

Feature



Salt terrains of Iran

Salt only survives at outcrop in desert climates, and southern Iran has more than its share of salt mountains created by rising diapirs. With their white salt cliffs and creeping salt glaciers, these constitute amazing landscapes with collapsing dolines that feed into spectacularly decorated caves.

Most of the Persian Gulf region is underlain by the Hormoz Salt. This lies at depths of 4–10 km, and has no outcrop within its stratigraphic sequence, but has been mobilized into diapirs that intrude its cover rocks and reach the surface in more than 200 salt domes. In the desert climates of the region, with about 170 mm of annual rainfall in the coastal regions (though rising to about 500 mm in the high Zagros Mountains), salt survives at outcrop on the rising diapirs. The southern mountains of Iran have the world's most extensive and most spectacular salt terrains.

Originally the Hormoz Salt was more than a kilometre thick, with red banding created by the 2–10 per cent of insolubles within the pure white halite. It formed two major units separated by a suite of volcanics that are now seen as rafts, some over a kilometre across, within the salt domes. The same rafts include shales with Cambrian trilobites that date the sequence. Beds of anhydrite and sylvite are also preserved in some of the domes.

Covering the Hormoz Salt are three units of rock, each of which is more than 2000 m thick. Carbo-Permian clastics are followed by limestones that dominate the succession from Jurassic to Palaeogene, including the 250-m thick Asmari Limestone, the major oil reservoir rock, near the top. These are followed by the Palaeogene and Neogene Fars Series, with salt and gypsum within its mixed clastic sequence. There is very little disconformity throughout the entire sequence, as it rests on the stable Arabian platform of Precambrian rocks. But all these earlier rocks were folded during the Miocene Zagros orogenesis, and were followed by deposition of thick conglomerates and then finer clastics, of the Pliocene Bakhtiari sequence.

Through all of these rise the diapiric intrusions of Hormoz Salt. Remnants of the cover survive on some of the salt domes and around some upturned edges, but the main cap-rock on the salt is an insoluble residuum generally some metres thick. This clay-rich

soil commonly contains up to 50 per cent gypsum, which locally forms slightly hardened crusts of gypcrete, along with up to 15 per cent iron oxides that give it a dark red colour.

Salt diapirs

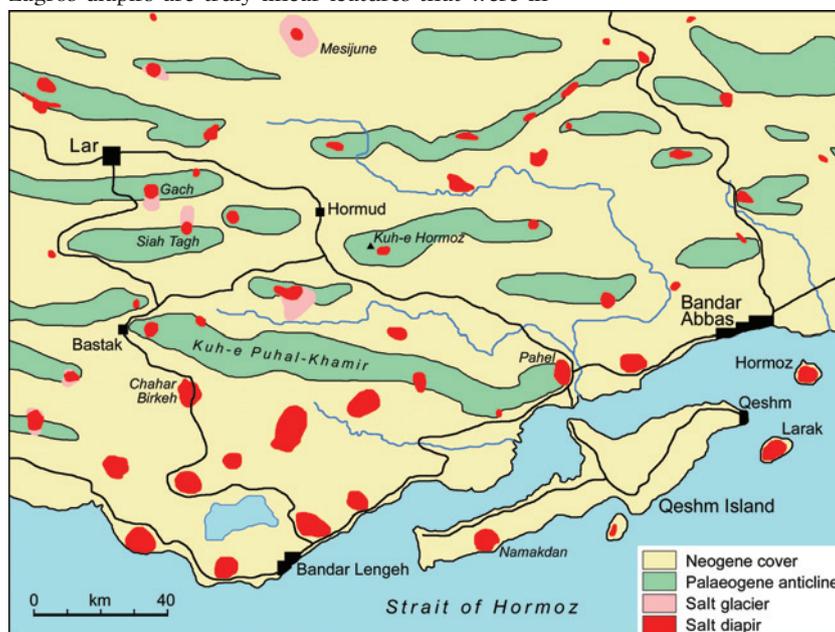
Whether known as diapirs, plugs or domes, these huge intrusions of salt—and their evolution into extrusive features—are a hallmark of Iran's southern Zagros Mountains (Fig. 1). There are more than 130 of them within the Zagros, and many reveal themselves as great domed mountains of white salt, gleaming in the sunlight except where capped with red soils (Fig. 2).

Exposed salt domes in the Zagros are 1–15 km across at outcrop. Some are almost perfectly circular, but less than 3 km in diameter, while most are elongate to some degree. Less than a quarter of the Zagros diapirs are truly linear features that were in-

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Fig. 1. Outline geology of the coastal Zagros Mountains close to Bandar Abbas.





truded along faults. A common name for the salt domes is *Kuh-e-Namak*, meaning 'Mountain of Salt' in Farsi, and one such near Bushehr rises 1300 m above the surrounding plateau. The salt retains the banding that was in its original bedding, except that it is drawn out into thinner bands, which are turned to vertical through most of each diapir.

Fig. 2. The Pahel salt dome is a classic of its kind, standing 300 m above the coastal plain inland from Qeshm Island.



Fig. 3. An anticlinal mountain near Hormud has the huge slabs of arched limestone that are characteristic of the Zagros.

The growth of diapirs is only possible from salt beds that are more than about 100 m thick, as it relies on plastic flow driven largely by differential overburden pressures within the salt. Rough trends of alignment among the Zagros diapirs suggest that many of them are located over basement faults. Vertical displacements on these are indicated by the many inclusions and rafts within the salt diapirs, of basement rocks (including granite and gabbro) that appear to have broken from fault zones before becoming entrained in the flowing salt. Uneven thicknesses of the incompetent salt then develop into anticlinal bulges known as pillows that are many kilometres across.

Further upward movement of the salt is driven by gravity. Crystalline salt maintains a constant density (about 2200 kg/m³) while overburden clastic sediments densify through burial (towards values of about 2500 kg/m³). When the cover exceeds about 1000 m, there is enough positive buoyancy within the salt to dome it further, though diapirism appear only to develop fully when the sedimentary cover exceeds about 3000 m. In the Zagros region, salt pillows developed in the Jurassic, and diapirism was driven by the increasing overburden pressure largely in and after the Cretaceous.

Most of the Zagros salt diapirs rise through anti-

clines within the cover rocks, either on their crest lines or on their flanks. These include many of the spectacular anticlinal mountains, for which the Zagros is famed, with their steep arches of Palaeogene and Cretaceous limestones (Fig. 3). Diapirs in anticlines with limestone at outcrop are indicated on the geological map (Fig. 1), and most of the diapirs in the coastal zone rise through further parallel anticlines that have only the younger Fars Series at outcrop. Rather than the anticlines guiding the diapirs, it appears that the contrary may apply; the salt pillows and initiation of the diapirs preceded the main orogenesis. The crumpling of the cover rocks may then have developed anticlines from gentle structures domed over the rising salt, and in turn may have allowed easier and more rapid diapiric intrusion through the fractured anticlines. Some diapirs pierced the surface in the late Cretaceous, as indicated by Hormoz rock debris within some of the adjacent Palaeogene cover, but others were later, as they intrude sequences right up into the Neogene.

Though most salt diapirs stand essentially close to vertical, there is some variation in their subsurface profiles. Borehole and geophysical investigations (mainly of diapirs with oil reservoirs in the upturned periphery of their host beds) have shown that many flare out as they approach the surface due to reduced confining stresses at shallower depths. The degree of flaring, sometimes described as a mushroom structure, appears limited in the Zagros diapirs where underground exposures in natural caves reveal banding that stands close to vertical near the diapir margins (but eases to low dips across their centres). The same

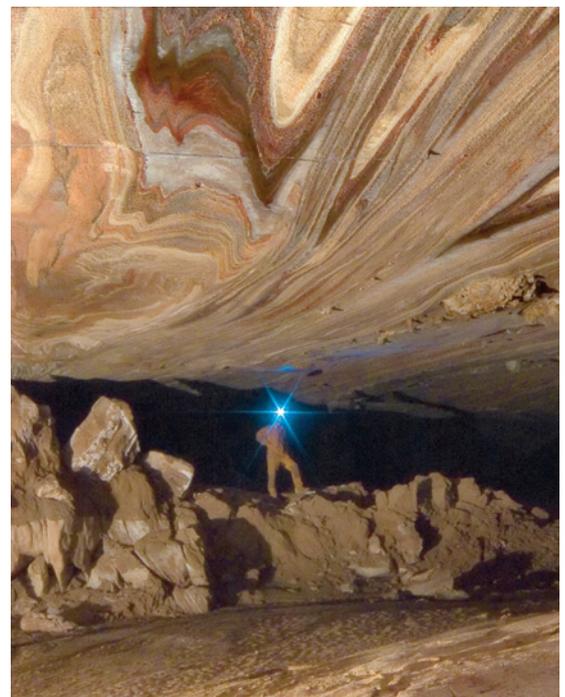


Fig. 4. A wide flat roof in a cave exposes spectacular flow folding in the banded salt that forms the Namakdan diapir. (Photo: Marek Audy and Richard Bouda.)

exposures show some spectacular folding developed by fluid flow within the rising salt (Fig. 4).

Debris within the salt is a feature of most diapirs, but that which forms the island of Hormoz (Fig. 1) is distinguished by large rafts of rhyolitic volcanic rocks that now form residual hills across the island's salt terrain. Hormoz also contains huge amounts of red, earthy hematite of syngenetic origin; this has been mined in the past, and there are still some millions of tonnes of reserves. Scattered over the surface of the Hormoz salt dome are crystals centimetres across of shiny, lamellar specularite, which appear to indicate elevated temperatures in circulating fluids during diapiric growth. All this insoluble debris accumulates on the surface of the salt domes to form the cap-rock soils some metres thick (Fig. 5).

Salt domes

The primary form of an extruded salt diapir is the salt dome that is so characteristic of the Zagros landscapes. To create such a mountain of salt requires that its diapir is still rising. Typical uplift rates for those in the Zagros are 2–6 mm/year, though some appear to be growing at up to 15 mm/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. They show that both these rising diapirs are still doming as they are extruded onto the surface. Mean rates through the Holocene for the Hormoz dome are 2 mm/year at its margin, at least 6 mm/year towards its interior, and by interpolation even higher at its centre.

These movement rates are for diapirs that have breached their cover and are now exposed as salt domes. Stratigraphical records indicate that rates of diapir intrusion, prior to extrusion at the surface, are orders of magnitude slower. Salt diapirs in Saudi Arabia rose more than 10 km during the late Mesozoic at mean rates of 0.1 mm/year, and salt pillows beneath Britain's North Sea appear to grow at rates of about 0.04 mm/year. Intrusion rates are lower than tectonic uplift rates of the Zagros anticlines, which are currently rising at just over 1 mm/year.

It is only reasonable that morphologies of the exposed 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, as at Namakdan on Qeshm Island (Fig. 1). Where diapiric uplift has ceased or is far slower than surface dissolution of the salt, the outcrop appears as a ruined dome, as at Chahar Birkeh, with a profile that is almost level or is a shallow cauldron with chaotic local relief created by subsidence of the thick residual soil. In contrast, uplift that

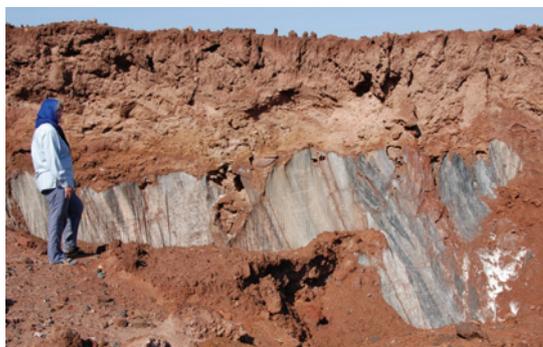


Fig. 5. Nearly 2 m of red residual soils overlie a corroded rockhead in bedrock salt exposed on the Hormoz dome.



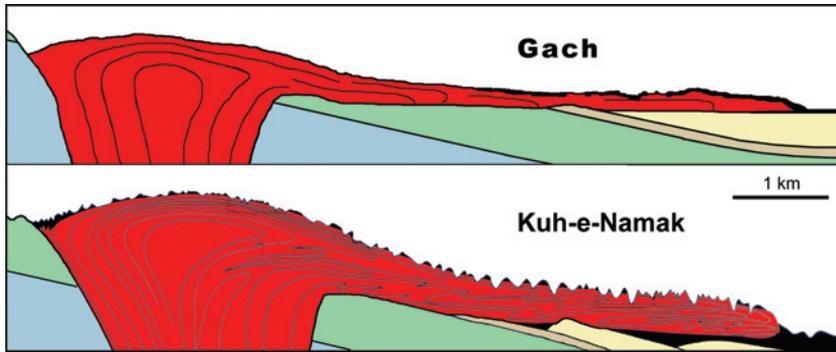
Fig. 6. Oblique satellite image of the Gar and Siah Tagh salt glaciers; cultivated field appear red, and the salt appears black in this false-colour image. (Photo: NASA)

far exceeds surface erosion provides an excess of salt that is unstable as a high dome and therefore flows away as a salt glacier, as at Gach and Siah Tagh (Fig. 1) among others.

Salt glaciers

With morphologies somewhere between ice glaciers and lava flows, salt glaciers are fascinating manifestations of geological processes. Salt extruded into a rising salt dome simply flows away, very slowly, most commonly down into an adjacent synclinal valley. Ridged and fissured, and covered by residual soils, the salt glaciers look like their moraine-covered cousins that spread onto the floors of alpine valleys. There are more than 20 diapirs that have extruded as large 'salt glaciers' within the Zagros, including six in the area around Bandar Abbas (Fig. 1).

Salt glaciers have morphologies comparable to those of some obsidian lava flows that were extruded just short distances from rising domes, although the salt is on lower overall gradients (Fig. 6). Each glacier advances in a tank-track motion, rolling over itself as the salt is deformed into recumbent folds; analogies are drawn with alpine nappe systems (Fig. 7). Unlike in an ice glacier, there is no basal shear, and a better comparison is drawn with an aa lava flow



with its hot core advancing over cooled rubble. A salt glacier can have the full width of its source dome, may extend to lengths of 5–10 km where topography permits uninterrupted flow, and can even over-ride minor escarpments.

The adjacent salt glaciers of Gach and Siah Tagh are classics of their type (Fig. 8). The Siah Tagh glacier is the more active of the two, with a steeper profile that drives a train of salt nearly 3 km wide for 5 km out across the valley floor from its source dome on the edge of a limestone anticline. It maintains steep flank walls along its length, and stands around 150 m high at its front end (Fig. 9). There, its surface is mantled by thick residual soil that is carved into a badland topography of steep gullies and sharp ridges with little exposed salt. Small streams emerge from its toe.

In contrast, the Gach glacier flows from a slightly larger dome, but appears to be significantly less active (Fig. 10). It spreads out more across the valley floor, and is rather thinner, though how much of its thickness lies buried beneath the valley fill is unknown (Fig. 7). Its entire surface is masked by thick residuum, which is raised into arcuate compression ridges at the front end of the glacier. Behind these, the surface is slightly depressed, suggesting that it has been lowered by dissolution of the salt at a rate faster than its re-supply from the dome. The toe of the Gach glacier is cut into by an ephemeral surface river, but no salt is exposed beneath the residual soil, and there are no emerging streams.

Flow rates have been estimated and measured on salt glaciers around Bushehr (far to the west of Bandar Abbas) by Chris Talbot and colleagues from Uppsala and Shiraz universities. Mean flow rate appears to be around 2 m/year, though old maps indicate that the front of the Kuh-e-Jahani salt glacier has advanced about 200 m within 25 years. Short-term movements were measured on a separate glacier nearby—which moved a few centimetres both up and down on a daily basis due to thermal expansion. On hot days there was an audible cracking of the salt glacier, mainly in the evening when it was cooling down under tension. Superimposed on this elastic flow was an irreversible

Fig. 7. Profiles along two salt glaciers. The profile of Gach (near Lar) is drawn from photographs, and Kuh-e-Namak is a generalized profile by Chris Talbot of a glacier near Bushehr.

down-slope movement of nearly a metre in just two days after a period of heavy rain. This was plastic flow, with minimal recovery as the salt dried out. It is likely that most salt glaciers move in comparable short bursts after winter rainstorms, and move very little through the long dry summers. This rapid flow showed how water pressure greatly reduces the viscosity of the salt within the glacier, and is further evidence that salt diapirism does not require high temperatures for effective intrusion through kilometres of cover rocks.

Salt glaciers do come larger and smaller than those at Gach and Siah Tagh. The Mesijune diapir is completely ringed by radiating glaciers, so that it looks like a spreading ice cap and has the overall profile of a wide-brimmed mushroom. At the opposite end of the size range, the Pahel diapir is one of many with small glaciers created where salt flows from stable domes down minor valleys cut into the surrounding country rocks.

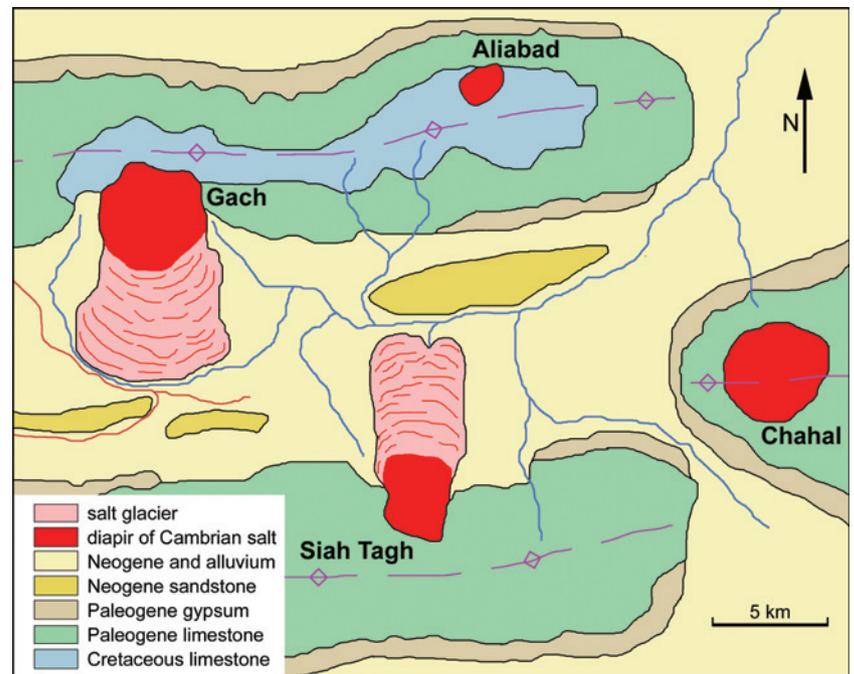


Fig. 8. Geological map of the four salt domes southeast of Lar, including the salt glaciers of Gach and Siah Tagh.

Fig. 9. High on the toe of the Siah Tagh salt glacier, with residual soils over the entire surface, though the small white patches in the centre of the view are crusts of salt deposited beneath springs and seepages of brine. The Chahal salt dome stands on the horizon.





Fig. 10. The Gach salt glacier, with its wasted central section across the valley floor beneath its high source dome; as seen from the Siah Tagh glacier.

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 (Fig. 11), where they have been well documented by Czech geologists led by Pavel Bosak. Both have only



modest thicknesses of residual soil over relatively stable bedrock salt, with the rather thicker soil of the Namakdan dome providing catchments for ephemeral streams that drain into the larger caves.

While the vertical faces of exposed salt are generally smooth and polished, inclined outcrop surfaces are deeply fretted into rillenkarren. These have very sharp crests and pinnacles between rounded runnels that are a centimetre or so wide (Fig. 12). These form rapidly. Repeated measurements against plastic plugs inserted by the Czech researchers show mean surface lowering of about 40 mm/year on the coastal domes, although the rate increases on more gentle slopes and also on the inland domes with greater rainfall. These rates exceed the theoretical maximum, whereby the mean annual rainfall of 170 mm can dissolve about 28 mm of salt, and this appears to be due to the monitored surfaces gathering extra run-off from adjacent cap-rock soils. Areas with a few metres of soil cover record only about 3 mm/year of mean surface lowering; part of this is due to soil erosion, while part is due to rockhead dissolution. Exposures of the rockhead reveal varying degrees of deep fissuring between modest remnant pinnacles (Fig. 5). Salt cliffs retreat

Fig. 11. On the Hormoz salt dome, cliffs of bare salt descend towards a polje floor that is crossed by a streak of white salt crusts in the channel of a brine stream flowing from one cave to another.

Fig. 12. Sharp edged rillenkarren cut into a block of salt on the Namakdan dome.

Fig. 13. The chaotic relief of closely packed dolines carved into both the residual soil and the bedrock salt on the Namakdan dome.

rapidly due to dissolution by sheetflow during rain events, but the main marginal cliffs around Hormoz and Namakdan were undercut by wave action before the uplift that now leaves them overlooking marine terraces.

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. Etched into the polygonal relief are thousands of closely packed dolines, each 5–30 m across. Most of these are partly or largely formed within the red cap-rock soils, but they reach downwards into open shafts or choked sinks within bedrock salt (Fig. 13). Rapid dissolution of the underlying salt creates areas of spectacular instability where the soils are actively collapsing into open voids on a scale that makes just walking across the land distinctly exciting. Thicker cap-rock soils within some of the larger depressions are carved into short valley systems that end at



Fig. 14. White salt crystals form crusts beside a permanently active channel, stained red by iron oxides, of a tiny brine stream emerging from the toe of the Siah Tagh salt glacier; the widest part of the red channel is about 300 mm across.



Fig. 15. A part of the main passage in the Tri Nahacu Cave, with a brine stream flowing over thick sediments beneath an arched roof that is the original profile created beneath a past level of the water table. (Photo: John Middleton)



sinkholes. On both Namakdan and Hormoz, a few closed basins have flat floors on thick sediments, and streams flowing in and out of the caves give them the appearance of karst poljes. All stream courses that emerge from caves appear as streaks of white across the landscape, where the brine has deposited thick crusts of sparkling white salt crystals (Fig. 14).

On the ruined domes, there is only buried karst, with a chaotic relief of depressions and pinnacles in the thick residual soils undermined by dissolutional loss of the salt. Similarly, there is only restricted karst on the rising domes with their salt glaciers. Salt pinnacles are reported from the upper parts of some glaciers, but these may be true dissolutional features (some are protected by summit boulders) or they may be left between tensional fissures in the style of ice seracs. Thicker soil masks any karst in the lower parts of glaciers, though streams emerging from the toe of the Siah Tagh glacier indicate the presence of karstic drainage.

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, where they have been documented by the Czech geologists.

The Tri Nahacu Cave has more than 6 km of pas-

sages, many of them more than 5 m high and wide, reaching between a sink and a resurgence that lie 2 km apart in the Namakdan salt dome. Although the cave is 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 has only a very gentle gradient right through to its resurgence (Fig. 15). The original drainage route through the salt followed a switchback profile of loops up and down, all beneath the water table. Uplift of the dome then allowed the water table to decline to a gentle gradient behind a new resurgence, and the cave graded to this. The roof of the still-flooded down-loops was rapidly dissolved, while the floor was protected beneath dense saturated brine and was buried beneath clastic sediments, so that the passage migrated up to the water table. Maximum dissolution was at the water table, so the cave widened there beneath a flat roof. Many parts of the passage are now up to 50 m wide, and silt and clay sediments have accumulated on their floors to a level less than a metre below the roof. This leaves a height of open passage in equilibrium with the sporadic winter floods that sweep through the cave.

A trip into Tri Nahacu therefore requires an excess of uncomfortable crawling. Respite is offered in the original up-loops, which now form the sections of larger passages and chambers. An early stage of a perched water table has left some galleries with wide flat ceilings about 4 m above the cave floor, and these reveal beautiful sections through the fold structures within the salt diapir (Fig. 4). Other chambers in Tri Nahacu, and in adjacent caves, have been modified by collapse. Some have broken roof profiles left by



Fig. 16. Twisted salt stalactites in one of the smaller caves in the Namakdan dome.



Fig. 17. A cave passage within the Namakdan dome with a profusion of salt crystals and stalactites growing down from its ceiling.



block collapse, but others have smooth arched profiles created by granular disintegration of the coarsely crystalline salt. These salt caves are still very active, and large blocks of bedrock salt fall from their ceilings at a frequency far greater than the very rare cave roof failures in limestone. Caves in the Hormoz dome also have low wide galleries at multiple levels, with canyon passages linking them, but these are smaller than the passages in Namakdan.

The caves of both Namakdan and Hormoz are also remarkable for their abundance of beautiful, pure white, salt decorations. Dominant are thick stalactites up to 4 m long (Fig. 16). 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, with jagged profiles more reminiscent of the gypsum chandeliers known in some limestone caves (Fig. 17). The Namakdan caves contain clusters of long thin straw stalactites, also made of salt, each with a diameter little more than that of a drinking straw. These are remarkable for their overgrowths of tiny helictites that twist away in all directions, again the product of randomly orientated crystal growth (Fig. 18).

Fig. 18. Tiny helictites of salt growing out from a straw stalactite (itself only about 5 mm in diameter and also made of salt) that hangs from the roof of a cave in the Namakdan dome.

Beneath all these stalactites, the cave floors that are not just loose mud and silt are lined with salt crystals and miniature rimstone dams deposited by the saturated brine streams. These are very similar to the deposits that line the beds of the brine streams out in daylight. All these snow-white deposits of crystalline salt are exceptionally beautiful, and the decorated caves beneath the ground complement the spectacular surface landforms to place the salt domes of Iran among the more unusual geological terrains in the world.

Suggestions for further reading

- Bosak, P., Bruthans, J., Filippi, M., Svoboda, T. & Smid, J., 1999. Karst and caves in salt diapirs, S E Zagros Mountains, Iran. *Acta Carsologica*, v.28, pp.41–75.
- Bosak, P., Jaros, J., Spudil, J., Sulovsky, P. & Vaclavek, V., 1998. Salt plugs in the eastern Zagros, Iran: results of regional geological reconnaissance. *Geo-Lines* (Praha), v.7, pp.3–174.
- Bruthans, J., Filippi, M., Gersl, M., Zare, M., Mekova, J., Pazdur, A. & Bosak, P., 2006. Holocene marine terraces on two salt diapirs in the Persian Gulf, Iran: age, depositional history and uplift rates. *Journal of Quaternary Science*, v.21, pp.843–857.
- Edgell, H.S., 1996. Salt tectonics in the Persian Gulf basin. *Geological Society of London Special Publication*, n.100, pp.129–151.
- Kent, P.E., 1970. The salt plugs of the Persian Gulf region. *Transactions of the Leicester Literary and Philosophical Society*, v.64, pp.56–88.
- Talbot, C.J., 1998. Extrusions of Hormuz salt in Iran. *Geological Society of London Special Publication*, n.143, pp.315–334.
- Talbot, C.J. & Jarvis, R.J., 1984. Age, budget and dynamics of an active salt extrusion in Iran. *Journal of Structural Geology*, v.6, pp.521–533.
- Talbot, C.J. & Rogers, E.A., 1980. Seasonal movements in a salt glacier in Iran. *Science*, v.208, pp.395–397.