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The enigma of inclusions in the Persian salt domes: Discussion

By CHRISTOPHER J. TALBOT and ROBERTO F. WEINBERG [1])

Professor Gansser is to be congratulated on a beautiful set of observations many of which are still unique despite being over 40 years old. These observations are relevant, not only to understanding how the Zagros front is actively deforming the coast of Iran, but also to the engineering activities in progress along that coast. Gansser's enigmatic inclusions seem to be disappearing into the construction of new harbours faster than geologists can study them. It would be ironic if engineers remove the geological evidence that their new constructions will disappear under the gulf (or rise into the sky) in the next few decades. The city of Bushir NW along this same coast is already awash due to its depression by the advance of one of the most active thrust-anticlines in the Zagros.

Professor Gansser reminds us of a long-recognised enigma (e.g. Kent 1979): of how large inclusions of contemporaneous sediments or volcanics come to be at the surface in diapirs of two different salt sequences in Iran. However, he introduces a new element when he worries about the orientation of the inclusions as well as their mass.

If he can quote three 1990 references in support, then Professor Gansser is obviously correct in claiming that diapiric salt movement is "generally assumed to be highly complex". However, he is not justified in arguing that the concentric structures obvious in many salt domes necessarily imply complicated intrusion mechanisms. This is because such concentric structures can be due to circulation within the diapir driven by viscous drag of country rocks of similar strain rate sinking around it (Jackson & Talbot 1989). Such circulation results in the initial salt stratigraphy developing a mushroom shape; this is a drastic simplification behind the complicated structural details of many salt diapirs. Gansser claims that observations of "normal" upright inclusions conformable within the salt are incompatible with them having mushroom shapes (Jackson et al. 1990). Here we discuss that claim before commenting on the main enigma.

Gansser's challenge to the simplification represented by the concept of mushroom-shaped diapirs is based on arguments that are the precise opposite of those used in the first challenge (Kupfer 1989, answered in Talbot & Jackson 1989). That challenge was based on the supposed *absence* of gentle dips in salt diapirs of the US Gulf coast and the generality that the only inclusions in those structures are *younger* than the enclosing salt. Ironically, the problem concerning salt in the Gulf of Mexico has recently changed to that of accounting for huge bodies of gently dipping allochthonous salt (Talbot 1990, 1992).

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In December 1990, CT was with Professor Gansser in the parties which visited the Larak dome of Hormuz salt in the Zagros (Gansser 1992, Figs. 4 and 4 A) and dome 22 of Eocene salt in the great Kavir (Gansser 1992, Figs. 14 and 15). CT can therefore attest to the veracity and beauty of Ganssers' field sketches. CT can also confirm that all the inclusions *visited* are still upright in normal (younging-upwards) positions conformable within gently dipping layering in the diapiric salt. Not only does the bedding of the salt dip gently, so does a foliation that is mylonitic with porphyroclasts in Larak, gneissose in dome 22, and axial planar to recumbent isoclinal minor folds in both cases. However, contrary to Gansser's inference, the mushroom model *predicts* gentle dips in large proportions of mushroom-shaped salt diapirs (Fig. 1). As only the crest of dome 22 is exposed, all in-situ inclusions in this particular dome can be expected to have gentle dips and young upwards. The test of the mushroom-diapir model is therefore not whether the inclusions are conformable or not, nor whether the salt layering dips gently or not. The crucial test is whether any inclusions and the surrounding stratigraphy young upwards (or outwards) in some places, and downwards (or inwards) in others (Fig. 1). The way-up evidence quoted by Gansser is inadequate to reject the concept of stratigraphic mushrooming even within the salt diapirs he quotes. For those with access to the Great Kavir it should be comparatively simple to apply the field test of the mushroom model implied in Figure 1 to some of the Kavir domes exposed at comparatively deep structural levels.

But is this mesoscopic field test really necessary? The internal macroscopic stratigraphy is clearly mushroom-shaped in air photographs of several of the well exposed salt domes in the Kavir (Jackson et al, 1990). So is the stratigraphy in many of the salt mines of Germany (Kockel 1990; Twiss & Moores 1992, pp. 260 and 443).

An enormous mass of trilobite-rich red Cambrian in the SE flank of the diapiric salt of Kuh-e-namak (Dashti) appears to be inverted (unpublished CT observation, 1977). Unfortunately, this is not a clear test of the standard mushroom diapir model because, as for many in the Zagros (but not the Kavir), the salt in this structure rises way into the sky before it spreads sideways under its own weight (Talbot & Jarvis 1984).

Having shown that any initial stratigraphy can be expected to young upwards in parts of mushroom-shaped diapirs is very different from solving Gannser's enigma. Diapirs of silicone putty lifting internal or underlying layers of denser plasticine (eg. Ramberg 1981, eg., pp. 270–273, 311–313 and 321–324) makes us doubt that there is an enigma.

However, if there is an enigma, it is shared by mantle xenoliths that have surfaced in basalts. Mantle melts are far more mobile ($\approx 10^2$ Pa s) than salt ($\approx 10^{17}$ Pa s) and yet carry their inclusions much further. It is merely necessary for the fluid to rise faster than the inclusions fall within it (eg. Gill 1981, p. 58).

Gansser nearly solves his own enigma by suggesting that the dry (and therefore stiff) salt could support entrained inclusions in the cores of diapirs that rise along softer margins of damp salt. In effect Gansser's suggestion restates two well-known facts, that rock salt in a pseudoplastic (power-law) fluid that is softened by water. Numerical modeling has just reached the stage of being able to explore the implications of power-law fluids to diapirism. Future modelling will be able to use Ganssers' enigmatic inclusions to constrain the fall rate of the inclusions relative to the rise rate of the surrounding salt.

This approach can be illustrated by applying Stokes' Law for simple viscous fluids to the 3000 m^3 inclusion of gneissic granite mentioned by Gansser. This inclusion is

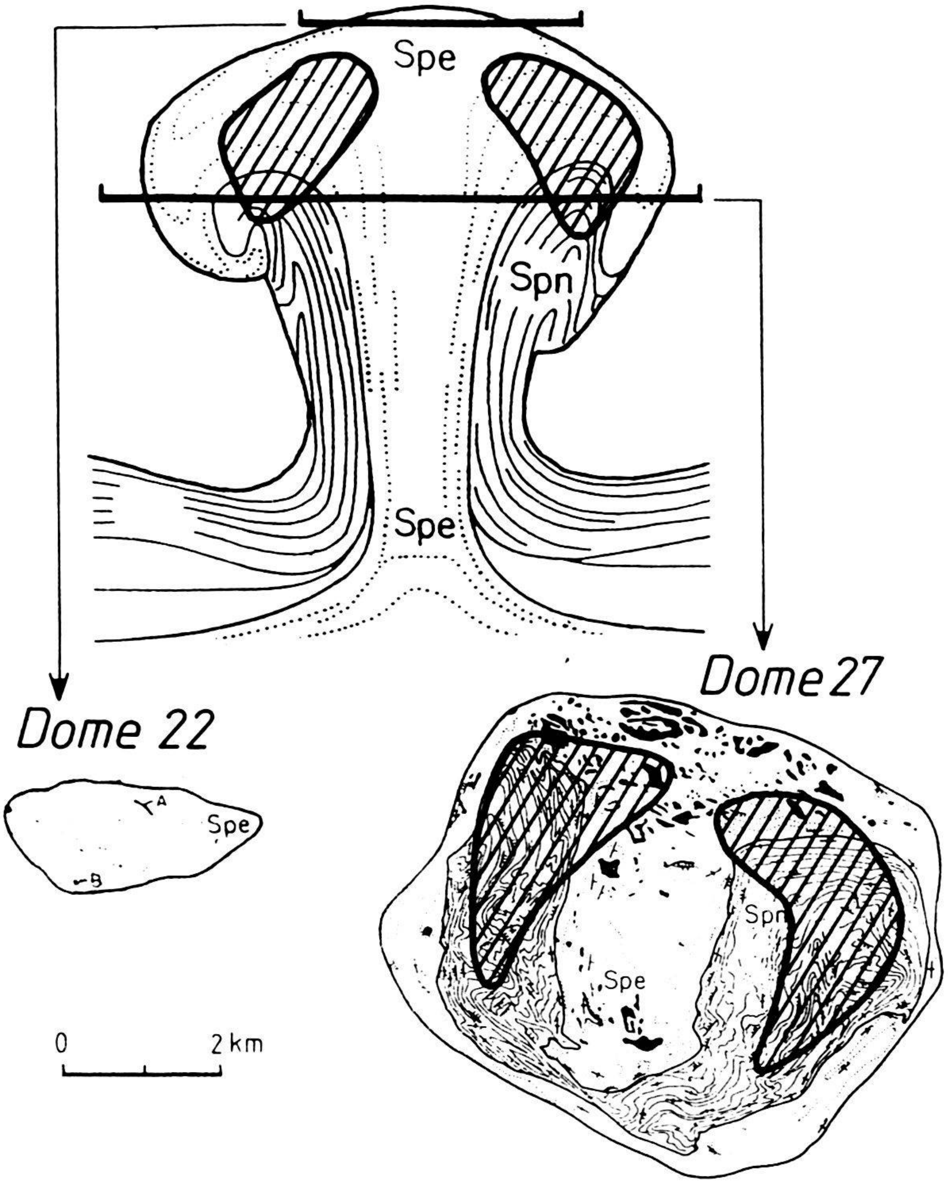

Fig. 1. Each of the 45 salt domes in the Great Kavir is exposed at a different structural level. The structural levels of maps distinguishing Eocene (Spe) from Miocene diapiric salt (Spn) for domes 22 and 27 in the Kavir are indicated in the cartoon profile above (modified from Jackson et al. 1990, Fig. 1.74, p. 82).

Heavy hachuring on both profile and maps indicates areas where the mushroom-diapir model predicts inverted layering (and inclusions) with gentle dips. All inclusions exposed in Dome 22 (see eg. Gansser 1992, Fig. 15 A) can be expected to have gentle dips and young upwards because only the crest of this dome is exposed. Dome 22 is therefore unsuitable as a test for the mushroom diapir model. By contrast, inclusions and stratigraphy in the hachured aeas of Dome 27 (ten km to the south of dome 22) can be expected to have, not only gentle dips, but also to be inverted.

equivalent to a sphere of radius ≈ 10 m that (asuming a density $\rho = 2400$ kg/m^3) would fall through damp salt with a viscosity of 10^{17} Pa s and $\rho = 2200$ kg/m^3 at a rate of ≈ 0.01 mm/year. If this inclusion is still supported by salt, then the salt has to be rising faster than a not-unreasonable 0.01 mm/y. The effective viscosity of salt is the main variable in such calculations and, in practice, is likely to vary over several orders of magnitude in different parts of the same structure. An order of magnitude *increase* in the effective viscosity of salt (eg. because it is drier, coarser, dirtier, colder or less stressed etc.) would imply an order of magnitude *decrease* in the rate at which the inclusion is sinking.

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