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Age, budget and dynamics of an active salt extrusion in Iran

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Abstract—The Hormuz salt of Kuh-e-Namak, Iran began rising through its Phanerozoic cover in Jurassic times and had surfaced by Cretaceous times. In Miocene times, the still-active Zagros folds began to develop and the salt is still extruding to feed a massive topographic dome and two surface flows of salt which have previously been called salt glaciers but are here called *namakiers*.

Two crude but independent estimates for the rate of salt extrusion and loss are shown to balance the salt budget if the current salt dynamics are assumed to be in steady state. First, to replace the extrusive salt likely to be lost in solution in the annual rainfall, the salt must rise at an average velocity of about 11 cm a^{-1}. Second, the foliation pattern shows that the extruding (and partially dissolved) salt column spreads under its own weight. The maximum height of the salt dome is consistent with a viscous fluid with a viscosity of 2.6×10^{17} poises extruding from its orifice at a rate of almost 17 cm a^{-1}. Both estimates are consistent in indicating that salt can extrude onto the surface 42–85 times faster than the average long term rate at which salt diapirs rise to the surface.

The structure, fabrics, textures and deformation mechanisms of the impure halite all change along the path of the extrusive salt from the dome down the length of both namakiers. Such changes tend to occur when the flowing salt encounters changes in its boundary conditions, and the recognition of buried namakiers is discussed in the light of such observations. Episodes of salt flow at a rate of 0.5 m per day have been measured along the margin of the N namakier after significant rain showers. Such brief episodes of rapid flow alternate with long periods when the namakier is dry and stationary. The shape of the colour bands cropping out on the N namakier indicate that the flow over the surface of impure salt with a mylonitic texture obeys a power law with $n \sim 3$. Although the reported annual rainfall has the potential of dissolving both namakiers in about 2000 years, a superimposed thin marine cover may protect static parts of them for as long as 30,000 to 300,000 years.

INTRODUCTION

THIS report describes one of the many bodies of Hormuz (Eocambrian–Cambrian) salt extruding through a thick sequence of Phanerozoic sedimentary rocks as they shorten along a NNE–SSW axis in the Zagros fold belt of Iran.

Most previous studies of bodies of deformed salt have been at structural levels at which the salt is confined to an intrusive pipe. Even if such diapirs reach the surface they are either inactive or the salt in them is dissolved as fast as it rises so that the salt ends upwards in a solution surface beneath a cap rock of relatively insoluble residues.

The majority of the 150 or so emergent diapirs of Hormuz salt in Iran are marked by topographic domes of extrusive salt indicating that their rise has been faster than their solution near or at the surface (Kent 1979). Sheets of salt have flowed from many of these domes down dip slopes of their country rocks to spread as piedmont lobes over the surrounding plains of recent sands and gravels.

The diapirs of Hormuz salt and their associated extrusives have an extensive literature and the following list is not exhaustive: de Böckh *et al.* (1929), Lees (1927, 1931), Harrison (1930, 1956), O'Brien (1957), Kent (1958, 1966, 1970, 1979), Gansser (1960), Gussow (1966, 1968), Gera (1972), Ala (1974), Fürst (1976), Barr (1977), Wenkert (1979), Talbot (1979, 1981), Talbot & Rogers (1980). The extrusive salt sheets have so far been known as salt glaciers but this is an inappropriate and unwieldy term and it is proposed here that a sheet or lobe which is predominantly of halite and which has flowed over the surface is called a *namakier*. This term is derived from *namak* which is Farsi for salt.

Descriptions of the salt structures and fabrics of such salt extrusives is long overdue in view of the questions as to whether the overhangs common to many buried salt structures have formed as intrusives or extrusives. Even quite thin sub-horizontal sheets of salt can be almost opaque to routine seismic investigations (but see Amery 1969) and might overlie and obscure far larger volumes of unsuspected hydrocarbon reservoirs than the subsurface overhangs developed in association with asymmetric or non-vertical diapirs (Talbot 1977).

Deformation maps (Verall *et al.* 1975, Arieli *et al.* 1980) which summarize several decades of theoretical and laboratory based salt mechanics do not yet allow for the possibility of namakiers flowing over the surface. It has therefore been suggested that the namakiers of Iran could only have extruded hot like lavas (Gussow 1966—but see Kent 1966 and Gera 1972) or that they only

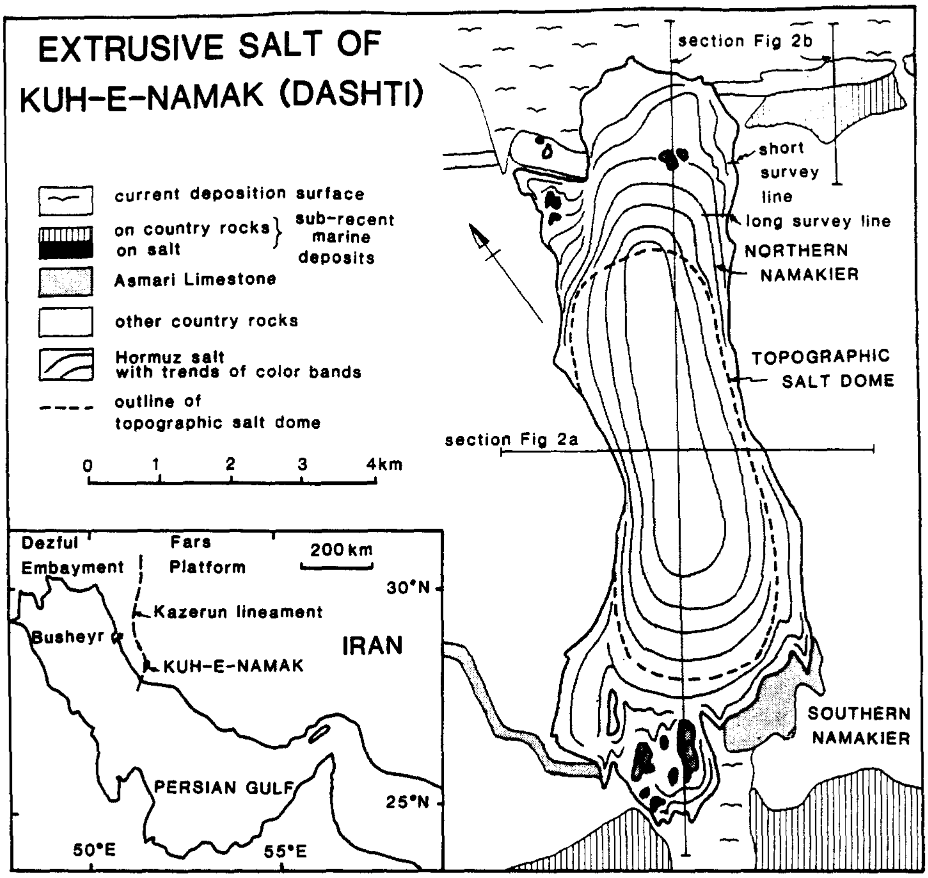

Fig. 1. Geological sketch map of the salt extrusives at Kuh-e-Namak (Dashti) showing locations of profiles in Fig. 2.

appear to move by the recementation of fallen blocks (Gussow 1968, Gera 1972).

The research programme which led to this report was cut short by the political situation in Iran and cannot be definitive; it therefore emphasizes problems by inference rather than solves them by measurements. The problems considered are the age of the salt extrusives, the budget of supply and loss of salt and the rate at which salt extrudes at the surface.

GEOLOGICAL SETTING OF KUH-E-NAMAK (DASHTI)

The Hormuz salt of Kuh-e-Namak (Dashti) has risen from depth where the south end of the Kazerun lineament crosses an anticline of typical NW–SE Zagros trend 120 km southeast of Busheyr about 40 km east of the coastline (Fig. 1). Kuh-e-Namak means 'mountain of salt' in Farsi and there are so many of these in the Zagros that the name of the province is usually added to identify a particular example; however, this convention will not be continued in this work which deals with the same Kuh-e-Namak throughout.

The Kazerun lineament is a 250 km N–S line of en-échelon wrench faults and local thrusts which are discontinuous on the surface but probably continuous along a major fault in the Precambrian basement (Kent 1979). This deep fault has been reactivated during several phases of movement since the Permian and appears to have been the site of several depocentres in Fars (Miocene–Pliocene) times (Kent 1979).

The Kazerun lineament separates the Fars platform from the Dezful embayment in the simply folded zone of the Zagros mountains. The Permian to Asmari (Eocene–early Miocene) cover in the Dezful embayment is thicker than it is on the Fars platform and, presumably as a consequence, the Zagros folds differ in style on either side of the Kazerun lineament. The anticline through which Kuh-e-Namak emerges crosses the Fars platform and is not alone in terminating close to the lineament.

The normal displacement across the Kazerun lineament reaches 5000 m further north (Kent 1979), but at the level of the Hormuz salt source layer beneath Kuh-e-Namak is only about 1000–1500 m down to the NW (Templeton pers. comm. 1977), and at the level of the Jurassic is only about 100 m (Figs. 2 and 3).

The surface expression of salt diapirs along the northern portion of the Kazerun lineament tends to be craters clogged with insoluble Hormuz debris. This suggests that they may be comparatively inactive, although the rainfall is higher there (Kent 1979); alternatively they may have been decapitated from their source by one or more thrusts spreading southwards as the basement beneath the simply folded Zagros moved northwards. Further south the salt extrusives become increasingly obvious and reach a climax at Kuh-e-Namak, which is probably one of the most active salt structures in Iran. Kuh-e-Darang, 20 km south-southwest and on the same

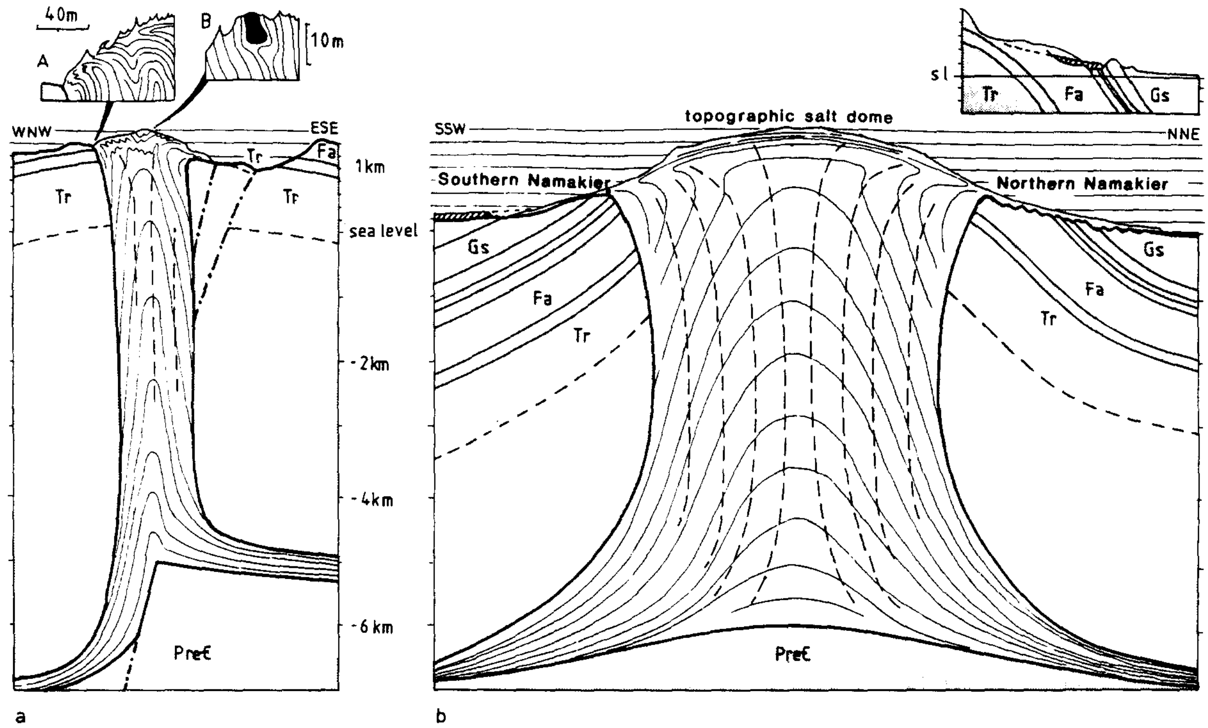

Fig. 2. Vertical cross (a) and longitudinal (b) sections of the Hormuz (= Eocambrian) salt mass showing the geometry of the flow profiles inferred from surface exposure. Locations of profiles are shown on Fig. 1. The colour banding (= bedding?) is shown in solid lines while the trace of the foliation (= stream lines) is indicated by dashed lines. Country rocks are: Pre€, Precambrian; Tr, Trias; Fa, Fahliyan-Surmeh Formation (Cretaceous); Grs, Gachsaran Formation (Miocene).

Inserts on Fig. 2(a): (A) The subvertical axial surface of mature folds inherited from depth curl to parallel the top free surface of the salt dome on its flank. These are joined or refolded by immature folds with axial planes which also curl to parallel the free surface but are too small-scale to illustrate (see Talbot 1979, fig. 8). (B) Occasional large blocks of insoluble Hormuz material (e.g. black limestone) are incorporated in the salt emerging in the dome. These are milled and dispersed in the halite if they are carried towards the distal portions of the namakiers in (rather than on) the salt.

Insert on Fig. 2(b): Cross section 1.5 km east of N namakier (see Fig. 1 for location) to show recent marine deposits (oblique ruling) and marine bevel (dashed) which define a recent surface (33,000–283,000 BP?) already showing significant folding. The same deposits and bevel can be seen to define the south limb of the recent increment of the Kuh-e-Namak anticline on the main longitudinal profile (Fig. 2b).

fault, has a salt core which is probably active but has not only not yet emerged, but may not even have yet reached the piercement stage (Kent 1979). Both Kuh-e-Namak and Kuh-e-Darang have developed from the same broad N–S trending salt pillow associated with attenuation of the Jurassic rocks exposed nearby (Kent 1979). The deep salt pillow at the south end of the Kazerun lineament is the oldest known indication of movement of the Hormuz salt in Iran (Kent 1979). Hormuz debris in Cretaceous sediments near Kuh-e-Namak indicate that, like others elsewhere in the Zagros, this particular diapir had already surfaced by Cretaceous times (Player pers. comm. 1976) long before the Zagros folding began. There can be little doubt that the rise of Hormuz salt in this structure was reactivated when the Zagros folds started to form in or around middle Miocene times (Kent 1979) and that both the folding and the salt extrusion are still active.

MORPHOLOGY OF KUH-E-NAMAK (DASHTI)

For descriptive purposes the salt body at Kuh-e-Namak may be considered to consist of the following components: two portions of a source layer at different structural levels, a sub-vertical pipe of elliptical cross-section, an extrusive topographic dome with a short extrusive flange along its southeast margin and two namakiers extending down to the plains just above sea level (Fig. 3). No piedmont lobes spread from either of these namakiers now, although moraines suggest that this may have happened in the past and such lobes are still common in other examples further east (Harrrison 1930).

If the orifice of the pipe is correctly inferred to underlie the steepest flanks of the extrusive salt dome (Fig. 1) then the orifice is a 6000 × 1000 m ellipse elongate NNE–SSW, along the fault bounding the southeast flanks of the salt bodies beneath both Kuh-e-Namak and Kuh-e-Darang.

Where the salt emerges in the extrusive dome it is coarsely crystalline (~4 cm in grain diameter), pale in colour and incorporates discrete blocks of insoluble Hormuz material up to several metres across (see insert B on Fig. 2a). Slight variations in the grain size and muted colours of the halite (pink, honey, pale green, grey and white) combine with the nature of entrained insoluble Hormuz debris (black limestone and sulphur, specular haematite, anhydrite, etc.) to define broad colour bands metres to tens of metres wide. These bands almost certainly represent the original bedding after it has flowed tens of kilometres sideways along the source layer and then several kilometres more up the pipe. These colour bands are generally steep and strike along the length of the extrusive salt dome and are also folded about doubly plunging fold axes with the same NNE–SSW orientation (see Fig. 2). A slight grain shape fabric in the halite, and the orientation of both the halite grains and any entrained spicules of insoluble materials define a foliation which is axial planar to folds exposed in the dome and both namakiers (Talbot 1979). Continual regeneration of this foliation ensures that it has only a short memory of its strain history (Talbot 1979). Increasing in intensity down the lengths of the namakiers, this flow foliation is interpreted as recording the stream lines of the salt mass (Talbot 1981).

The surface relief of the extrusive salt dome at Kuh-e-Namak is minor (~40 m) compared to its overall dimensions (6000 × 2000 × 1000 m). The salt emerging in the upper parts of the salt dome has incorporated within it mature (high amplitude/wavelength ratio) major folds which presumably generated at depth (Fig. 2a). The axial planes of these folds, and the foliation parallel to them, tend to be subvertical with a SSW–NNE strike along the SSW–NNE midline of the dome where the axes are doubly plunging and parallel the top free surface of the salt (and the shallow colour bands indicated on Fig. 2b). The axial surfaces splay outwards in the SSW–NNE trending slopes of the dome, curl through the horizontal just short of where any salt flows over the country rock, and thereafter dip gently downslope (Fig. 2a).

The colour bands inferred beneath the surface on Fig. 2 are probably grossly oversimplified in terms of the complications in known diapirs (Richter-Bernberg 1980) and ignore the possibility of thermal convection within the diapir (Talbot 1980).

In a vertical cross-section along the length of the topographic salt dome (Fig. 2b) the flow foliation, the colour bands and the fold axes broadly parallel the top free surface of the dome and the deeper stream lines can be inferred to spread beneath the summit. The emergent salt has been less confined in this section than in Fig. 2(a) and feeds two dip-slope namakiers.

Although the folds inherited from depth must extend into the upper reaches of both namakiers, none were recognized as such. Either any such folds were so isoclinal to be inconspicuous or the transition occurs beneath the surface (Fig. 2b). The colour bands and the foliation are close to being parallel throughout most of the exposed salt mass. Only where the porphyritic salt encounters abrupt changes in boundary conditions do the colour bands act as passive markers and fold around the stream lines indicated by the foliation (Talbot 1979).

The boundaries of the salt mass fall into two categories: those limited by rigid country rocks and those bounded by free air. The stream lines (flow foliations) of most previously described salt bodies are truncated upwards by an erosion surface. This is not the case at Kuh-e-Namak where Fig. 2 illustrates that the stream lines tend to parallel not only the rigid country rock boundaries but also the free boundaries of most of all the extrusive salt.

ACTIVE FOLDING OF THE COUNTRY ROCKS AND THE AGE OF THE NAMAKIERS

Remnants of an unsorted clastic deposit without any noticeable Hormuz components lie on the south namakier up to a height of about 300 m above sea level. A similar deposit lies up to about 365 m above sea level on the north namakier where it is dammed by a ridge of Asmari limestone. These deposits, only a few metres thick, are unbedded and consist of unsorted angular to sub-rounded clasts, up to a few centimetres in diameter and of at least three different types of fossiliferous limestone, supported by a fine grained calcareous matrix. These sediments contrast with the remainder of the insoluble material on the salt which are recognizably Hormuz in derivation. The exotic sediments are interpreted as the remnants of a formerly continuous cover of marine sediments which were deposited on the lower portions of both namakiers when they were below sea level and then jumbled as they settled because of the loss by solution of some of the underlying halite. It is noticeable that the remnants only survive on what are interpreted as inactive parts of the extrusive Hormuz salt.

Kent (1979) refers to a Bakhtyari conglomerate free of Hormuz debris on top of part of the Kamarj North salt plug 160 km north of Kuh-e-Namak (Dashti). He considered (1979, p. 138) that such conglomerates were deposited on a modern erosion plane cut across a dead intrusion emplaced before the Bakhtyari, probably in Miocene–Pliocene times. This may be so for the Kamarj North plug, but the present writers consider the exotic deposits on both namakiers at Kuh-e-Namak to be younger; indeed, they will be interpreted as contemporaneous with a sub-recent depositional surface recognizable over large parts of the area surrounding Kuh-e-Namak.

Only a tiny strip of this surface survives (up to a height of about 400 m above sea level) behind a protecting ridge of Asmari limestone east of the snout of the north namakier (see insert on Fig. 2b). What is assumed to be the same surface on the south side of Kuh-e-Namak towers above the distal feather edge of the south namakier and is bypassed by rivers currently draining off the salt. This surface extrapolates up to a height of close to 400 m above sea level on both namakiers where it is represented by the exotic deposits but is interrupted by the extrusive salt dome. However, the same surface can be recognized with few disturbances southwards from Kuh-e-Namak across a gentle syncline in the topography

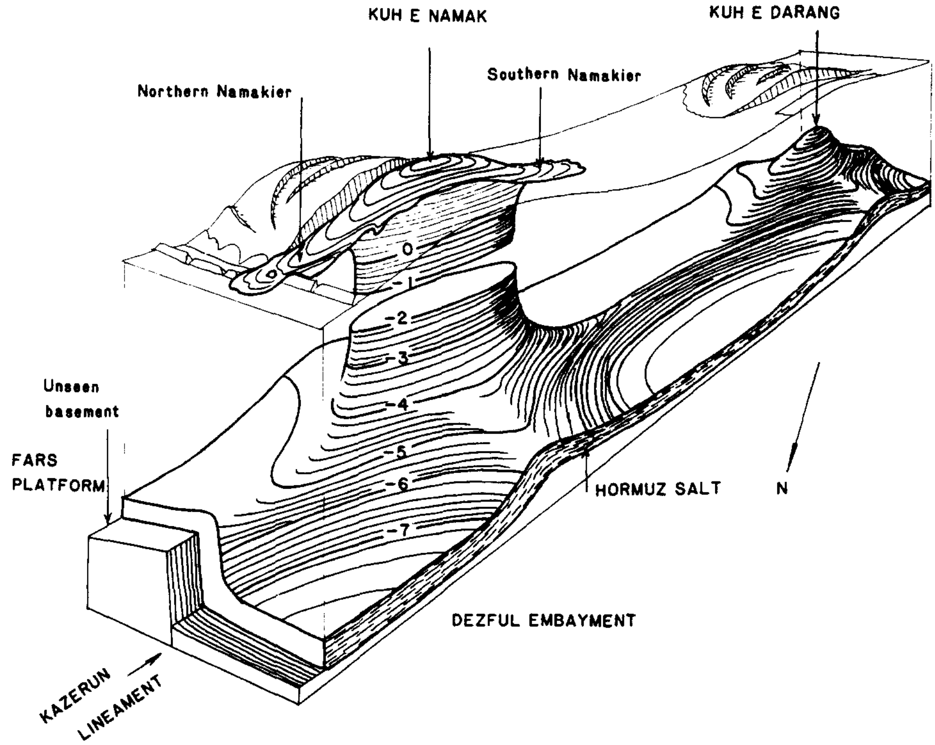

Fig. 3. Three-dimensional sketch of the salt bodies at Kuh-e-Namak and Kuh-e-Darang rising from the same salt pillow which developed at the southern end of the Kazerun lineament in Jurassic times. The recent surface mentioned in the caption to Fig. 2(b) and text can be seen to define an anticline through the rift across Kuh-e-Darang and a syncline between Kuh- e-Namak and Kuh-e-Darang.

to a smooth anticline which can be traced along a central rift through Kuh-e-Darang where it rises to 395 m above sea level (Fig. 3).

Vita-Finzi (1979) has dated the rise of similar recent surfaces and demonstrated that the next anticline inland of that through which Kuh-e-Namak rises is shortening between 14 and 18 mm a^{-1} where it meets the Gulf coast west of Banda Abbas. The rate at which this anticline has risen over the last 7000 years is spasmodic but averages between 1.4 and 1.9 mm a^{-1} using the eustatic factor of Flint (Vita-Finzi 1979). This is not as fast as the rate of rise of 7.4 mm a^{-1} calculated for folds east of Banda Abbas (Vita-Finzi 1979) or 12 mm a^{-1} for the Shaur anticline near the head of the Gulf (Lees & Falcon 1952). If the exotic deposits on the salt and what is interpreted as the contemporaneous depositional surface round about are taken as having formed near sea level, and if their maximum heights are attributed to uplift along Zagros anticlines at rates of between 1.4 and 12 mm a^{-1} then they are likely to be between 33,000 and 283,000 years old.

SALT BUDGET

Unlike a glacier, which is replenished with snow from above and loses ice by melting and ablation mainly in its lower reaches, a salt dome and any namakiers flowing from it are fed through a diapiric pipe from below and can lose salt by solution in rain falling on and draining off all exposed surfaces. On Kuh-e-Namak the topographic surface of the salt truncates former flow planes to an increasing degree from the dome down to the distal ends of both namakiers. However, minor refolding of the colour bands about axial surfaces parallel to the current free surface indicates that the direction of salt flowage can adapt to changes in its free boundaries which can only have been comparatively recent (see insert A on Fig. 2a).

We will approach the problem of the salt budget by attempting to calculate the volume of salt required to rise up the pipe to replenish the potential loss of salt by solution in the run-off of the rainfall. Both namakiers have been thicker and more extensive in the past than now but this analysis will assume that the current budget of supply and loss is approximately in balance.

All the extrusive salt is proud of its immediate surroundings so that all rain falling on it will be assumed to drain off it. The surface area of the exposed salt is huge because of the small-scale relief of the solution surface (pinnacles, fluting, etc.). However, because rainfall is measured in vertical cm we are interested in the area of salt in plan. The area of the salt dome (minus the flange along its ESE lip) is ~8.4 km^2. The area of the extrusive salt is about 23 km^2; that of the salt which is judged to be currently active about 20 km^2 (see later). The rainfall is confined to December and January and in 1945 was recorded as having a mean of 28 cm a^{-1} (Anon 1945).

At 25°C, 100 cc of pure water can dissolve 36 g of NaCl of density 2161 kg m^3. One cm of rain can therefore potentially dissolve 0.1667 cm of salt and the annual 28 cm rainfall on Kuh-e-Namak can dissolve a vertical thickness of 4.7 cm. The 100 m thick namakier could therefore potentially dissolve in 2150 years and the 1000 m high salt dome could disappear in 21,000 years if they were not replenished by more salt rising from below.

It will be assumed that the evaporation is low during the short rainy season and that all the falling rain runs off fully saturated with NaCl. The rain falling on the dome alone could then dissolve 39.2×10^{10} cm^3 of salt per year. To replace such a volume of salt requires a rise of salt of 4.6 cm a^{-1} averaged over the complete area of the orifice. However, such a calculation ignores the finding that a large volume of salt leaves the dome by flowing into the namakiers. It is therefore the area of all the active salt extrusives which is relevant.

The rain falling on all the exposed salt judged to be still flowing is $20 \times 10^{10} \times 28 = 560 \times 10^{10}$ cm^3. At 25°C this could dissolve approximately

$$\frac{560 \times 10^{10} \times 36}{2.161 \times 100} = 93.3 \times 10^{10} \text{ cm}^3 \text{ of NaCl.}$$

To replace this volume, the salt needs to rise out of the 8.4 km^2 (8.4×10^{10} cm^2) orifice at a rate of just over 11 cm a^{-1}.

This figure is an average for the complete area of the orifice and can be expected to be higher than average in the centre of the orifice and rather less at the margins. This figure is also likely to be a maximum for, although some rain undoubtedly evaporates while still on the salt, and, like the insoluble halite debris, some of the halite may be carried off as a solid load, it is unlikely that all of the actual run-off carries its full potential load of NaCl.

Even a rate of rise of 11 cm a^{-1} would mean that only 0.02% of the area of the extrusive salt dome in Fig. 2(b) is actually passing through the dome each year. Another way in which such a rate of rise can be put in perspective is to consider that a rainfall of 67 cm a^{-1} could dissolve the salt as fast as it rises (by this calculation). This implies that an emergent salt body as active as Kuh-e-Namak would be extrusive in most areas of the world.

THE DYNAMICS OF THE EXTRUSIVE SALT DOME

Another, independent, approach to the problem of how fast the salt extrudes from the orifice in the bedrock beneath Kuh-e-Namak is to consider the topography in terms of the fluid dynamics of the salt as a viscous fluid. If the extrusive column of salt is driven only by the weight of the more dense cover rocks resting on the source layer (e.g. Lees 1931, see also Gera 1972), then the height of the salt column (from source to summit) multiplied by its density (2200 kg m^{-3}) should equal the average density of the country rocks (2500–2600 kg m^{-3}) multiplied by their thickness.

Mapping, gravity, seismic and drilling surveys over the last few decades suggest that a stratigraphic thickness of at least 9 km of Phanerozoic sediments overlies the Hormuz salt in the Zagros fold belt as a whole and that the present cover to the salt round about Kuh-e-Namak is about 5000 m on the Fars platform and about 7000 m in the Dezful embayment (Kashfi written pers. comm. 1981). A salt column supported by a cover 5500 m thick could theoretically rise 2200 m above the surrounding plains while a cover 7000 m thick could extrude a salt column 2800 m high. Such calculations of the potential height of the summit are almost certainly underestimates because the still active folding of the country rocks is also likely to be pressurizing the salt and, in effect, driving it upwards.

In fact the summit of Kuh-e-Namak is just over 1600 m above sea level and about 1400 m above the surrounding plains. However, the splaying of the stream lines visible in the top free surface (which can be inferred from Fig. 2) demonstrates that the salt column at Kuh-e-Namak cannot support (and is spreading under) its own weight. The height of the dome is therefore not a simple measure of the forces expelling the salt from its vent. Nevertheless, we will use the height of the dome to approximate the rate of extrusion of the salt beneath it.

As Figs. 2 and 3 demonstrate that the vast majority of the salt leaves the dome in the NNW–SSE section (Fig. 2b), the extrusion dynamics will be treated in two dimensions. Ignoring, at this stage, the loss of salt at the surface by solution, the top free surface of the salt dome will be considered to be in a steady state and to owe its shape to the gravitational spread over a horizontal rigid surface of a viscous fluid rising out of a line source (aligned perpendicular to Fig. 2(b), see Fig. 4). We will neglect the inertial forces because the viscosity of salt is so high. The stream function ψ of a viscous fluid extruding vertically out of a narrow orifice in xy space has the form

$$\psi = \left(\frac{m}{\pi}\right)\left(\tan^{-1}\ \frac{y}{x}\ + \frac{xy}{(x^2+y^2)} - \frac{16}{3}\frac{x^2y}{a^3} + \frac{10}{3}\frac{x^3y}{a^4}\right) \tag{1}$$

where m is the mass/unit time/unit distance and a is the maximum height the fluid reaches above its orifice (i.e. x at $y = 0$).

At the top free surface $\psi = 0$, in which case

$$\tan^{-1} y/x + xy(x^2 + y^2) = \frac{16}{3}\frac{x^2y}{a^3} - \frac{10}{3}\frac{x^3y}{a^4} \tag{2}$$

and substituting

$$x = \Gamma \cos\theta, \qquad y = \Gamma \sin\theta \text{ in (2)}$$

we find

$$\theta + \sin\theta\cos\theta = \frac{16}{3}\frac{x^3}{a^3}\cdot\tan\theta - \frac{10}{3}\frac{x^4}{a^4}\tan\theta$$

and therefore

$$\frac{x^3}{a^3} - \frac{5}{8}\frac{x^4}{a^4} = \frac{3}{16}\cos\theta\left(\frac{\theta}{\sin\theta} + \cos\theta\right). \tag{3}$$

The left hand side of expression (3) $= f(\theta)$, is independent of the viscosity, and has been solved by iteration to yield Fig. 4(a). This is the non-dimensional shape of the top free surface of a viscous fluid extruding onto a

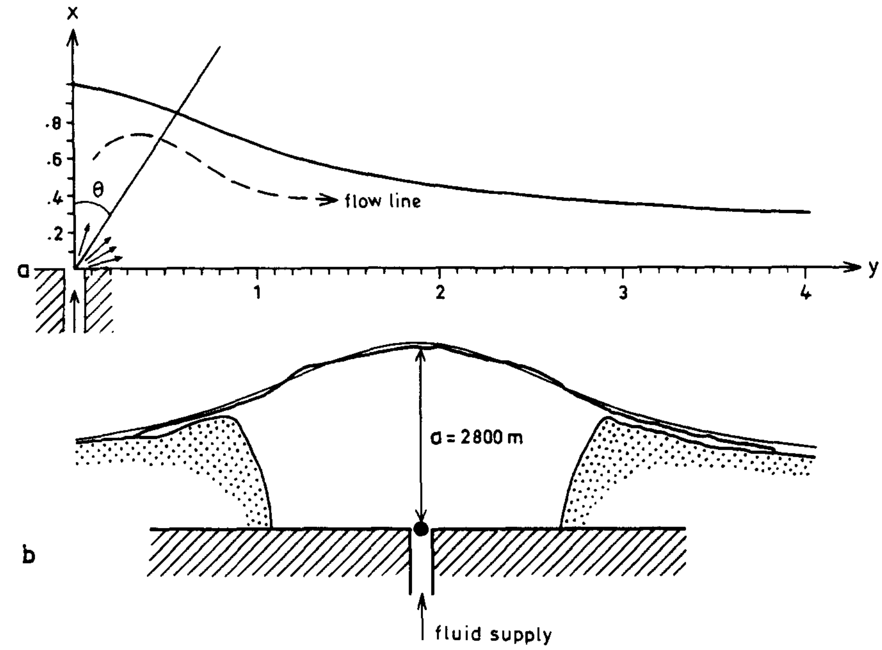

Fig. 4. (a) Shape of the top free surface (where the stream function, $\psi = 0$) of a viscous fluid extending out of a narrow linear orifice (an xz crack perpendicular to page) onto a plane yz (horizontal) surface. (b) The top free surface of the salt in longitudinal profile (Fig. 2b) scaled to fit the curve of (a) reflected about $y = 0$. Notice that 'a', the maximum height the free surface reaches above its line source (normal to the page and indicated by black dot) is 2800 m.

horizontal plane rigid surface through a narrow orifice.

Figure 4(b) illustrates a dimensionalized version of this curve superimposed on the longitudinal profile of Kuh-e-Namak and shows that the fit is good if the line source is considered to be 2800 m below the summit. This is the height 'a' expected if the salt column extruded because of the weight of the overburden acting on the source layer at depth and if it did not spread under its own weight. However, this fit is coincidental, particularly over the lengths of the namakiers, because the approach we have used is only designed to fit the top surface of the fluid extrusion closely near $y = 0$. The orifice at Kuh-e-Namak has finite width and the rigid boundaries over which the salt extrudes are neither plane nor horizontal. More important, Fig. 4(a) takes no account of the very substantial loss of the extruded salt in solution. Thus Fig. 4(a) shows significant thicknesses of viscous fluid large distances from the orifice along y whereas neither of the namakiers extend beyond 6 km from $y = 0$. However, the correspondence between the theoretical curve and the topography of Kuh-e-Namak emphasizes what the geology already suggests that, despite the considerable loss of salt by solution, the flow lines adapt to changes in the boundary conditions on a short time scale.

We know too little about the rate of salt flow in the dome to attempt to adapt the shape of Fig. 4(a) to take account the loss of 4.7 cm thickness of salt per year. Instead we notice by inspection of Fig. 2(b) that the geology suggests that 'a' is in fact about 1000 m.

In the appendix it is argued that, where $y = 0$, the mass flow/unit time/unit distance of a viscous fluid extruding from a narrow orifice, has the relationship

$$m = 3\pi \rho g a^3/112\mu$$

where ρ is the density, g the acceleration due to gravity and μ the viscosity. Substituting in (4) the following realistic values $\rho = 2200$ kg m^{-3}, $g = 9.81$ m s^{-2}, $a = 1000$ m and $\mu = 2.6 \times 10^{13}$ m^2 s^{-1} ($=2.6 \times 10^{17}$ poise for dry rock salt at NTP from Griggs 1929) we find

$$m \sim 0.07 \text{ kg s}^{-1} \text{ m}^{-1}.$$

We approximate the rate of extrusion $\dot{E}$ through an orifice 6000 m wide by $\dot{E} = m \times$ seconds in a year (3.16×10^7)/width of orifice $\times$ density $\simeq 17$ cm a^{-1}.

As in the earlier calculation for the rate of salt extrusion required to replace the potential loss of NaCl in solution, so the rate of extrusion calculated as necessary to account for the maximum height the salt reaches above its rigid orifice is averaged over the complete elliptical area of the orifice. Notice that our use of a narrow orifice is likely to be an underestimate for what is in fact extrusion through an orifice of significant width.

We have already estimated that, of the annual average of 17 cm of salt extruded through the orifice, 11 cm can be dissolved from its surface by the annual rainfall. If we take the value of $a = 2800$ m suggested by the best fit of the topography of the salt dome with our model of an extruding viscous fluid and remove from it 11/17 of its height,

$$2800 - \left(\frac{2800 \times 11}{17}\right) = 2800 - 1800 = 1000 \text{ m}$$

we find the actual value of 'a' suggested by the geology.

By taking note of the effect the solution of salt has on the maximum height that the salt reaches above its orifice in this simple manner we find that our budget of salt supply and loss is balanced.

THE SOUTHERN NAMAKIER AT KUH-E-NAMAK

About 2000 m long and 3500 m wide, the south namakier may exceed a thickness of 50 m in places. This sheet consists of almost pure white and pink halite and its former extent is marked by soil-free country rocks rather than the lateral and terminal moraines of the north namakier. Kent (1979) considers that this namakier may still be active and he may well be correct for salt periodically avalanches from a cliff backed by successive curling bergschrunds in the SE corner of the topographic dome. (This was the only area of routine avalanches encountered; elsewhere the salt movement was predominantly by dynamically recrystallizing flow.) However, the eroded relief of the south namakier is of the same order as its thickness, its distal margin has a feathered edge and five or six significant windows of country rock are visible in it (see Fig. 1); it is therefore considered relatively inactive compared to the north namakier.

THE NORTHERN NAMAKIER AT KUH-E-NAMAK

Down the length of both namakiers the fabric and texture of the salt undergo episodic but cumulative changes reflecting changes in the mechanisms of deformation at successive changes in the rigid boundary conditions (Talbot 1981). The sequence of changes is now abbreviated in the south namakier but is well represented down the length of the more active north namakier. This namakier is now 3000 m long, 2000–2500 m wide and different parts of the same ridge of Asmari limestone form a window in the lower part of the main salt stream and a dam to a triangular area of almost static salt on the western margin (Fig. 5 & Talbot 1979). This ridge is one of perhaps 15 buried scarp and dip slopes encountered by the salt as it flows down to the plains only 30–40 m above sea level.

Rather than eroding its bedrock channel the north namakier tends to partially fill in and smooth out irregularities in its bottom and side boundaries and shear over or past such static infills by sliding on the face-parallel plane of halite grains (Talbot 1981). Wherever the salt mass decelerates and thickens to surmount bedrock obstructions, the stream lines marked by the flow foliation diverge and become axial planar to trains of asymmetric folds which progressively tighten to flow up and over the obstruction (Talbot 1979). Each train of folds dramatically thins and repeats several times the colour bands inherited from upstream. Such folds are only obvious where they are generating for, in between obstructions, they are isoclinal and become very inconspicuous. Each bedrock obstruction is of course stationary and the moving salt picks up and then carries with it internal slides and folds generated at the obstruction.

All the halite of the dome is coarsely crystalline and clear and transparent. Diffusion processes, which probably characterize the salt flow at depth, appear to persist into the dome. However, dynamic recrystallization of tiny sub-grains around the grain boundaries within each zone of folding (or refolding) increases the proportion of fine grained translucent salt at the expense of porphyroclasts of transparent halite surviving from the dome. More and more of the salt assumes a mylonitic texture down the lengths of both namakiers until perhaps only 0.1% of the salt in the 30 m high snout of the north namakier, and perhaps 10% of the distal feather edge of the south namakier consist of clear porphyroclasts greater than 1 cm across.

As well as the internal banding being thinned and repeated, the colours of the namakier also intensify at every obstruction. This is partly due to the conversion of transparent coarse-grained halite to translucent fine-grained halite and partly due to the comminution and dispersion of insoluble entrained minerals. Progressive solution of halite down the length of the namakiers occurs but is considered to be a largely superficial phenomenon (resulting in surface moraine) rather than an internal process.

RECOGNITION OF BURIED NAMAKIERS

Buried namakiers are more likely to be associated with salt diapirs which have surfaced in arid climates (or saline seas) rather than those in temperate or tropical climates or less saline bodies of water. Where a namakier surmounts an obstacle in its path the colour bands and any grain shape or orientation foliation in it may be steep; however, along most of its length such features are likely to dip at low angles away from a steep feeder with a steep grain shape fabric.

The colour bands and any foliation may also be subhorizontal in a deeper source layer but a formerly extrusive namakier may be distinguishable from its source layer by the following differences:

(1) stratigraphic and structural levels,

(2) the colours are likely to be more intense in thinner bands,

(3) a higher proportion of insoluble components which are finer grained and more dispersed and

(4) the smaller grain size and porphyroclastic texture can be expected to survive annealing until quite deep burial.

Fossil namakiers may not spread from the top of a salt plug as the salt in the pipe (and even parts of the namakier) may rise further during subsequent dome-building. Spreads of insoluble Hormuz material deep in the stratigraphic succession close to salt diapirs in Iran could indicate the moraines of former (but dissolved) namakiers if they are not too reworked by superimposed fluvial or marine processes.

THE DYNAMICS OF A NAMAKIER

Measurements were made of movements along two lines of markers on the east flank of the north namakier

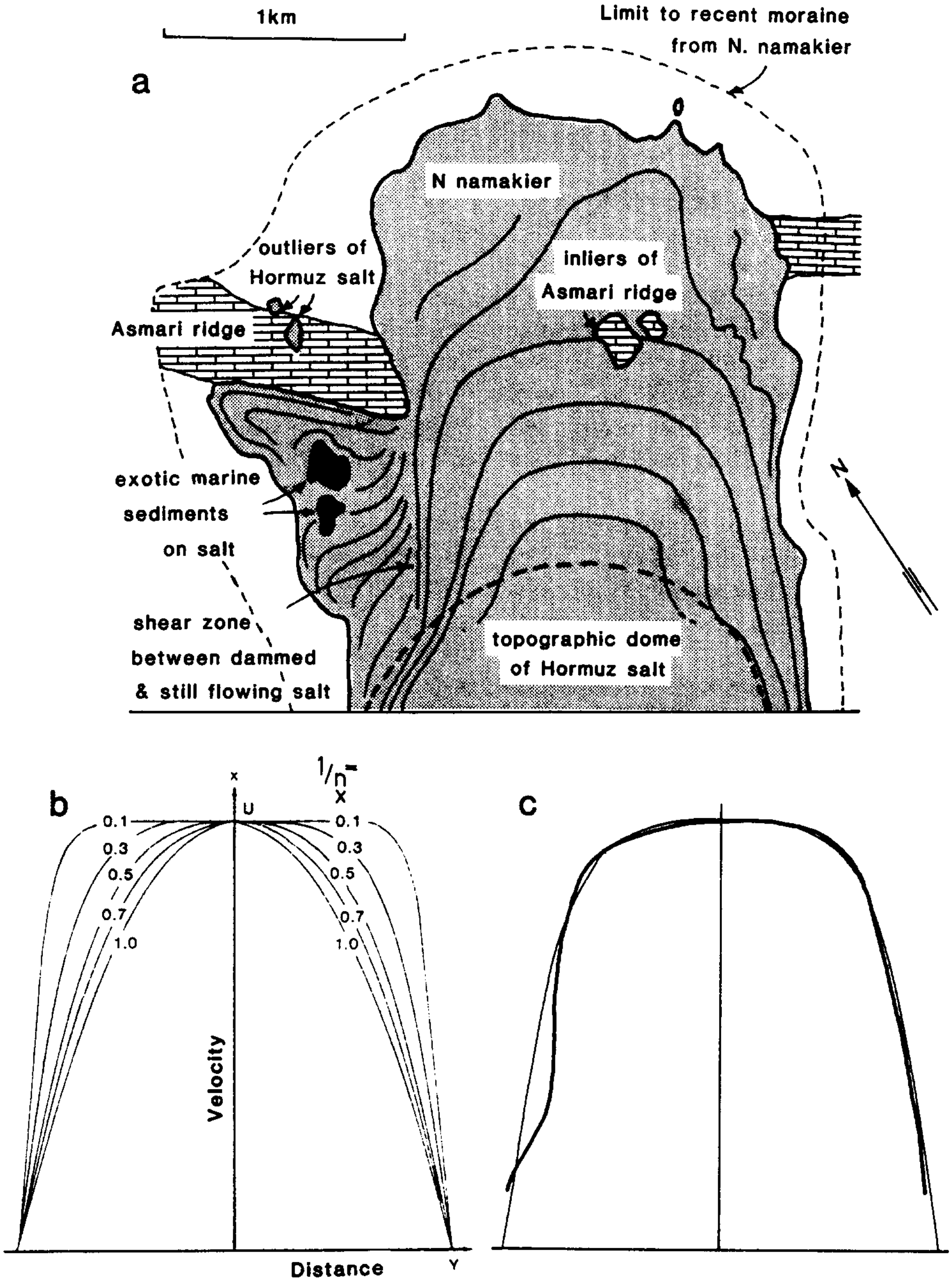

Fig. 5. (a) The outcrop of the colour bands on the top free surface of the N namakier are interpreted as recording the flow profile of a fluid flowing between two rigid walls upstream of the ridge of Asmari limestone. (b) Velocity profiles of Newtonian ($n = 1$) and strain-thickening fluids in a channel of width Y, U is the maximum velocity in the x direction. Labels on curves are $1/n$. (c) Superimposition of the colour band crossing the inliers of the Asmari ridge from (a) with the strain-thickening fluid profile with $n = 3$ from (b) suggesting that mylonitized rock salt flows over the surface with $n \sim 3$.

(see Fig. 1). When the extrusive salt was dry on the surface (as it is most of the year) the markers moved both up and downstream a few cms in a daily cycle with small movements occurring in immediate response to small temperature changes hundreds of metres away (Talbot & Rogers 1980). During most of the year the dry salt in the lower portions of the north namakier deforms as an elastic solid. However, within a day of a significant rain shower the salt softened and no longer transmitted thermal forces elastically. Instead some of the markers moved downstream at a rate of 0.5 m day^{-1}. The strain along both lines of markers was differential and persisted longer where a stream flowed over the surface. As the surface dried, the namakier shrank for four days and recovered parts of its advance. There can be little doubt that the wet salt flowed with an effective viscosity of about 10^{12} poises ($\sim 10^8$ m^2 s^{-1}) with a basal shear stress close to 2.5 kg cm^{-2} for about 5 days of the monitoring session (Talbot & Rogers 1980). If a large portion of the north namakier only flows when it is sufficiently damp then such flow is episodic and only likely for a few weeks each year.

A minimum estimate of the long term rate of flow of the north namakier is provided by the absence from the main stream of what is supposed to have been a continuous cover of marine sediments deposited an estimated 283,000–33,000 years ago. The highest remnants of this former cover survive 1730 m behind the present snout (Figs. 1 and 5a). The main stream needs only to have advanced at an average rate of between 6 mm a^{-1} and

5 cm a^{-1} to shed entirely any former superimposed marine cover.

Figures estimated earlier suggest a more likely, but very approximate, value for the average annual rate of flow of at least the upper reaches of the north namakier. Of the ~17 cm a^{-1} estimated to extrude out of the country rock orifice, ~5 cm a^{-1} are dissolved from the surface of the dome itself. This leaves ~12 cm a^{-1} to flow into the heads of two namakiers. As the flow of the north namakier is judged to be considerably more vigorous than that to the south, we will rather arbitrarily assume that ~10 cm a^{-1} of the extruded salt enters the upper reaches of the north namakier. As these have a cross-sectional area of $\sim 2.2 \times 10^5$ m^2, the average rate of flow of the salt entering the top of the north namakier is something like 2 m a^{-1}.

The scenario of a slow (continuous?) input of salt into the head of the north namakier with brief episodes of much faster flow punctuating long stationary periods further down its length can be reconciled by various lines of evidence.

Firstly, the bulk material properties of the salt mass can be inferred to change continually from the deep source, up the pipe, through the dome and in each of several fold generation zones down the length of the namakier to its snout. Any potential slowing of flow by the dispersion of entrained impurities (see e.g. Verrall *et al.* 1975, p. 11) must be outweighed by the decrease in the average grain size of the halite. This is illustrated by the change of deformation mechanisms and structures down the length of the namakier (Talbot 1981). The internal slides and then a crenulation fail to develop upstream of obstructions of much the same size. Eventually all internal folding ceases to develop and the (superplastic?) salt mass flows over the last few bedrock ridges without internal folding—a situation attributed to a lack of a significant proportion of halite porphyroclasts in the salt near the snout (Talbot 1979). These halite porphyroclasts demonstrate that the grain boundary diffusion in the dome is largely replaced in the namakier by dynamic recrystallization together with tensional separation and sliding along the face parallel planes of the halite grains.

The softening of halite by water has been known since 1908 as the Joffée effect (Odé 1968). The theory assumes that halite is inherently ductile but, by absorbing gases (e.g. ozone) from the atmosphere, becomes 'case hardened' so that intercrystalline flaws driven by strain cannot reach the poisoned surface unless they are wet. The Joffée effect was originally described in single crystals but also appears to hold for the north namakier at Kuh-e-Namak. Wenkert (1979), in the theoretical approach which so far comes closest to accounting for the behaviour of a namakier, attributes the flow of wet polycrystalline halite to the intercrystalline diffusion of ions down chemical gradients through an interstitial brine. However, a major difficulty remaining is to visualize how an elastic salt sheet 50–100 m thick can start flowing within a day (if not a few hours) of a few mm of rain falling on it (Talbot & Rogers 1980). Brittle fractures exist in the salt but are tightly closed during the day. Even though they open when the temperature drops, we have to imagine a few mm of rain softening a relatively large volume of salt surprisingly rapidly.

The outcrop of the colour and dirt bands on the top surface of the south namakier (Fig. 1) reflects its current relief rather than a flow pattern. The top free surface has been dissolved progressively deeper into the stream lines down the length of the north namakier but the arcuate outcrop of the bands can be treated in a manner analogous to studies of glaciers (Nye 1965, Paterson 1969).

The thickness of the north namakier is variable and unknown in detail but is probably between 50 and 100 m over most of its area. The half-width of the main salt stream is 1000 m. The ratio W (half-width divided by the thickness) is about 10–20, far higher than W for most valley glaciers which ranges between 1 and 4. Compared to most glaciers therefore the north namakier is almost infinitely wide although the current active salt sheet flow is confined laterally by parallel rigid walls (Fig. 1). Unlike valley glaciers in which the surface flow patterns are complicated by variations in thickness and the influence of the bottom boundary across their widths, the influence of the bottom boundary of the north namakier is expected to be more or less uniform across its width. The surface flow pattern is therefore only likely to be controlled significantly and consistently by the rigid sides.

In effect this means that the flow profile on the top surface of the namakier can be treated as though the salt were flowing between two walls. Figure 5(b) illustrates the flow profiles of fluids which obey different power laws flowing in such a channel (Coward 1980). For Newtonian fluids $n = 1$, $n > 1$ for dilatant or strain-thickening fluids like ice (or salt) and $n < 1$ for pseudoplastic fluids. A comparison between these curves and the shape of the colour bands cropping out on the surface of the north namakier (Fig. 5c) suggests that n for impure salt flowing over the surface is close to 3. This is at the lower end of the range determined experimentally for dry rock salt where $3 < n < 12$ (Tsianbaos 1978).

SUMMARY

The Hormuz salt at Kuh-e-Namak is known to have started rising in the Jurassic period and to have reached the surface by Cretaceous times, long before the current Zagros folding began. Whether salt extrusion was continuous from Cretaceous times to the present is unknown. However, the survival on both namakiers of what are interpreted as parts of a marine cover inferred to be between 33,000 and 283,000 years old implies that namakiers can survive beneath a thin but relatively impermeable cover for such intervals. The distortion of a depositional clastic surface interpreted to be of the same age close to Kuh-e-Namak up to a height of 365 m above sea level over the crest of the rising salt body beneath Kuh-e-Darang indicates that the local Zagros folding is still vigorous.

A commonly accepted figure for the rate of rise of the top surface of salt diapirs averaged over geological periods is about 2–4 mm a^{-1} although local spines have been known to rise 8–15 mm a^{-1} for brief intervals (Gera 1972, Kupfer 1976). Gera (1972) recognized that salt is likely to rise fastest when it has just disrupted the surface for then the pressure differential on the source layer due to the weight of the overburden is at its greatest value. At Kuh-e-Namak we have the additional factor that the salt beneath the orifice is pressurized to an unknown degree by active folding of the Phanerozoic cover. If it were rigid the extrusive salt column could theoretically rise to 2800 m above the surrounding plains even if the only driving force were the weight of the cover rocks. However, anticlines near Kuh-e-Namak are rising at rates of between 1.4 and 1.2 mm a^{-1} and such tectonic forces are likely to extrude a salt column of even greater height. Nevertheless, despite such potential, the summit of Kuh-e-Namak is only about 1600 m above sea level, 1400 m above the surrounding plains and 1000 m above its rigid rock orifice. This is because the extruding salt is dissolved from its surface and because the salt column spreads under its own weight as it rises. The height and shape of the longitudinal profile of the extrusive salt dome has been shown to be close to that expected if the extrusive salt deforms with a Newtonian viscosity of 2.6×10^{17} poise and rises up the elliptical pipe with an average velocity of almost 17 cm a^{-1}. About 11 cm of this extruded salt could be dissolved each year.

These rates of extrusion and solution are independent order-of-magnitude approximations based on simple models applied assuming that the extrusive salt dynamics are now at a steady state. Nonetheless they combine to suggest that, at 17 cm a^{-1}, the salt beneath the summit of Kuh-e-Namak is currently extruding 42–85 times faster than the generally accepted figure for the rate of rise of salt diapirs averaged over geological periods.

The mobility of the Hormuz salt sequence may decrease as it rises from depth because of a fall in temperature; although this effect may be outweighed by strain softening and (or) shear heating in such rapidly moving salt (Gera 1972). The supply of salt to the base of the dome is likely to be continuous and the salt volume is likely to take a long time to adjust to any changes in the mass balance of the dome; the flow of the north namakier is likely to have a much shorter response time and at least part of it is known to be episodic on a time scale of days and weeks. Furthermore, the seasonal nature of the mobility of the namakier can be inferred to intensify down its length. Thus the strain softening visible as a decrease in grain size down its length appears to overcome any poisoning effect of the entrained insoluble minerals. Such strain softening accounts for the change in deformation structures, mechanisms of flow, and measured or inferred flow velocities from the salt dome down the north namakier. The Hormuz salt is inferred to rise continuously up the pipe as a Newtonian fluid at an average rate of about 17 cm a^{-1} and to flow into the head of the north namakier at about 2 m a^{-1}, and yet temporary flows at 0.5 m day^{-1} have been measured along parts of its margins. Such a velocity, which probably implies flows at over a metre per day along the centre line of the namakier, raises the problem of how a substantial thickness of dirty mylonitized halite ($n \sim 3$) can be softened by small volumes of water in a matter of days if not hours.

Extrusive salt can be softened by rain or sea water and buried salt can be softened by groundwater or by water released by dehydration reactions (e.g. gypsum → anhydrite). The height of the summit of Kuh-e-Namak could be constant despite the throughput of salt beneath; just as the movements of a table tennis ball supported on a water fountain are no measure of the velocity of the water jet beneath. The buried top surface of pipe-like or tabular bodies of salt may not move much whereas the underlying salt could be convecting vigorously (Talbot 1980, Talbot *et al.* 1982).

A general understanding of salt deformation becomes increasingly significant as salt rock engineering grows more sophisticated. Not only are mined and solution cavities in salt becoming larger and deeper but their uses are multiplying. Engineering on, in or near salt bodies which are either as active as Kuh-e-Namak, or could become as active in the life of the engineered facility, could have difficulties if the potential dynamics of the salt mass are not fully appreciated.

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APPENDIX

The flow of a viscous, incompressible fluid issuing from a long straight crack in a horizontal plane boundary

We choose axes $0xyz$ with $0x$ vertically upwards and such that the plane boundary is given by $x = 0$ and the crack by $x = y = 0$. Figures 4(a) & (b) in the main text illustrate the orientation of these axes in relation to the longitudinal profile of the salt mass.

We assume that the flow is that due to a line source of strength m per unit length along the crack, that it is two-dimensional, and that the effects of inertia are negligible. The vertical and horizontal components of velocity may then be found from $u = \partial\psi/\partial y$, $v = -\partial\psi/\partial x$, where the stream-function ψ satisfies Stokes's equations

$$\mu \frac{\partial}{\partial y}(\nabla^2\psi) = \frac{\partial p}{\partial x} + \rho g,$$

$$\mu \frac{\partial}{\partial x}(\nabla^2\psi) = -\frac{\partial p}{\partial y}.$$

Here $\nabla^2\psi = \partial^2\psi/\partial x^2 + \partial^2\psi/\partial y^2$, μ is the viscosity and ρ the density of the fluid, p is the excess of the pressure in the fluid above atmospheric pressure and g is the gravitational acceleration.

The boundary conditions to be satisfied are that $u = v = 0$ on $x = 0$ and that the upper surface of the fluid, which may be taken to be the streamline $\psi = 0$, should be stress free. This zero-stress condition leads to the equations

$$p \cos 2\theta = 2\mu \frac{\partial^2\psi}{\partial x\,\partial y},$$

$$p \sin 2\theta = \mu\left(\frac{\partial^2\psi}{\partial y^2} - \frac{\partial^2\psi}{\partial x^2}\right),$$

where θ is the downward inclination of the surface to the horizontal, to be satisfied on $\psi = 0$. In addition the symmetry of the flow requires that $\psi(x, -y) = -\psi(x, y)$.

It is convenient to rewrite the equations in non-dimensional form by setting $x = ax'$, $y = ay'$, $\psi = (m/\pi)\psi'$, $p = (\mu m/\pi a^2)p'$, where a is the maximum height of the free surface, which is attained on $y = 0$. Then on dropping the primes we obtain

$$\frac{\partial}{\partial y}(\nabla^2\psi) = \frac{\partial p}{\partial x} + \lambda,$$

$$\frac{\partial}{\partial x}(\nabla^2\psi) = -\frac{\partial p}{\partial y}, \qquad \text{(A1)}$$

where $\lambda = \pi\rho g a^3/\mu m$, with the zero-stress conditions

$$p \cos 2\theta = 2\frac{\partial^2\psi}{\partial x\,\partial y}, \qquad \text{(A2)}$$

$$p \sin 2\theta = \frac{\partial^2\psi}{\partial y^2} - \frac{\partial^2\psi}{\partial x^2}, \qquad \text{(A3)}$$

to be satisfied on the free surface.

The general solution of equations (A1) which also satisfies the boundary conditions on $x = 0$ may be written

$$\psi = \tan^{-1}\frac{y}{x} + \frac{xy}{x^2 + y^2} + \sum_{n=0}^{\infty}\frac{(-1)^n(n+1)x^{2n+2}}{(2n+2)!}f^{(2n)}(y) + \sum_{n=0}^{\infty}\frac{(-1)^n(n+1)x^{2n+3}}{(2n+3)!}g^{(2n)}(y), \qquad \text{(A5)}$$

$$p = k - \lambda x + \frac{2(x^2 - y^2)}{(x^2 + y^2)^2} + \sum_{n=0}^{\infty}\frac{(-1)^n x^{2n+1}}{(2n+1)!}f^{(2n+1)}(y) - G(y) + \sum_{n=0}^{\infty}\frac{(-1)^n x^{2n+2}}{(2n+2)!}g^{(2n+1)}(y), \qquad \text{(A6)}$$

where f and g are arbitrary functions, $G(y) = \int_0^y g(z)\,dz$, $f^{(r)}$ denotes the rth derivative of f, and k is a constant.

The exact determination of the functions f and g is not possible due to the non-linearity of (2) and (3), but assuming the curvature of the free surface is small we may obtain an approximate solution as follows.

When the curvature of the free surface is small f and g may be approximated by $f(y) = Ay$, $g(y) = By$, the terms omitted being of order y^3, and the free surface may be approximated by $x = h(y) = 1 - \alpha y^2$. On expanding the condition $\psi(h(y), y) = 0$ in powers of y and equating to zero the coefficients of y and y^3 we obtain

$$\frac{1}{2}A + \frac{1}{6}B + 2 = 0,$$

$$\alpha A + \frac{1}{2}\alpha B - 2\alpha + \frac{4}{3} = 0,$$

whence

$$A = -16 + \frac{8}{3\alpha}, \quad B = 36 - \frac{8}{\alpha}.$$

Similarly expanding p, $\cos 2\theta$, and $\partial^2\psi/\partial x\partial y$ on $x = h(y)$ in powers of y and equating constants and coefficients of y^2 in (A2) we obtain

$$k - \lambda + 4 - \frac{4}{3\alpha} = -\frac{8}{3\alpha},$$

$$\alpha\lambda - 16\alpha - \frac{56}{3} + \frac{4}{\alpha} = \frac{104}{3}(1 - 2\alpha),$$

whence

$$\lambda = \frac{160}{3}\left(\frac{1}{\alpha} - 1\right) - \frac{4}{\alpha^2},$$

$$k = -\frac{172}{3} + \frac{156}{3\alpha} - \frac{4}{\alpha^2}.$$

Likewise equating coefficients of y in (3) we find $\alpha = \frac{1}{2}$.

Thus $A = -32/3$, $B = 20$, $\lambda = 112/3$ and $k = 92/3$.

It follows that the maximum height a and the mass flux m are related approximately by

$$\frac{\pi\rho g a^3}{\mu m} = \frac{112}{3}$$

which gives

$$m = \frac{3\pi\rho g a^3}{112\mu} = 0.084\rho g a^3/\mu.$$