Analogue modelling of entrainment of non-evaporitic rocks by salt diapirs

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Analogue models are used to study the mechanism responsible for the entrainment of denser blocks by salt diapirs. Model results suggest that these blocks are detached parts of layers (e.g. anhydrite or volcanic rocks) initially embedded within the salt layer before initiation of the diapirs. During diapir initiation, due to the viscous flow of the diapiric material, interbedded layers are extended, boudinaged, and rotated to a steep position in the stems of the diapirs where they are entrained upward by the rising salt. However, for the same amount of differential loading, models show that in order to be broken into separate blocks by the ductile layer, the denser embedded layer needs to be thin ($1/10^{th}$ of the initial thickness of the salt layer).

Model results suggest that the denser anhydrite and dolomite members of Zechstein formation and the layers of black dolomite and other non-evaporitic units of Hormuz formation encountered within the salt diapirs of Germany and southwestern Iran have undergone a similar evolution history as the models. These layers are stretched to blocks that were later entrained within the diapirs during the diapiric rise.

1. INTRODUCTION

Many salt diapirs of the Hormuz formation carry large exotic blocks (3-6 km^2) of non-evaportitic units[1]. Undisturbed Hormuz sediments (stromatolite limestone and dolomite, and sanstone) and large blocks of basic volcanic rocks (rhyolite) are brought to the surface by the salt diapirs in the Zagros mountain belt[1, 2, 3]. Igneous blocks are found in salt diapirs from other places: northern Spain[4], Arctic Canada[5]. The blocks in the salt diapirs of Hormuz salt are of the same age as the salt itself[2]. Thick intercalation of anhydrite observable in larger exposures in mines of German salt diapirs are broken into larger blocks surrounded by the salt units showing ductile flow[6] (Fig. 1). These blocks are interpreted to be detached parts of the denser members of the Zechstein Group initially interlayered with the salt before initiation of diapirism. Using centrifuge models, Ramberg[7] showed that denser layers embedded within a diapiric layer are deformed as they are brought to the surface by the diapir. Weinberg[8] used two-dimensional numerical models to conclude that most power-law salt diapirs would be capable of lifting denser inclusions as those observed in the Hormuz salt diapirs if they rise at geologically reasonable velocities. In this study, physical models are used to study the effect of the thickness of denser layers embedded within a diapiric layer on their later entrainment into the diapirs.

2. MATERIAL PROPERTIES AND MODEL PREPARATION

Two different rock behaviours were simulated in the current modelling approach: the frictional behaviour of the non-evaporitic sediments and the ductile behaviour of the rock salt. Since loose sand exhibits a nearly perfect Mohr-Coulomb behaviour, it is a suitable analogue for the sedimentary rocks of the brittle upper crust[9]. In the current study, dry quartz

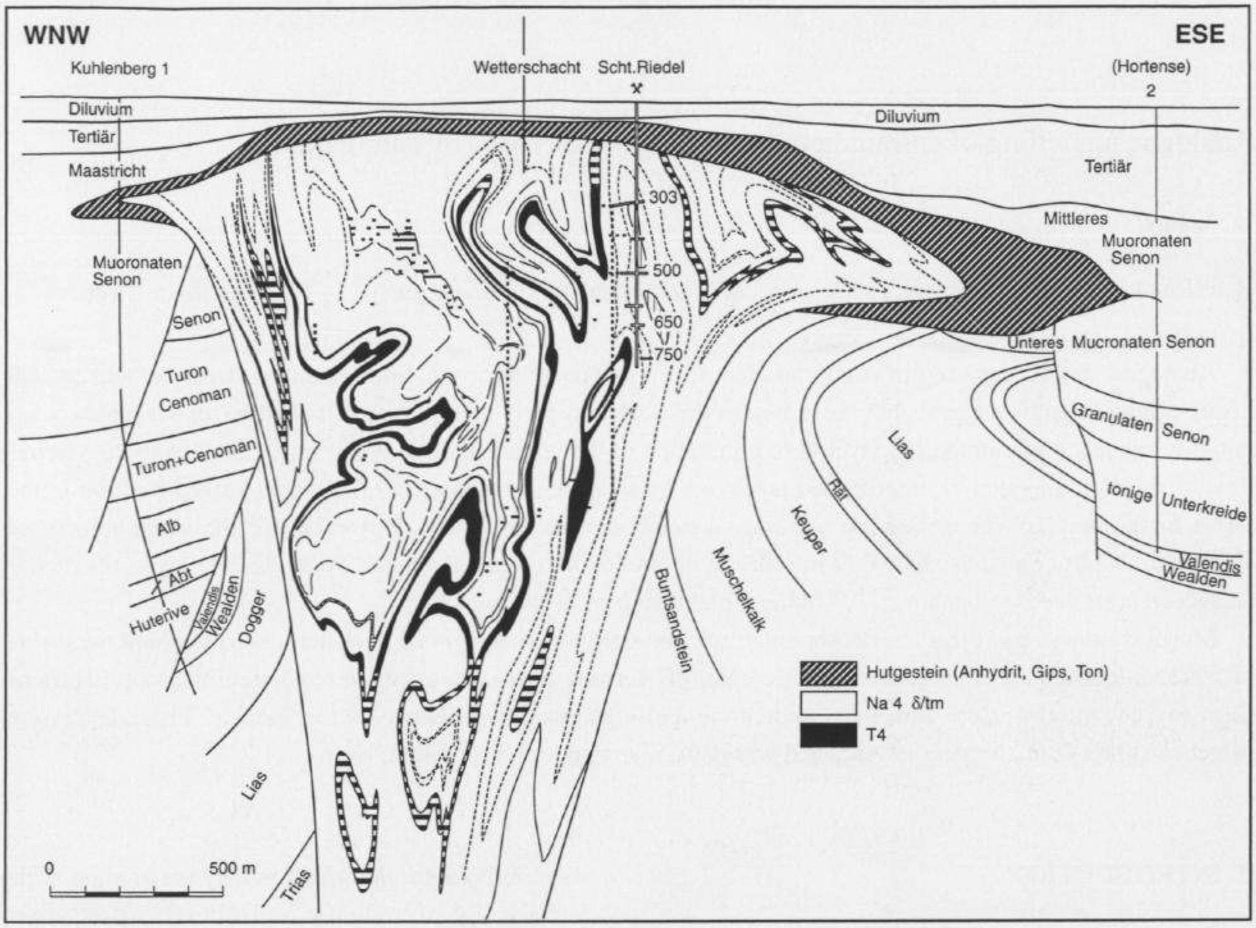

Figure 1. Line drawing of a WNW-ESE profile of the Hänigsen diapir (Germany) showing entrained and deformed layers of the denser members (anhydrite) of the Zechstein Group. These denser units were initially interlayered with the less dense salt member of Zechstein Group before they were entrained and deformed within the salt diapir. Modified after Richter-Bernburg[6].

sand, sieved to an average grain diameter of 35 μm, was used to simulate the brittle overburden overlying rock salt. The angle of internal friction of the uncompacted loose sand used in the models was 36^0 giving a coefficient of internal friction of 0.7. To simulate ductile rock salt, a transparent Silicon gel (SGM36) was used. SGM36, which is manufactured by Dow Corning Ltd., is a Newtonian viscous material with a strain-rate-independent viscosity of 5×10^4 Pa s at room temperature[10].

Two sets of models are prepared here to study the effect of thickness of an embedded denser layer on its later entrainment within the resulting diapirs. Each model consisted of a basal ductile layer of SGM36. A 2-mm thick layer of loose sand in the first set of models, and 4-mm thick in the second set of models, was placed on this ductile basal layer. Then a 4-mm thick layer of SGM36 was placed on the sand layer. A diapir was initiated by creating a 5-mm thick perturbation on the upper SGM36-layer

(Fig. 2). A 5-mm thick layer of loose sand was placed on the top of the model. This sand layer covered the upper ductile layer but for the perturbation (Fig. 2). The differential loading created by the sand layer triggered the flow of the ductile layer towards the perturbation which formed a dynamic bulge rising above the model surface. Then the diapir was downbuilt by adding layers of passively laminated loose sand on the top of the model as soon as the dynamic bulge formed above the diapir. Due to the addition of sand layers, differential loading increased with time to be highest at the later stages of the diapir evolution (Fig. 3).

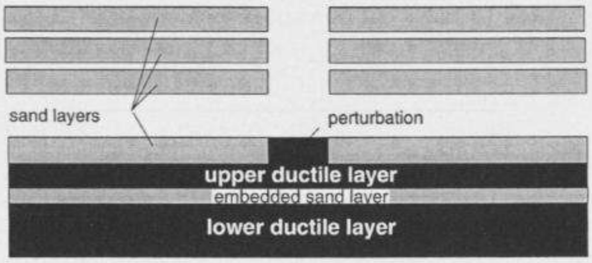

Figure 2. Schematic diagram showing model set-up. The diapir was downbuilt by adding a layer of sand on the top of the model without covering the crest of the diapir. The thickness of the embedded sand layer was varied between 2-mm to 4-mm.

In the first set of models, the embedded sand layer was only 2 mm thick and located within the upper half of the ductile unit, which had a total thickness of 2 cm. The thickness ratio between the ductile layer to the embedded sand layer was 10. In the second set of models, the embedded sand layer was 4 mm thick giving a thickness ratio of 5.

3. MODEL RESULTS

In the first set of models with a thin (2-mm thick) sand layer, as the diapir initiated, the ductile flow of the diapiric material resulted in extension of the sand layer to form separate blocks that were carried upward with the diapir. The layer was extensively extended to form two-dimensional blocks that were taken up by the rising diapir. During their transport, the blocks rotated to upright position within the diapir stem and turned upside down as the diapiric material spread laterally and formed a diapiric overhang (Figs. 4 and 5). In one of the models, the detached blocks of the embedded layer were entrained into the diapir to the surface, where they were rotated to overturned position by the spreading overhang (Fig. 5).

In the second set of models with the thick embedded sand layer (4-mm thick), differential loading created ductile flow that was sufficient to stretch the embedded sand layer directly beneath the stem of the rising diapir (Fig. 6). However, since the sand layer was thick, viscous drag was not sufficient to extend the sand into separate boudins to be brought up by the diapir. Instead, the sand layer was bend upward into the stem of the diapir only to allow the flow of the lower ductile layer to feed the diapir (Fig. 6).

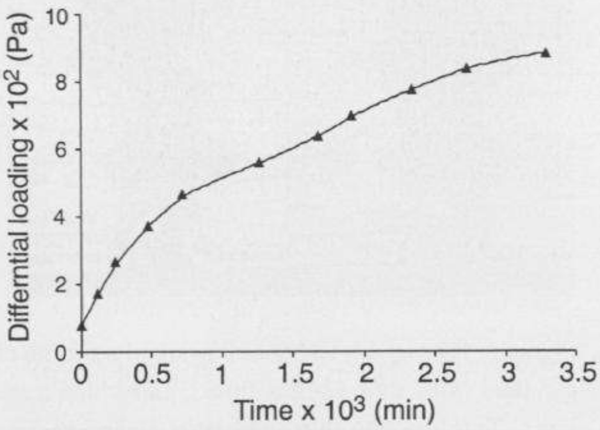

Figure 3. Plot of differential loading versus time for the models. This differential loading drives the ductile layer into the vertical diapir. The ductile flow in turn promotes viscous drag that extends the embedded layer into boudins. Note that the differential loading does not increase at the same rate at later stages of the model implying a decrease in salt withdrawal.

4. DISCUSSION

Well and underground data are used to draw cross section for the Gorleben and Hänigsen diapirs (Fig. 1). These sections show that the denser anhydrite and carbonate members of the Zechstein Group are entrained within the stem of the diapirs (Fig. 1). Model results show that entrainment of layers embedded initially within a diapiric layer requires that the layer be thin (less than 1/10th of the thickness of the ductile layer). With constant shear strength, thinner embedded layers could relatively easily be broken into separate blocks by extension created by viscous drag during the flow of the diapiric layer. During diapir initiation, interlayered denser layers are extended, boudinaged, and rotated to a steep position in the stems of the diapirs where they are entrained upward by the rising salt. The presence of interlayered denser anhydrite and non-evaporitic sediments (volcanics) in many salt diapirs in Germany and Iran supports this interpretation.

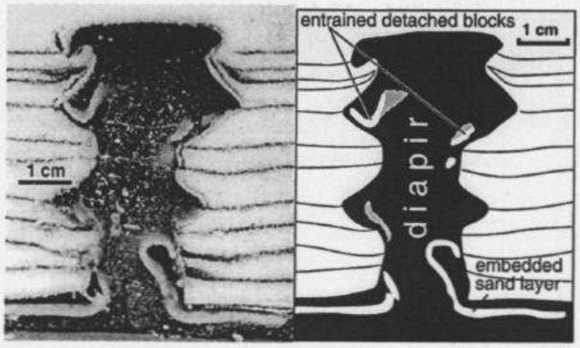

Figure 4. Photograph and line drawing of a profile of a model with thin (2-mm thick) embedded sand layer. Note that the thin sand layer is broken into separate blocks, some of which are entrained within the stem of the diapir to very shallow levels.

In the models with thin embedded sand layer, the viscous drag initiated by flow of the ductile layer as a result of differential loading was higher than the shear strength of the sand layer. Hence it extended the sand layer to boudin blocks which were carried up by the rising ductile material through the stem of the diapir. In the model with the thicker (4-mm) embedded sand layer, the differential loading was not able to create enough viscous drag to overcome the shear strength of the embedded sand layer to break it into boudin blocks that could be transported by the ductile material. The ductile flow created by the differential loading must have been greatest beneath the perturbation where it could overcome the shear strength of the layer and extend it (Fig. 6). In these models, the embedded sand layer was extended only beneath the perturbation to allow upward flow from the lower ductile layer to feed the rising diapir. The extended and separated embedded sand layer was bent upward within the lower part of the diapir stem (Fig. 6).

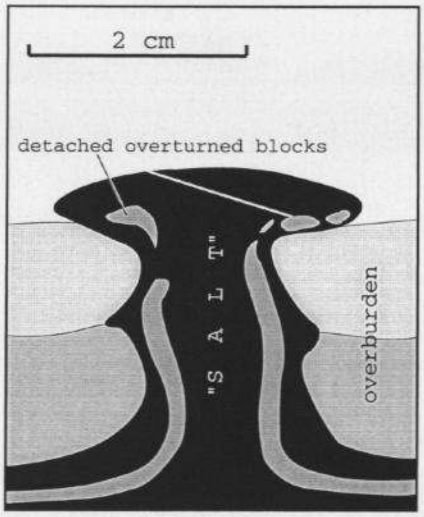

Figure 5. Line drawing of a model profile showing that the diapir (black) has entrained an embedded layer of sand (grey) within its stem. The extended detached parts of the entrained layer are turned upside-down as they are carried out within the spreading overhang.

It is suggested here that at higher differential loading which could initiate relatively greater ductile flow within the salt, the resulting viscous drag may be able to extend thicker embedded layers into separate blocks that could be brought up by salt diapirs. It is after all the final dimension of the blocks rather than their initial thickness that govern whether they could be carried up by the diapir or not. However, based on model results it is proposed that thick competent layers embedded within a salt layer are less likely to be broken into separate blocks by the viscous drag and hence less likely to be carried upward by any resulting diapir. The viscous drag would be insufficient to break a thick competent anhydrite layer into separate blocks that could later be carried upward by the rising diapir.

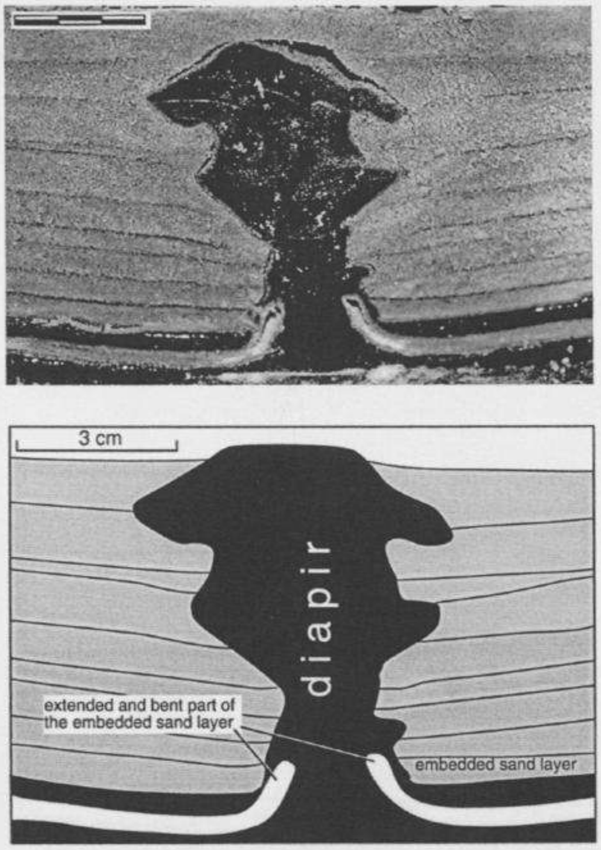

Figure 6. Photograph and line drawing of a profile of a model with thick (4-mm thick) embedded sand layer. Note that the embedded sand layer is extended, broken and bend into the stem of the diapir directly beneath the stem of the diapir. The rest of the layer is continuous.

5. CONCLUSIONS

1. Model results confirm that non-evaporitic and denser units that are embedded within a layer of salt can be entrained within the diapirs and brought to the surface.
2. Entrained blocks are the detached parts of layers initially embedded within the salt layer.
3. Denser layers embedded with a salt layer can be broken into separate blocks by flow of the ductile layer when the viscous drag created by the ductile flow can overcome the shear strength of the embedded layer.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. P. E. Kent, J. Petrol. Geol., 2 (1979) 117.
2. A. Gansser, Eclogae Geol. Helv., 85 (1992) 825.
3. C. J. Talbot and R. Weinberg, Eclogae. Geol. Helv., 85 (1992) 847.
4. R. Brinkmann and H. Lögters, AAPG Mem., 8, (1968) 275.
5. D.B. Gould and G. De Mille, AAPG Mem., 8 (1968) 183.
6. G. Richter-Bernburg, Bull. Cent. Rech. Explor.-Prod. Elf-Aquitaine, 4, 1 (1980), 373.
7. H. Ramberg, Gravity, deformation and the Earth's crust in theory, experiments and geological applications, Academic Press, London (1981).
8. R. F. Weinberg, Tectonophysics, 228 (1993) 141.
9. R. Weijermars, M. Jackson and B. Vendeville, Tectonophysics, 217 (1993) 143.
10. R. Weijermars, Tectonophysics, 124 (1986) 325.