>
<th>Cumulative thickness of overburden, m</th>
<th>Cummulate thickness overburden, m</th>
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Fig. 1. A. Fig. 9 of Jallouli et al. (2005) converted to a natural horizontal=vertical scale. B. The same taking account of different thicknesses of sediments of particular ages shown on either side of Jebel Debadib by those authors' gravity models in Fig. 7. Fault throws assumed are labelled but no attempt has been made to take account of any inversion of the deep normal fault during lateral shortening events. Note the potential freeboard of the extruding salt.
is nearly 3 times the rate that salt diapirs are currently extruding in Israel and Qeshm, 1/5 the rate of Qum Kuh in central Iran and 1/60 the rate of Kuh-e-Jahani in the Zagros Mountains. It is also over 20 times faster than the fastest overburden sedimentation rate averaged over the 7 Ma of Aptian times (Table 1).

In summary, currently active salt extrusions both offshore and onshore in regions of low rainfall develop distinctive shapes with significant freeboards that evolve slowly through similar geometries whatever their extrusion rates. The freeboards of past salt extrusions can be approximated using static mechanics that ignore salt degradation rates and lateral tectonic forces. The different thicknesses of Jurassic and Albian–Cenomanian sediments modelled on either side of Jebel Debadib by Jallouli et al. (2005) suggest the fault zones in the Tihama plain, NW Yemen. In: Alsop, G.I., Blundell, D.J., Dawson, L. (Eds.), Coastal Tectonics, Spec. Publ.-Geol. Soc. Lond., vol. 99, pp. 225–237.

References


