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Karst and caves within the salt domes of Iran.

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Abstract: The salt domes of southern Iran are mountains of pure salt kilometres across formed at the outcrop of deep seated salt diapirs. Namakdan and Hormoz are two domes that support some of the most spectacular landscapes of doline karst eroded into the salt. Beneath the surface, caves contain long passages and some large chambers, all decorated with beautiful displays of salt stalactites.

Keywords: salt karst, salt cave, salt stalactite, salt dome, Iran.

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INTRODUCTION

Beneath most of the Persian Gulf region, the kilometre-thick bed of Hormoz Salt lies at depths of 4 to 10km, but it has also been mobilized into diapirs that intrude its cover rocks and reach the surface in more that 200 salt domes (Kent, 1970, 1979; Bosak et al, 1998; Waltham, 2008). In the desert climates of the region, with about 170mm of annual rainfall in the coastal regions (though rising to about 500mm in the High Zagros Mountains), the salt survives at outcrop. The 130 salt domes in the southern Zagros are eroded into some of the world's finest salt karst landscapes (Fig.1), and they also contain the world's longest and largest caves in salt.

Compared to nearly all other rocks, common salt (or halite) is extremely soft and mobile, so it will flow as diapirs that intrude through other rocks on a scale only matched by molten magma in igneous intrusions. The driving force behind diapirs is the positive buoyancy of salt because its density is so much lower than that of other lithified rocks. At depths of 5km or more, the huge overburden pressure is enough to squeeze the salt into any weakness in the same overburden rocks. The movement commonly starts with some fault displacements, but once established a diapir can push its way up through any cover of much stronger sedimentary rocks (Fig.2). Many of the Zagros salt diapirs rise through anticlines of the cover rocks, to emerge on the crests or flanks of the steep anticlinal mountains of Tertiary limestones and sandstones for which the Zagros are justly famous. The diapirism process is slow, but over millions of years diapirs can rise through kilometres of cover. Once the salt breaches the surface, it is less constrained, and intrusion rates increase to typically 5mm/year.

SALT DOMES

When the rate of diapiric uplift exceeds the mean rate of dissolutional loss beneath soil cover in the desert regimes, the salt can rise to form domes that stand hundreds of metres above the surrounding countryside. Most of the domes are 1 to 10km across, so they form substantial topographical features that are a hallmark of Iran's southern Zagros Mountains (Fig.3). The great domed mountains have bare outcrops of white salt that gleam in the sunlight, but much of their surfaces are masked by red soils. The main caprock soil, generally some metres thick, is a residuum of the insoluble components from within the original salt beds. This is dominated by clays and silts, but commonly contains up to 50% gypsum, which locally forms slightly hardened crusts of gypcrete. The red colour is derived from up to 15% iron oxides, mainly in the form of earthy haematite. Also included within the caprocks are blocks and rafts (with some that exceed a kilometre across) of various rock types that include material from the diapir walls entrained within the salt. The cover rocks are commonly upturned around the edges of the domes, with some remnants extending up onto the salt outcrops.

__Figure 1__. Doline karst with a thin soil cover, broken by steep slopes of bare salt, on the Namakdan dome on Qeshm Island.

__Figure 2__. Almost vertical banding within the salt, with some flow folding on the right, exposed in the roof of Fatima Cave on Hormoz Island.

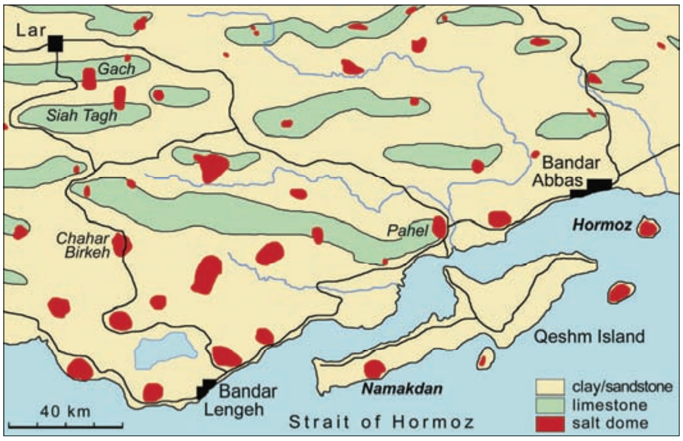

***Figure 3**. Outline geology of the coastal Zagros Mountains around Bandar Abbas, with names on the salt domes referred to in the text.*

The existence of these mountains of salt requires that their underlying diapirs are still rising. Typical uplift rates for those in the Zagros are 2 to 6mm/year, though some appear to be growing at up to 15mm/year. The best records come from dated shell beds that have been uplifted to exposures in inclined marine terraces around the coastal diapirs of Hormoz and Namakdan (Bruthans *et al.*, 2006a). These show that both rising diapirs are still doming as they are extruded onto the surface. Mean rates through the Holocene for the Hormoz dome are 2mm/year at its margin, at least 6mm/year towards its interior, and by interpolation even higher at its centre.

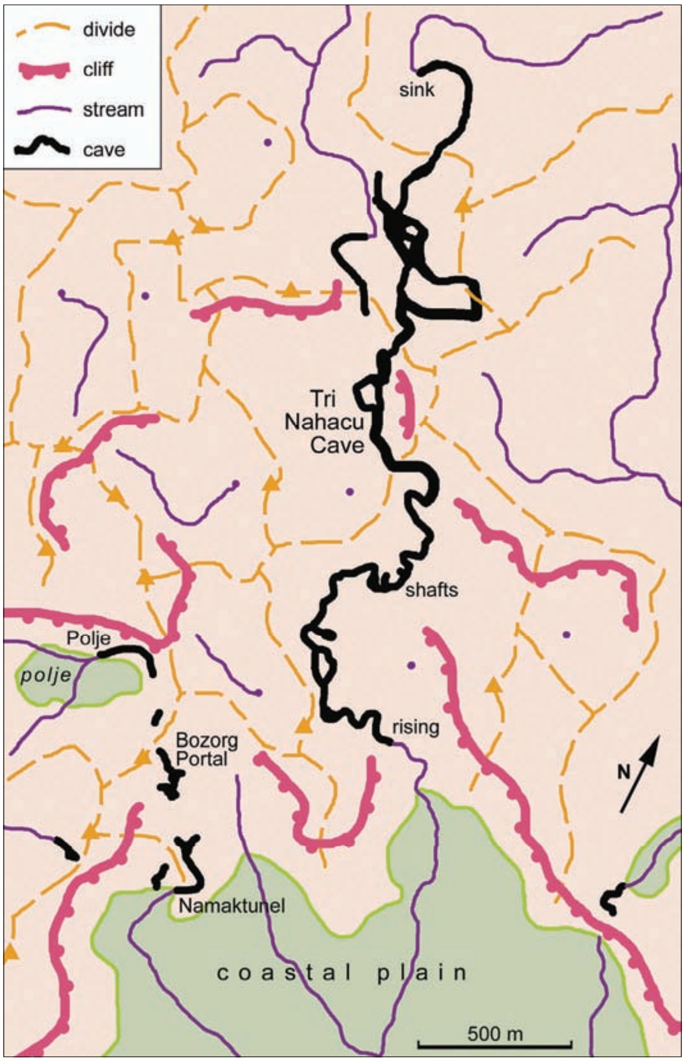

***Figure 4**. Features of the karst geomorphology in the eastern sector of the Namakdan salt dome (after cave maps by Bruthans and colleagues). The topographical divides define the large-scale polygonal karst; most of the streams are normally dry channels; only the larger cliff lines are marked; the sediments of the poljes and coastal plain overlie the salt.*

***Figure 5**. Doline karst near the northern margin of the Hormoz salt dome.*

It is not surprising that the topographical features of the salt domes are determined by the relationships between their current uplift rates and their erosion rates. When these are close to equilibrium, the diapirs develop substantial salt domes, with extensive salt outcrops that are eroded into karst landscapes with caves beneath.

Where diapiric uplift has ceased, or is far slower than surface dissolution of the salt, the outcrop appears as a ruined dome, with an overall profile that is almost level or is a shallow cauldron created by loss of the salt though long-term dissolution. Chahar Birkeh is a ruined dome, marked by chaotic local relief of less than 100m, in the form of irregular mounds and steep-sided depressions all within the thick residual soil. The depressions are effectively dolines that appear to have been created by both suffosion into the underlying salt and also by collapse of the bedrock salt.

In contrast, diapiric uplift that far exceeds surface erosion provides an excess of salt that becomes unstable as a high dome, and therefore flows away as a salt glacier (Talbot, 1998). With morphologies somewhere between ice glaciers and lava flows, salt glaciers are extruded from rising salt domes, to simply flow at mean rates of a few metres per year down into an adjacent synclinal valley. They can reach lengths of 5km or more, with widths typically of a few kilometres between steep margins more than 100m high. The

***Figure 6**. Vertical shaft in the Namkadan salt dome.*

***Figure** 7. The northern part of the Hormoz salt dome, looking down into the polje crossed by the salt-crusted streambed that drains into Fatima Cave (which lies beneath the camera position).*

salt glaciers of Gach and Siah Tagh, near Lar, are fine examples. Their surfaces are mantled by thick residual soil that is carved into badland topography of steep gullies and sharp ridges with little exposed salt. Dolines are recognisable on some glaciers, and small streams emerge from the toes of some, but karst landforms are subordinate to those produced by the glacier movement. Significant caves are not known, and are not likely to be accessible, in active salt glaciers.

SALT KARST

Even in the deserts of Iran there is enough rainfall to create spectacular karst topography on the highly soluble salt. Karst landforms are best developed on the stable salt domes, and are especially splendid on the coastal salt domes of Namakdan and Hormoz, where they have been well documented by teams of Czech geologists led by Pavel Bosak (1999). Both have only modest thicknesses of residual soil over relatively stable bedrock salt, with the rather thicker soil on Namakdan providing catchments for ephemeral streams that drain into the larger caves.

The net effect of dome denudation is to create spectacular doline karst. At the kilometre scale this is polygonal, with networks of interfluves around closed depressions that each drain into a central sinkhole or cave (Fig.4). Etched into the polygonal relief are thousands of closely packed dolines, each 5 to 30m across. Many of these lie in areas of only thin soil cover, whereas others are formed partly or largely within the red caprock soils, but they all reach downwards into open or choked sinks within bedrock salt. They form extremely jagged, and clearly unstable, terrain on parts of both the Namakdan and Hormoz domes (Fig.5). Though these look like areas of thick soil cover (and there are very limited exposures of salt), satellite imagery reveals well-defined banding that traces the near-vertical bedding in the banded salt, so much of the doline relief does appear to be carved into the bedrock salt.

Rapid dissolution of the underlying salt creates areas of spectacular instability where the soils are actively collapsing into open voids. An area of sloping ground between Namaktunel and Bozorg Portal Cave is riddled with open shafts in bedrock salt, and also steep-sided dolines with slumping walls, between patches of crumbling soil that are clearly failing into underlying caves; just walking across this land is distinctly exciting. There are numerous vertical shafts on the Namakdan dome (Fig.6), of which just a few reach down into the Tri Nahacu Cave.

Thicker caprock soils within some of the larger depressions are carved into short valley systems with ephemeral streams that end at sinks. On both Namakdan and Hormoz, a few closed basins have flat floors on thick sediments, giving them the profiles of classical karst poljes. The analogy may be drawn further, as one on Namakdan drains into Polje Cave, and one on Hormoz has open cave passages draining both into it and out of it (Fig.7). Development of their flat floors and steep marginal slopes has probably been aided by a close match between the rate of dissolutional lowering of their sub-soil salt floors and the rate of diapiric uplift, both of which can be a little under 5mm/year. The stream course across the Hormoz polje is one of many fed by resurgence caves that appear as streaks of white across the landscape; as the brine from the caves is fully saturated, it has deposited thick crusts of sparkling white salt crystals due to evaporational losses along the open channels exposed to the desert air (Fig.8).

Exposed surfaces of bedrock salt are deeply fretted into excellent rillenkarren, with very sharp crests and pinnacles between small rounded runnels (Fig.9). Repeated measurements against plastic plugs inserted by the Czech researchers have shown that these form rapidly (Bruthans *et al*., 2008). Mean surface lowering on the bare salt is about 40mm/year on the coastal domes of Namakdan and Hormoz. Rates increase significantly on more gentle slopes, and vertical faces of exposed salt are generally smooth and polished without any karren runnels. Surface erosion rates are also higher on the inland salt domes that receive greater rainfalls. These rates exceed the theoretical maximum, whereby the mean annual rainfall of 170mm can dissolve about 28mm of salt; this appears to be due to the monitored surfaces gathering extra run-off from adjacent areas of caprock soils.

Dome landscapes with a few metres of soil cover record only about 3mm/year of mean surface lowering; but it is unclear how much of this is due to soil erosion, and how much is due to dissolution at the rockhead. Exposures of the rockhead reveal varying degrees of fissuring to depths of some metres, in places leaving remnant pinnacles of similar height (Fig.10). Salt cliffs retreat rapidly due to dissolution by sheetflow during rain events, but the main marginal cliffs around Hormoz and Namakdan were undercut by wave action before uplift that now leaves them overlooking marine terraces.

SALT CAVES

Across the world, caves in salt are a rarity. They are known in Israel, Chile, Romania and some other countries, but the largest and longest yet found lie within the more stable salt domes of Iran, notably Namakdan and Hormoz. These caves have all been explored and mapped during eight very productive expeditions by the Czech geologists and cavers (Bosak *et al*., 1999; Bruthans *et al*., 2002), and the same teams are now finding major new caves in other domes within the Zagros. Their major discovery to date has been Tri Nahacu Cave. Its name is Czech for Three Naked Men, and it is also known as 3N Cave now that the main passages explored in from the

***Figure** 8. Crusts of white salt along the channel of the brine stream that resurges from Fatima Cave on the Hormoz salt dome.*

Figure 9. *Rillenkarren on bedrock salt on the Namakdan dome.*

resurgence have been connected to the principal sink. Namakdan means Salt Cellar in Farsi, a variant on the Kuh-e Namak (meaning Mountain of Salt) that is applied to so many of the larger Zagros salt domes.

Tri Nahacu Cave

This is now the world's longest cave in salt (Bruthans *et al*., 2006b). It has more than 6km of passages, many of them more than 5m high and wide, reaching between a sink and a resurgence that lie 2km apart in the Namakdan salt dome. Even though Tri Nahacu appears to be almost entirely of Holocene origin, the rapid salt dissolution has already allowed it to evolve to an almost perfectly graded profile; it descends steeply from the sink, but then is only a very gentle gradient right through to its resurgence (Fig.11). The original drainage route through the salt followed a phreatic switchback profile of up-loops and down-loops. Uplift of the dome then allowed the water table to decline to a gentle gradient behind a new resurgence, and the cave has graded to this. Trenches were incised through the up-loops, but their eroded floors are now mostly buried by sediment. The roofs of the still-flooded down-loops were rapidly dissolved, while the floors were buried beneath accumulating clastic sediments, so that the passage migrated up to the water table (Fig.12). This classic style of paragenesis was enhanced by the variable density of the brine. Saturated brine has a significantly higher density, so that it sinks to the floor where it is incapable of further dissolution, while lighter, unsaturated water rises to the top and directs maximum dissolutional effect right at the water table.

Figure 10. *Salt rockhead fissured along fracture lines and exposed above the resurgence exit of Fatima Cave on Hormoz Island.*

Figure 11. *Gently graded streamway in Tri Nahacu Cave, with salt crusts over a sediment floor (photo: John Middleton).*

The maximisation of dissolution at the water table has created wide erosional slots beneath flat roofs. Many parts of the passage are now up to 50m wide. Unfortunately, silt and clay sediments have accumulated on the cave floors up to levels generally less than a metre below the roof (Fig.13). This has left a height of open passage that is in equilibrium with the sporadic floods that sweep through the cave with flows of some cubic metres per second following brief winter storms of intense rainfall; base flow through the cave is only a few litres per second. A trip in through the Tri Nahacu resurgence therefore requires an excess of uncomfortable crawling, mostly in shallow water over floors of soft silt or spiky salt crystals (the sink entrance is frequently choked with gravel, so the Czech cavers preferred to use the shaft entrances midway along the passage, though these have their own difficulties in establishing secure belay points).

Respite from the crawlways of Tri Nahacu is offered in the original up-loops, which now form splendid sections of larger passages and chambers. In the upstream part of the cave, an early stage of development had a perched water table dammed behind an up-loop. This left some galleries with wide flat ceilings about 4m above a cave floor that was subsequently entrenched after the up-loop was removed. Both these and some other sections of clean phreatic roof are notable for their beautiful sections cut through the flow structures within the salt's banding, which stands close to vertical within the diapirs (Fig.14).

Most of the larger chambers in Tri Nahacu and the other Namakdan caves have been modified by collapse (Fig.15). Some have broken roof profiles left by normal block collapse. Others have

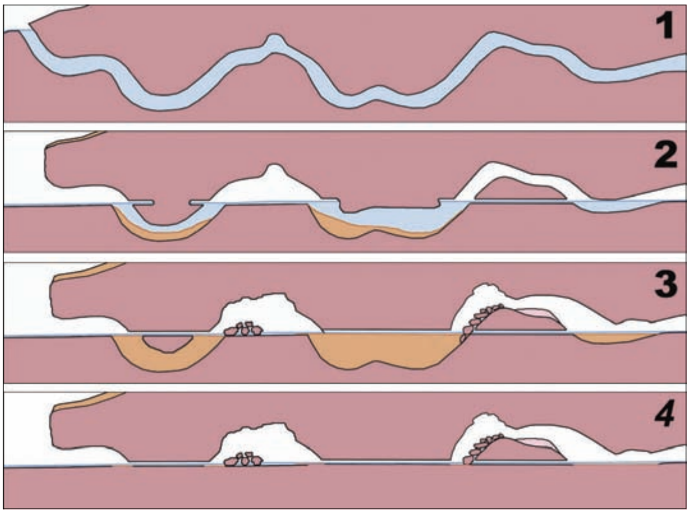

Figure 12. *Paragenetic development with excessive dissolution at the water table in the style of the passages in Tri Nahacu Cave.* ***1****: initial phreatic drain.* ***2****: dissolution concentrated at the level of a new water table.* ***3****: graded profile achieved at the new water table, with some modification by roof collapse.* ***4****: how the cave appears with alternating high and low sections over unseen sediment fills in original down-loops.*

***Figure 13**. Approach to a low section in the main Tri Nahacu streamway (photo: John Middleton).*

***Figure 15**. The entrance chamber, modified by roof breakdown that is still active, in Bozorg Portal Cave in the Namakdan salt dome.*

smooth arched profiles created by granular disintegration of the coarsely crystalline salt. Within Tri Nahacu, the Hangar is a 35m-long side chamber that has a near-perfect arched profile across its 20m span. Its floor is loose salt gravel that was fed by a rain of grains breaking away from the tension zone within an originally flatter roof, until stability was achieved by the compression arch that forms the present profile. Sadly, no camera has yet survived the journey by the few groups that have visited this spectacular chamber.

Other caves in Namakdan and Hormoz

With its large open entrance near the Namakdan coast road, Namaktunel Cave is a fragment of large passage well known to visitors to Qeshm Island (Fig.16). Its spacious tunnel was once well decorated with salt stalactites, but these have now all been destroyed. The tunnel leads to a very low crawl (over an original down-loop) before ending in a large chamber containing its own mountain of salt gravel. Many other caves have been found by the Czechs in the Namakdan dome (Bosak *et al*., 1999). Most notable are a series in from Namaktunel that appear to represent fragments of a major passage now dissected and truncated by surface erosion. At their upper end, Polje Cave still takes the drainage from a wide alluviated basin (Fig.17).

With or without their own streams, all these salt caves are still very active. Most notably, large blocks of bedrock salt fall from their ceilings at a frequency far greater than is typical of cave roof failures in limestone. Collapses at the exposed entrances are ever likely to be more frequent than in the less weathered environment of the caves' interiors. In the few years since the first Czech explorations, a large new entrance has been created by a major cliff failure over the eastern entrance to Polje Cave, and large block failures have modified both the sink and resurgence entrances to Tri Nahacu.

***Figure 14**. Large gallery in Tri Nahacu Cave with steeply inclined banding of the salt exposed along a phreatic roof (photo: Marek Audy and Richard Bouda).*

Among the caves in the Hormoz dome, Fatima Cave carries the drainage out of the deep polje near the north coast. Its mainly low and wide galleries occupy at least two levels, with chambers and crawlways that are smaller versions of the Tri Nahacu passages. It also has more exposed vadose features, with some sections of meandering canyon, and small cascades over bedrock steps.

The caves of both Namakdan and Hormoz are remarkable for their abundance of beautiful, pure white, salt decorations. Dominant are thick stalactites up to 4m long (Fig.18). Most of them are curved, because they formed as lattices of salt crystals that could grow away from the vertical, before gathering overgrowths that gave them their smoother final profiles. Others remain as just skeletal frames of crystals, whose jagged profiles are more reminiscent of the gypsum chandeliers known in some limestone caves (Fig.19). The Namakdan caves contain clusters of long straw stalactites. These are remarkable for their overgrowths of tiny helictites that twist away in all directions, again the product of randomly orientated crystal growth (Fig.20). It is assumed that they are also of salt, but they mimic the delicate growths of epsomite known elsewhere, and their composition has not been confirmed by analysis.

Cave floors that are not just loose mud and silt are veneered with crusts of sharp salt crystals or small popcorn growths that have formed in pools retained behind gour barriers just a few centimetres

***Figure 16**. Entrance to Namaktunel Cave.*

Figure 17. *The main passage in Polje Cave, in the Namakdan salt dome, modified by roof collapse just inside its eastern entrance.*

high. These are very similar to the deposits that line the beds of the brine streams out in daylight. Fatima Cave, on Hormoz, is notable for some deeper pools within the bedrock canyons; where these have partly drained out, they are lined with sparkling salt cubes each up to a centimetre across.

These snow-white deposits of crystalline salt make some passages in the Zagros salt caves exceptionally beautiful. They are an added bonus to the suite of splendid surface karst features and magnificent caves that mark the salt domes of Iran as very special geological terrains.

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Figure 18. *Typical thick curved salt stalactite in one of the smaller Namakdan caves.*

Figure 19. *Small chandeliers of salt crystals growing from the roof of Fatima Cave, Hormoz.*

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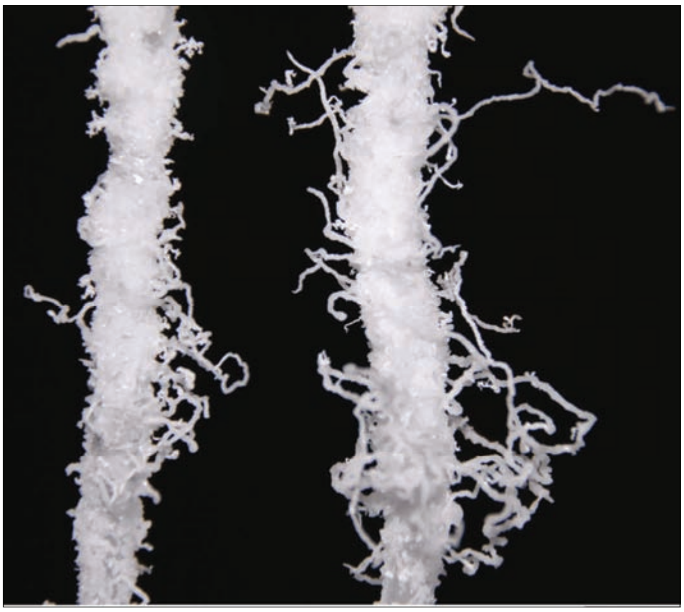

Figure 20. *Helictites on salt straws in one of the smaller Namakdan caves.*