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Numerical modelling of rise and fall of a dense layer in salt diapirs

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SUMMARY
Numerical models are used to study the entrainment of a dense anhydrite layer by a diapir. The anhydrite layer is initially horizontally embedded within a viscous salt layer. The diapir is down-built by aggradation of non-Newtonian sediments (n = 4, constant temperature) placed on the top of the salt layer. Several parameters (sedimentation rate, salt viscosity, perturbation width and stratigraphic position of the anhydrite layer) are studied systematically to understand their role in governing the entrainment of the anhydrite layer. High sedimentation rates during the early stages of the diapir evolution bury the initial perturbation and, thus, no diapir forms. The anhydrite layer sinks within the buried salt layer. For the same sedimentation rate, increasing viscosity of the salt layer decreases the rise rate of the diapir and reduces the amount (volume) of the anhydrite layer transported into the diapir. Model results show that viscous salt is capable of carrying separate blocks of the anhydrite layer to relatively higher stratigraphic levels. Varying the width of the initial perturbation (in our calculations 400–800 m), from which a diapir triggers, shows that wider diapirs can more easily entrain an embedded anhydrite layer than the narrower diapirs. The anhydrite layer is entrained as long as rise rate of the diapir exceeds the descent rate of the denser anhydrite layer. We conclude that the four parameters mentioned above govern the ability of a salt diapir to entrain an embedded dense layer. However, the model results show that the entrained blocks inevitably sink back if the rise rate of the diapir is less than the rate of descent of the anhydrite layer or the diapir is permanently covered by a stiff overburden in case of high sedimentation rates.

Key words: Numerical solutions; Geomechanics; Sedimentary basin processes; Dynamics: gravity and tectonics; Diapir and diapirism; Mechanics, theory, and modelling.

1 INTRODUCTION
Inclusions of denser rocks are common in salt diapirs. Such inclusions are seen both in extruding salt diapirs (e.g. Zagros fold-thrust belt, Kent 1979) and in seismic sections of diapirs (Gorleben salt diapir, Bornemann 1991). The existence of different densities and compositions of different evaporitic cycles is confirmed in many places (Hübscher et al. 2007). Seismic characteristics of evaporitic sequences record internal reflectors that are suggested to be a change in evaporite facies (Netzeband et al. 2006). Sedimentary, volcanic and even some plutonic inclusions characterize many of the diapirs in the Zagros fold-thrust belt (Gansser 1992). Some of these inclusions are several kilometres in diameter (Gansser 1992). The size and lithology of such entrained inclusions in diapirs vary from place to place. An example of a diapir which has entrained dense blocks is the Gorleben diapir in Germany (Bornemann 1991). Geophysical and subsurface data confirm that large blocks of denser anhydrite are present at relatively shallow depth within the Gorleben salt diapir (Richter-Bernburg 1980). These anhydrite blocks, deformed within the diapir, form a key horizon in the Zechstein salt sequence. The presence of an anhydrite layer within a layer of salt plays a very important role with respect to nuclear waste storage because any salt diapirs may entrain such a denser layer.

Due to its low permeability, salt layers and structures have been targeted as repositories for hazardous waste [e.g. Gorleben and Morsleben salt diapirs in Germany; WIPP site in USA and Anloo, Gasselte (Drenthe) and Winschoten (Groningen) in Netherlands]. Tectonic stability of a salt diapir is a significant factor in evaluating its suitability as a repository for waste disposal. Zirngast (1996) studied the evolution history of the Gorleben diapir and estimated the vertical rise rate to vary between 0.08 mm a⁻¹ in Cretaceous and 0.02 mm a⁻¹ in Miocene-Quaternary. The Gorleben diapir has, therefore, been considered as relatively inactive during the last 20 Myr (Zirngast 1996) and suitable as a repository for radioactive waste disposal. However, Koyi (2001) used analogue and numerical models to show that the Gorleben diapir may be active internally due to the presence of denser anhydrite blocks within the diapir. Koyi (2001) showed that such dense blocks sink back into the diapir when the rate of rise of the diapir, which once entrained the anhydrite blocks, was not sufficiently high to keep the blocks within the diapir. The analogue models showed that denser blocks can be carried upward by diapiric flow of salt if the rate of diapiric rise is
greater than the rate of decent of the denser entrained blocks (Koyi & Schott 2000; Koyi 2001). At the later stages of diapirism, when the ascent velocity of salt falls below the rate of descent of the entrained blocks, the denser blocks sink within the salt diapir. The maximum negative buoyancy of such blocks that a diapir may lift varies considerably due to large variations in rheology and, thus, the effective viscosity of salt (Weinberg 1993).

Many investigators numerically modelled different aspects of salt diapirism (e.g. Woidt 1978; Schmeling 1987; Romer & Neugebauer 1991). However, few studies have addressed the problem of downbuilding and multicompositional salt structures. In this paper, the results of 2-D numerical calculations are used to quantitatively analyse the four parameters (viscosity of salt, sedimentation rate, stratigraphic position of denser layers within the salt layer and width of the perturbation) that govern the rise and fall of dense anhydrite blocks within salt diapirs. These models are not scaled to any particular salt diapir. However, the Gorleben salt diapir has been used as a general guideline for our modelling.

2 METHODS

2.1 Governing equations

The dynamic evolution of the gravitationally unstable, initially horizontally multilayered system, can be described by the equations of conservation of mass, momentum and composition for a Boussinesq fluid as (e.g. Weinberg & Schmeling 1992)

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

$$0 = -\nabla P + \frac{\partial \tau_{ij}}{\partial x_j} - \rho g$$

$$0 = \frac{\partial c_k}{\partial t} + \nabla c_k,$$

where inertial forces are neglected, and \( v, P \) and \( \tau_{ij} \) are the flow velocity, pressure, and deviatoric stress tensor, respectively. \( \rho \) is density, \( g \)-gravitational acceleration, \( t \)-time and \( c_k \)-concentration of the \( k \)-th chemical component. The viscous stress is related to the velocity field by the constitutive equation

$$\tau_{ij} = \eta \left( \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right),$$

where \( \eta \) is the viscosity.

The eqs (1) and (2) are solved using a 2-D finite difference code (FDCON). The problem of numerical diffusion due to moving compositional fields (eq. 3), which contain sharp discontinuities through a discrete mesh, is overcome by using a method of characteristics based on marker points (Weinberg & Schmeling 1992). The marker technique is very effective for multiphase flows, where each phase has different rheological properties and densities. The markers are moved according to the velocity field using a fourth-order Runge–Kutta algorithm.

The problem of interpolating the viscosity from the marker fields to the discrete FD mesh near boundaries between different materials is overcome by defining an effective viscosity for the mixture as:

$$\log \eta = \frac{1}{n} \sum_{k} c_k \log \eta_k.$$  

The deformation behaviour of rock is described by a power-law ductile creep (Kirby & Kronenberg 1987). The viscosity is related to \( n \)-th power of the deviatoric stress by

$$\eta = A \cdot \tau^{1-n},$$

where \( A \) is a pre-exponential constant, and \( \tau_0 \) is the second invariant of the deviatoric stress tensor.

3 MODEL SETUP

A 2-D box with the dimensions of \( 4 \times 4 \) km and a grid resolution \( 161 \times 161 \) is used for the modelling. At the rigid basement, a no-slip bottom boundary is assumed. The top and the side boundaries are free-slip and reflective, respectively. An anhydrite layer is modelled as an 80-m (\( \rho_s = 2900 \) kg m\(^{-3}\)) thick layer placed within a 1040-m thick layer simulating the Zechstein salt formation (Fig. 1). The anhydrite layer is assigned non-Newtonian rheology (Kirby & Kronenberg 1987), and during the experiment its effective viscosity ranges between \( 10^{19} \) and \( 10^{21} \) Pa s. The stratigraphic position of the anhydrite layer is varied systematically. A 160-m thick overburden, representing a pre-kinematic layer, is placed on the salt layer apart from the perturbation to initiate salt flow. A pre-kinematic perturbation (400 or 800 m wide) is initiated at the left-hand side of the upper boundary of the salt layer as a trigger for diapirism. The perturbation is down-built by aggrading sediments at a rate that is varied systematically. In all models, sedimentation is done by aggradation according to the following method.

The space above the top of the overburden (background of the box) is filled with an arbitrary material of initial viscosity \( 10^{16} \) Pa s and density \( 1000 \) kg m\(^{-3}\) (Fig. 1). This medium is arbitrarily assigned a viscosity one to three orders of magnitude less than the salt to simulate a free surface (water or air above the surface of the model). As long as the viscosity of the background medium does not exceed the viscosity of the salt, the growth rate and the time for initiation of the instabilities are not significantly affected. The main goal of this study is to investigate the entrainment and the evolution of an initially horizontally embedded anhydrite layer within a salt structure. We therefore, assume that the medium, into which the diapir is growing represents air or water.

Two different modes of sediment aggradation, constant and variable, are used in the simulations. Sediments accumulate on the top of the model with a prescribed rate, \( s_z \). The initial position of the sediment surface is given by the top of the pre-kinematic overburden, \( z_{so} \). Above the initial model surface, background markers are assumed with a low viscosity and a low density. During sedimentation, the position of the surface of sediment layer, \( z_s \), rises with the prescribed rate,

$$z_s = z_{so} + s_z t,$$

thereby thickening the overburden. If the salt surface lies below \( z_s \), then the salt is also covered with sediments. During sedimentation, sediments are deposited at each time step between the previous model surface at time, \( t - dt \), \( z_s(t - dt) \), and the new sedimentation surface, \( z_s(t) \) [but only where \( z_s(t - dt) \) is below \( z_s(t) \)]. This is done by assuming all background markers, whose position is between \( z_s(t - dt) \) and \( z_s(t) \) sedimentary rock properties.

In the variable sedimentation mode, the sedimentation rate varies according to the evolution of the crest of the diapir. During the simulation, the velocity at which the crest of the diapir rises \( (v_c) \) is determined. A quarter of this velocity is assigned to the sedimentation rate, so the surface of the sediment layer grows depending on the evolution of the crest of the diapir.

$$z_s = z_{so} + \int_0^t \frac{1}{4} v_c \, dt.$$

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Figure 1. Line drawing showing the initial geometric condition and the points (A, B, C and D), which are monitored throughout model evolution. A 400-m-wide pre-kinematic perturbation is imposed as a layer of salt. The box has no-slip at the bottom, free-slip at the top and reflective side boundaries. The box can be considered as showing the right hand half of a symmetric structure.

The choice of the factor 1/4 in the variable mode of the sedimentation is manually calibrated to form a columnar diapir. The quarter of the rising velocity of the crest of the diapir seems to be a good approximation for the formation of the diapir whose crest remains uncovered and possess a columnar shape.

The salt is modelled with Newtonian rheology of an average viscosity $10^{17}$–$10^{19}$ Pa s (e.g. Urai et al. 1986; Spiers et al. 1990; Hunsche & Hampel 1999). The sedimentary overburden rocks simulated in all our models are assigned a higher viscosity (effective viscosity ranges between $10^{17}$ and $10^{19}$ Pa s; $n = 4$) than previously used in analogue and numerical modelling (Biot 1965; Ramberg 1968; Woidt 1978; Poliakov et al. 1993). The rationale behind this decision is because most sedimentary rocks (clastic or carbonate) behave as non-Newtonian material or as brittle solids, rather than in a ductile way, depending on factors such as their depth of burial, etc. (Vendeville & Jackson 1992a). Our assumption of a very high viscosity keeps ductile deformation in the overburden extremely small.

Salt dissolution or regional extension, both of which may play a significant role in halokinesis (Koyi 1988, 1998; Jackson et al. 1994) are not considered in the models. However, the pre-kinematic perturbation represents a graben that may have formed at an earlier stage of extension. Faults do not develop in the overburden since the modelling approach is based on the mechanics of continua rather than fracture mechanics.

Several models have been deployed, where one of the four parameters (viscosity of salt, sedimentation rate, stratigraphic position of the anhydrite layer and width of the pre-kinematic perturbation) was changed systematically (Table 1). Constant sedimentation rates varied from 5 to 0.1 mm a$^{-1}$ (in one case 0.025 mm a$^{-1}$), and only one model was run with a variable sedimentation rate, where the rate of sedimentation was kept equal to a quarter of the (time-dependent) rate of diapiric rise in order to down-build a columnar diapir with subvertical boundaries. In each model, several points, within the anhydrite layer and the crest of the diapir, were monitored throughout the evolution of the diapir (Fig. 1). All models are down-built until the crest of the diapir reaches a height of 3.6 km, after which the diapir is covered by a 400-m-thick stiff overburden layer that terminates further growth of the diapir. Table 2 lists all the parameters that were constant throughout the modelling.

Inside the finite difference domain, we used $1000 \times 3200$ markers. The markers are initially distributed on a rectangular grid with small random displacements. Model results are found to be stable with respect to the increase in grid resolution and number of markers.

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Table 1. Summary of the calculated models and material properties: $\eta_s$ is the viscosity of salt, $\dot{s}_e$ is the sedimentation rate, $P_w$ is the perturbation width and $L$ is the stratigraphic location of the anhydrite layer from the bottom of the model.

<table>
<thead>
<tr>
<th>Model #</th>
<th>$\eta_s$ (Pa s)</th>
<th>$\dot{s}_e$ (mm a$^{-1}$)</th>
<th>$P_w$ (m)</th>
<th>$L$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10^{17}$</td>
<td>5</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>2</td>
<td>$10^{17}$</td>
<td>3</td>
<td>400</td>
<td>800</td>
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<tr>
<td>3</td>
<td>$10^{17}$</td>
<td>1</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>4</td>
<td>$10^{17}$</td>
<td>0.1</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>5</td>
<td>$10^{17}$</td>
<td>var.</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>6</td>
<td>$5 \times 10^{17}$</td>
<td>0.1</td>
<td>400</td>
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</tr>
<tr>
<td>7</td>
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<td>8</td>
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<td>0.1</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>9</td>
<td>$10^{19}$</td>
<td>0.1</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
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<td>800</td>
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<td>800</td>
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<tr>
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<td>NO</td>
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<tr>
<td>15</td>
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<td>400</td>
<td>200</td>
</tr>
<tr>
<td>17</td>
<td>$2 \times 10^{19}$</td>
<td>0.025</td>
<td>800</td>
<td>480</td>
</tr>
</tbody>
</table>

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Table 2. Model parameters. \( A \) is the pre-exponential coefficient given in non-dimensional form and \( n \) is the dimensionless constant.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain height</td>
<td></td>
<td>4000 m</td>
</tr>
<tr>
<td>Domain width</td>
<td></td>
<td>4000 m</td>
</tr>
<tr>
<td>Density of the anhydrite</td>
<td>( \rho_a )</td>
<td>2900 kg m(^{-3})</td>
</tr>
<tr>
<td>Density of the overburden</td>
<td>( \rho_o )</td>
<td>2600 kg m(^{-3})</td>
</tr>
<tr>
<td>Density of the background material</td>
<td>( \rho_b )</td>
<td>1000 kg m(^{-3})</td>
</tr>
<tr>
<td>Density of salt</td>
<td>( \rho_s )</td>
<td>2200 kg m(^{-3})</td>
</tr>
<tr>
<td>Gravitational acceleration</td>
<td>( g )</td>
<td>10 m s(^{-2})</td>
</tr>
<tr>
<td>Thickness of the anhydrite layer</td>
<td>( h_a )</td>
<td>80 m</td>
</tr>
<tr>
<td>Thickness of the pre-kinematic overburden</td>
<td>( h_{ini} )</td>
<td>160 m</td>
</tr>
<tr>
<td>Viscosity of the overburden</td>
<td>( \eta_o )</td>
<td>(10^{23} - 10^{25}) Pa s ((A = 10^1; n = 4))</td>
</tr>
<tr>
<td>Viscosity of the anhydrite</td>
<td>( \eta_a )</td>
<td>(10^{19} - 10^{21}) Pa s ((A = 10^{-1}; n = 2))</td>
</tr>
<tr>
<td>Viscosity of the background material</td>
<td>( \eta_b )</td>
<td>(10^{16}) Pa s</td>
</tr>
</tbody>
</table>

4 RESULTS

4.1 Variation in sedimentation rate

The model with high sedimentation rate (Model 1; \( \dot{s}_s = 5\) mm a\(^{-1}\); \( \eta_s = 10^{17}\) Pa s) exhibits an initially slow rate of diapiric rise relative to sedimentation rate. The diapir rises a few hundred meters during the first 0.25 Ma (equivalent to a rate of rise 1.2 mm a\(^{-1}\)). Most of the movement takes place at the early stage of diapirism, while the surface of salt is still free. The anhydrite layer is perturbed in the region of high salt flow velocity, near the initial perturbation. However, the fast rate of sedimentation soon buries the diapir, which ceases to rise (Fig. 2a). As a result, the anhydrite layer locally sinks into the salt layer after 15 Ma, initiating an internal salt flow (Figs 2b and c). Large-stretched segments of the anhydrite layer settle at the bottom of the model after 16.68 Ma (Fig. 2d).

Decreasing the sedimentation rate to 3 mm a\(^{-1}\) (Model 2; \( \eta_s = 10^{17}\) Pa s) considerably alters the evolution of the diapir. As the rate of diapiric rise in this model is still lower than the rate of sedimentation, the diapir immediately narrows upward from its initial perturbation width (Fig. 3a). However, differential loading, generated by subsequent sedimentation, forces the salt towards and into the diapir, thereby dragging the anhydrite layer into the diapir. After the salt bursts through the stretched anhydrite layer, the diapir widens upward due to accelerating salt flow (Figs 3b and c). At this stage, the rate of rise of the diapir is higher than the rate of sedimentation. The diapir evolves rapidly and reaches an elevation of 3.6 km in less than 1 Ma, after which it is rapidly covered by a 400-m-thick layer of overburden (Fig. 3d). The diapir is not able to penetrate this layer.

Figure 2. Snapshots of the time evolution of model 1, with dimensions 4 × 4 km. Sedimentation rate is 5 mm a\(^{-1}\), viscosity of salt is \(10^{17}\) Pa s and perturbation width is 400 m.
overburden and does not grow any further, although the remaining salt source layer is still thick (370 m). The anhydrite blocks in the diapir start to sink immediately after the diapir is covered (Fig. 3d).

The model with sedimentation rate of 1 mm a$^{-1}$ (Model 3; $\eta_s = 10^{17}$ Pa s) evolves differently from the previous models. The diapiric rise keeps pace with the sedimentation rate during the early stages and a columnar diapir forms (Fig. 4a). The anhydrite layer is bent, detached, and lifted as a separate segment to the surface (Fig. 4b). The removal of the horizontal anhydrite layer from the diapiric stem allows rapid salt flow and the diapir widens upward due to the higher rise rate of the diapir relative to the sedimentation rate (Fig. 4c). As the diapir widens, the accelerating salt flow entrains most of the anhydrite layer. During the entrainment, the competent anhydrite layer is folded due to vertical compression and its segments are transported into the overhang, where salt flow is slow. Segments of the anhydrite layer entrained earlier are detached and sink to the bottom of the overhang of the diapir (Fig. 4d). Later segments follow a similar evolution. As the salt layer thins, the rate of salt supply decreases relative to the rate of sedimentation, and the crest of the diapir narrows upward (Fig. 4e). The decrease in the rate of salt supply and upward flow results in a gradual decrease in the rate of entrainment of the anhydrite layer. Nevertheless, above the narrow part of the feeding stem, the anhydrite segments continue to rise while anhydrite segments within the bulb/overhang are sinking. Once a stiff overburden layer covers the crest of the diapir, all the entrained anhydrite segments start to sink (Figs 4e and f).

In model 4, the sedimentation rate ($\dot{s}_e = 0.1$ mm a$^{-1}$; $\eta_s = 10^{17}$ Pa s) is lower than the rise rate of the diapir. The salt layer above the anhydrite sequence flows towards the perturbation, until the anhydrite layer blocks the feeding stem as it is entrained by the salt flow (Fig. 5a). The entrained anhydrite layer does not allow the upper salt sequence above the anhydrite layer to move any further, and the deeper salt layer beneath the anhydrite layer mainly supports the stem of the diapir (Fig. 5a). The faster rise rate of the diapir relative to the sedimentation rate leads to the formation of a wide overhang soon after the breakup of the anhydrite layer. As the overhang grows laterally and vertically, the pre-kinematic overburden starts to bend towards the diapir and a secondary rim syncline forms (Fig. 5b). The diapir extrudes into a wide overhang. Later, sedimentation on the crest of the diapir splits the diapir and displaces its crest sideways (Fig. 5c). The overburden layers that bend towards the diapir weld at the bottom of the model and cut the salt supply and the diapir becomes inactive (Fig. 5d). Continued sedimentation accumulates in mini-basins, which further segments the diapir and results in secondary internal flow of salt (Fig. 5e). Several additional mini-basins segment the diapir into relatively detached pods of salt, which are buried by the accumulating sediments. However, the diapir continues to rise with limited salt supply and the overburden layers eventually bury it after 10 Ma (Fig. 5f). The remaining salt layer forms a large pillow beneath the accumulating sediments, where the remnant anhydrite layer sinks.

One model (Model 5; $\eta_s = 10^{17}$ Pa s) is run with a variable sedimentation rate, which is matched to the rise rate of salt, to keep the crest of the diapir free. The resulting columnar diapir evolves rapidly and detaches a block from the anhydrite layer, as the lower salt bursts through it. This detached block of anhydrite, which has approximately the same width as the initial perturbation, is rotated and carried upward, almost to the surface (Fig. 6a). However, as the diapir grows very fast, this block stays close to the surface throughout the evolution of the diapir. In spite of the high salt flow velocity, only the detached block is entrained, whereas the rest of the anhydrite layer is stretched towards the perturbation. After 0.76 Ma,
the crest of the diapir, which rises to height of 3600 m, is rapidly covered by a 400-m-thick overburden. This thick, stiff layer prevents salt from rising any further, and the entrained anhydrite block starts to sink back through the stem of the diapir (Fig. 6b).

4.2 Variations in viscosity

This section presents results of models 4 and 6–9 (Table 1), where the viscosity of the salt varies from $10^{17}$ to $10^{19}$ Pa s. The sedimentation rate is kept at 0.1 mm a$^{-1}$.

At the early stages of model 6 ($\dot{s}_s = 0.1$ mm a$^{-1}$; $\eta_s = 5 \times 10^{17}$ Pas), the external geometry of the diapir evolves in a similar manner to that in model 3 ($\dot{s}_s = 1$ mm a$^{-1}$; $\eta_s = 10^{17}$ Pa s). A columnar diapir carries segments of the anhydrite layer towards the surface (Figs 7a and b). In spite of the similar geometries of these two diapirs during the early stages of the evolution (models 3 and 6), the time required for initiation of the perturbation is different. The main difference is that the diapir in model 6 grows slowly and widens upward during the later stages of its evolution (Fig. 7a). In this model, the detached segments of the anhydrite layer start to sink after salt supply from the source ceases and the vertical flow inside the diapir becomes slower than the sinking rate of the anhydrite blocks induced by their negative buoyancy. The sinking anhydrite blocks drag down the crest of the diapir creating a local surface depression, which is filled by sediments, and segments the diapir (Fig. 7b). This process continues until a 400-m-thick overburden layer buries the diapir after 24 Ma. Hence, the vertical growth of the diapir ceases, and the entrained anhydrite segments start to sink (Fig. 7c). In this model, the diapir drags an embedded anhydrite layer up to 1650 m before the crest of the diapir reaches its maximum elevation of 3650 m.

The rise rate of the diapir in model 7 ($\dot{s}_s = 0.1$ mm a$^{-1}$), compared to models with less viscous salt, is retarded due to the increased viscosity of salt to $10^{18}$ Pa s. However, the crest of the diapir evolves similar to that in model 6, and an increase of the salt viscosity by a factor of 5 results in lower rate of salt flow and formation of a narrower overhang (2.5 km, Figs 7d and e). The external geometry

Figure 4. Reference model 3 showing the development of the diapir with sedimentation rate 1 mm a$^{-1}$. Viscosity of the salt is $10^{17}$ Pa s and perturbation width is 400 m.
Figure 5. Reference model 4 showing the development of the diapir with sedimentation rate 0.1 mm a$^{-1}$. Viscosity of the salt is $10^{17}$ Pa s and perturbation width is 400 m.

Figure 6. Snapshots of model 5 showing the development of a diapir with variable sedimentation rate (a quarter of the vertical velocity of salt). Viscosity of salt is $10^{17}$ Pa s and perturbation width is 400 m.

of the diapir in model 7 evolves in a similar manner as in model 3 ($\dot{s}_e = 1$ mm a$^{-1}$; $\eta_s = 10^{17}$ Pa s; Fig. 4). These two models (3 and 7) differ in the time it takes for the diapir to evolve. In model 7, the diapir reaches its maximum elevation (3648 m) after 24 Ma (Fig. 7f) compared to the diapir in model 3 which evolves much faster (elevation of 3648 m in 2.53 Ma; Fig. 4f).

Increasing the viscosity of salt five times in model 8 ($\dot{s}_e = 0.1$ mm a$^{-1}$; $\eta_s = 5 \times 10^{18}$ Pa s) initially results in formation of
a columnar diapir (Fig. 8a). However, after the detachment of the entrained anhydrite layer, the diapir starts to widen upward (Fig. 8b). Detached blocks of the anhydrite layer are transported sideways to the right margin of the stem of the diapir (close to contact with overburden layers). Withdrawal of salt dominates in the lower part of the salt layer, whereas the folded anhydrite layer blocks the upper salt layer (Fig. 8b). Further acceleration of the salt flow within the diapir transports the folded anhydrite layer into the diapir and carries it to high levels than in models with lower salt viscosity (Fig. 8c). The diapir in this model is narrow (maximum 1 km width) and reaches an elevation of 3.6 km before the source layer depletes. The anhydrite blocks continue to rise before a stiff overburden layer covers the diapir after which they start to sink (Fig. 8d). Further increase of the viscosity of salt to $10^{19}$ Pa s results in burial of the initial perturbation during the early stages, even for the case of very slow sedimentation rate (e.g. 0.05 mm a$^{-1}$).

### 4.3 Variations in perturbation width
Several models are run to investigate the role of the perturbation width on entrainment of the anhydrite layer. To illustrate this, we tabulate additional model snapshots and corresponding time
Model 11 (\(\dot{s}_e = 3\) mm a\(^{-1}\); \(\eta_s = 10^{17}\) Pa s), with a greater perturbation width (800 m), develops an approximately 2.5-km-wide overhang (Fig. 1a). Because of increased salt flow into the diapir and formation of a wider overhang, the anhydrite layer is transported into the diapir as a whole layer (Fig. 10b). The process of entrainment is accompanied by folding of the anhydrite layer. Early entrained parts of the anhydrite, which are transported sideways, towards the overhang, sink into the diapir while within the diapiric stem entrainment is still active. Entrainment is accomplished when a stiff overburden layer covers the diapir (Fig. 10c). A rapid burial of the diapir by a 400 m overburden induces an overall sinking of the entrained and folded anhydrite layer, which reaches the bottom of the model after 10.65 Ma.

The evolution of model 13 with a constant sedimentation rate 0.1 mm a\(^{-1}\), a viscosity of salt of 10\(^{17}\) Pa s, and a perturbation width of 800 m is faster than in model 4 (Figs 11 and 5). The diapir widens upward as the rise rate of the diapir is higher than the sedimentation rate and the overhang occupies nearly the whole width of the model (Fig. 11a). This wide overhang is segmented by sinking mini-basins (Fig. 11b). The diapir is intensively segmented by sinking mini-basins and sedimentation on the top of the diapir that disconnects salt supply (Figs 11c and d). The anhydrite layer is initially drawn towards the stem of the diapir, where it is folded. The folded segments start to sink within the diapir, as soon as the latter is segmented by the mini-basins.

4.4 Stratigraphic position of the anhydrite layer

Before we present the results of the models, where the stratigraphic location of the anhydrite is changed, we will explore the principle effect (influence) of the presence of an anhydrite layer on salt flow.
For this purpose we consider model 14 ($\dot{s}_c = 0.1 \text{ mm a}^{-1}; \eta_s = 10^{17} \text{ Pa s}$) with an absent anhydrite layer (see discussion Fig. 18). The absence of the anhydrite layer in the salt layer allowed the diapir to form a wider overhang. Salt flow is accelerated in earlier stages of diapirism, and the rise rate of the diapir soon exceeds the sedimentation rate. In model 3, where the anhydrite layer is acting as lid, the diapir reaches its maximum elevation in 2.53 Ma, whereas in the model without the anhydrite layer the diapir reaches the same elevation in 5.05 Ma.

Figure 10. The evolution of the diapir in model 12 with initial perturbation width 800 m, sedimentation rate 1 mm a$^{-1}$ and viscosity of salt $10^{17}$ Pa s.

Figure 11. Reference model 13 showing the effect of perturbation width with slow sedimentation rate. Model parameters: perturbation width 800 m, sedimentation rate 0.1 mm a$^{-1}$, and viscosity of salt $10^{17}$ Pa s.

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Figure 12. Snapshots of the development of the diapir in model 15 with an anhydrite layer embedded at 480 m (from the bottom of the model) stratigraphic location. Sedimentation rate is 0.1 mm a$^{-1}$ and viscosity of salt $10^{18}$ Pa s.

height in almost half that time (1.32 Ma). This finding demonstrates that the presence of the anhydrite layer strongly retards the growth rate of a diapir.

In the following, we study the effect of the stratigraphic position of the anhydrite layer within the salt layer (Table 1). Since rapid sediment aggradation will bury a potential diapir, we chose a low sedimentation rate (0.1 mm a$^{-1}$). Model 7 ($\dot{s}_e = 0.1$ mm a$^{-1}$; $\eta_s = 10^{18}$ Pa s) is rerun with the anhydrite layer positioned at 480 m stratigraphic level within the salt layer (model 15). As down-building starts, the upper salt starts to flow and feeds a columnar diapir, which widens (Fig. 12a). Salt flow carries the anhydrite layer upward into the stem (Fig. 12b). However, after the lower salt bursts through it, the anhydrite layer starts to sink within the stem (Fig. 12d). The folded anhydrite layer beneath the stem is dragged up in the middle of the stem (Fig. 12c). The diapir widens and the detached segments of the anhydrite are transported sideways towards the overhang, where they start to sink due to the lack of upward salt flow (Fig. 12e). This process continues for 11.8 Ma, after which the anhydrite layer is completely withdrawn from the source layer leaving only small blocks in the thinned salt layer (Fig. 12e). At this stage, due to decreasing salt supply, the entrained anhydrite segments start to sink, inducing an internal flow within the diapir. The resulted downward flow within the diapir creates a depression at the surface of the diapir that is filled by sediments and forms a mini-basin (Fig. 12e). With further sedimentation, this mini-basin grows, subsides and segments the diapir (Fig. 12f).

The same model is repeated by placing the anhydrite layer at a deeper level of 200 m (Model 16). During the first 3.8 Ma, the anhydrite layer remains at its initial level meanwhile the upper salt forms a diapir (Fig. 13a). Further acceleration of the salt flow initiates folding of the anhydrite layer, and after 6.33 Ma, the anhydrite layer is fully entrained into the diapir (Fig. 13b). As the diapir grows, it widens upward before salt supply significantly decreases. The net motion of the anhydrite layer is directed upward. However, after 10 Ma, the rise rate of the diapir becomes smaller than the sedimentation rate (Fig. 13c). A depression forms on the crest of the diapir, which develops into a mini-basin, and pushes the entrained segments of the anhydrite downwards (Fig. 13d). Consequently, the anhydrite segment entrained within the crest of the diapir start to sink (Fig. 13d).
**5 Discussion**

This study investigates the effect of four parameters on the growth rate of a salt diapir and its entrainment of an anhydrite layer initially embedded within it. It is shown here that sedimentation rate, salt viscosity, width of the perturbation and stratigraphic position of the anhydrite layer influence growth and rate of rise of the diapir and the degree of entrainment of the denser anhydrite layer. Below, we discuss the effect of each of these parameters.

Previous work has shown that the shape of a diapir is a function of the net rise rate of a Newtonian diapir and the rate of aggradation of the encasing sediments (e.g. Vendeville & Jackson 1992a,b; Koyi 1998). The sedimentation rate changes the shape of the diapir, and thereby controls the entrainment of an embedded anhydrite layer.

In the models presented here, the rise rate of the diapir is directly influenced by the rate of sedimentation. The rise rate of the diapir is initially zero, and increases as the overburden aggrades and increases the driving pressure (differential pressure) on the underlying salt layer. Previously, it has been shown that the history of salt flow can be constrained from the shape of the diapir that records its evolution (Vendeville & Jackson 1991, 1992b; Koyi et al. 1995; Koyi 1998).

No diapirs form in the models where the burial of the perturbation is followed by fast and continued sedimentation (e.g. model 1; \( \dot{\varepsilon}_s = 5 \) mm a\(^{-1} \); \( \eta_s = 10^{17} \) Pa s; Fig. 14a). Therefore, no entrainment of the anhydrite layer occurs in the models where a diapir does not form.

Diapirs down-built by slow sedimentation rate (\( \dot{\varepsilon}_s = 0.1 \) mm a\(^{-1} \); \( \eta_s = 10^{17} \) Pa s) are characterized by a slow vertical growth, because the salt extrudes and spreads laterally faster than it ascends vertically. In the regions of slow vertical salt movement, entrained blocks may sink (e.g. within the overhang). The entrained anhydrite segments are carried sideways into the wide overhang. In contrast, where vertical flow dominates, the anhydrite blocks will be entrained and dragged up to higher levels. When the overhang widens faster than the overburden thickens, the pre-kinematic overburden is bent downwards (Fig. 14d). The sinking pre-kinematic overburden cuts all the salt supply to the diapir from the salt layer. The crest of the diapir is covered by additional sediments that form mini-basins and segment the diapir in its later stages (Fig. 14d). The sinking mini-basins push the anhydrite blocks down as they sink into and segment the diapir.

Comparison of geometry of diapirs in models where only the sedimentation rate is varied shows that the sedimentation rate controls the behaviour of the anhydrite layer (Fig. 14). In models with viscosity \( 10^{17} \) Pa s, the highest rate of sedimentation which allows a diapir to form is 3 mm a\(^{-1} \) (Model 2; Fig. 14b). In this model, a block of the embedded anhydrite layer is carried to the highest level (3.5 km) relative to all the other models. Point A, which is an arbitrary point placed in the anhydrite layer for monitoring, is in all models located beneath the perturbation (initial coordinates \( x = 40 \) m and \( y = 840 \) m; Fig. 1). This point is transported vertically to higher levels than the other monitoring points (B–D) in all the models for different sedimentation rates (5, 3, 1 and 0.1 mm a\(^{-1} \), Fig. 15a).

Sedimentation rate can also influence the rate of sinking of the anhydrite layer. The anhydrite sinks in all models where a lid of overburden stops the diapir. In models where a high sedimentation rate suppresses the formation of a mature diapir the sedimentation rate indirectly influences the descent rate of the anhydrite layer. Rapidly accumulated sediments bury the perturbation and suppress the formation of a potential diapir. As a result, the anhydrite layer remains horizontal within the salt layer for a longer time. However if the initial perturbation is given time to grow, the anhydrite layer
is folded due to the flow of salt towards the perturbation. As such, when the diapir is buried, the folded part of the anhydrite starts to descend even though sedimentation is fast.

Viscosity of salt that has a significant impact on the structural evolution of the diapirs is one of the controlling parameters for the entrainment of embedded dense layers within a salt layer. Hence, deformation style of an embedded anhydrite layer within a layer of salt depends on salt viscosity. An anhydrite layer sinks easily into less viscous salt, whereas salt that is more viscous can prevent sinking of the anhydrite layer for longer time. Furthermore, a more viscous salt provides a larger viscous drag, and hence, assists in entrainment and carrying upward of the anhydrite layer.

In models with the same sedimentation rate, the external geometries of the diapirs depend on the viscosity of the salt. A comparison of models, in which viscosity of salt is varied, but in which the sedimentation rate is 0.1 mm a\(^{-1}\), illustrates the differences in structural evolution (Fig. 16).

Low viscous salt (e.g. \(\eta_s = 10^{17}\) Pa s) is driven easier by sedimentation, which maintains a differential pressure on the salt layer. Diapirs of low viscous salt can rise faster than the sedimentation rate. This evacuates salt from the source layer and results in the formation of a wide overhang. Faster rise rate of the diapir relative to sedimentation rate is accompanied by fast salt withdrawal from the source layer, which results in formation of a withdrawal rim-syncline adjacent to the diapir. As a result, the pre-kinematic overburden bends towards the diapir. As the pre-kinematic layer sinks, it cuts off the salt supply to the diapir. A large pillow is left behind (Fig. 16a). The embedded anhydrite layer rise until the diapir is segmented into small patches after which it starts to sink back though the diapiric stem and accumulates at the bottom of the diapir.

An increase of viscosity of salt for the same sedimentation rate (0.1 mm a\(^{-1}\)) significantly alters the structural evolution of the diapir. In the model with higher salt viscosity (model 6; \(\dot{s}_s = 0.1\) mm a\(^{-1}\); \(\eta_s = 5 \times 10^{17}\) Pa s), the diapir initially grows as a columnar as the rate of diapiric rise equals the sedimentation rate (Fig. 16b). However in the later stages, the columnar diapir evolves into upward widening diapir forming a 3-km-wide overhang. In this particular example, the diapir narrows upward due to continued, constant sedimentation over the depleted salt supply. In spite of higher salt viscosity and wider diapiric overhang, the initially entrained anhydrite layer starts to descend as the salt supply ceases.

Models with the same sedimentation rate and varied salt viscosity show that the viscosity of salt significantly alters the geometry, the rate of rise of the diapir, and its ability to entrain the anhydrite layer. The rate of salt supply has an impact on the entrainment of the anhydrite layer, which in turn is governed by salt viscosity.

The evolution of the crest of the diapir versus time for different viscosities (5 \(\times\) 10\(^{17}\), 10\(^{18}\), 5 \(\times\) 10\(^{19}\) Pa s) shows a similar evolution of the crest of the diapirs (Fig. 15b). The difference in the height of the diapirs is negligible (Figs 16b–d). In spite of similar evolution of the crest of the diapirs, increase of the salt viscosity by one order of magnitude (from 5 \(\times\) 10\(^{17}\) to 5 \(\times\) 10\(^{18}\) Pa s) influences the entrainment of the anhydrite layer significantly. The heights of the monitored points within the anhydrite layer show that more viscous salt (\(\eta_s = 5 \times 10^{18}\) Pa s) can entrain segments of the anhydrite layer to higher levels (2300 m, Fig. 15c). The drag provided by low salt viscosity is less capable to carry detached anhydrite blocks vertically. Instead, the entrained blocks are transported sideways to the widening overhang. Models with relatively low viscosity are characterized by frequent folding of the anhydrite layer, which is transported into the overhang of the diapir where they sink.

Perturbation width is one of the parameters altering the geometry and the time evolution of the diapir. In model 12 (\(\eta_s = 10^{17}\) Pa s; \(\dot{s}_s = 1\) mm a\(^{-1}\)) with larger perturbation width (800 m),
Figure 15. (a) Plot showing the path of the tracer point A embedded within the anhydrite layer for models with viscosity of salt $10^{17}$ Pa s and sedimentation rates: 5, 3, 1 and 0.1 mm a$^{-1}$. (b) Plot of the evolution of the top of the diapir for models with sedimentation rate 0.1 mm a$^{-1}$ and salt viscosities $5 \times 10^{17} - 10^{19}$ Pa s. Note: that the linear development of the diapir (viscosity $5 \times 10^{18}$ Pa s) indicates a columnar diapir. (c) The path of the trace point A for models with constant sedimentation rate 0.1 mm a$^{-1}$ and salt viscosities $5 \times 10^{17}, 10^{18}, 5 \times 10^{18}$ and $10^{19}$ Pa s. The columnar diapir ($5 \times 10^{18}$ Pa s) entrained the anhydrite at highest level.

The initial stratigraphic level of the salt layer is another important control on the amount of entrainment and the final distribution of the entrained blocks. In addition, time evolution of the diapir is significantly altered by the presence of an anhydrite layer and its stratigraphic location.

Entrainment of high-density, high-viscosity material into buoyant diapirs has been investigated by Cruden et al. (1995). For density and viscosity parameters used in this study, Cruden et al. (1995) models predict entrainment of the anhydrite layer of only 3–10 per cent. However, models presented in this study frequently show 30–90 per cent entrainment. This difference results from the different model setup: in the models used by Cruden et al. the dense layer is situated directly on a rigid basement beneath the buoyant layer, whereas in our models the denser anhydrite layer is embedded within the weak buoyant (salt) layer.

In order to quantify the effect of the presence of the anhydrite layer on the evolution of the diapir, we compare the results of models 3 and 14. In model 3 ($\dot{s}_e = 1$ mm a$^{-1}$ and $\eta_s = 10^{17}$ Pa s), where an anhydrite layer is embedded within the salt layer the crest of the diapir reaches an elevation of 1920 m in 0.51 Ma (rate of rise 1.7 mm a$^{-1}$, Fig. 18a). In model 14 ($\eta_s = 10^{17}$ Pa s and $\dot{s}_e = 1$ mm a$^{-1}$), where an anhydrite layer is absent, the crest of the diapir reaches 2280 m height in 0.51 Ma (rate of rise 2.4 mm a$^{-1}$, Fig. 18b).
Figure 16. Snapshots of models (4, 6, 7 and 8) after 10 Ma where viscosity of salt is varied and sedimentation rate is kept the same (0.1 mm a$^{-1}$). (a) Viscosity of salt is $10^{17}$ Pa s. (b) Viscosity of salt is $5 \times 10^{17}$ Pa s. (c) Viscosity of salt is $10^{18}$ Pa s. (d) Viscosity of salt is $5 \times 10^{18}$ Pa s. Note that the diapir with viscosity of salt $10^{19}$ Pa s and sedimentation rate 0.1 mm a$^{-1}$ is buried.

Figure 17. Comparison of models 3 and 12. (a) Model 3 with a 400 m perturbation width, viscosity of salt is $10^{17}$ Pa s and sedimentation rate is 1 mm a$^{-1}$. (b) Model 12 with an 800 m wide perturbation, viscosity of salt is $10^{17}$ Pa s and sedimentation rate is 1 mm a$^{-1}$.

Comparison of the overall time evolution for the diapir crest of these two diapirs shows that presence of an anhydrite layer within the salt layer decelerates the diapirc growth rate by 17 per cent (Fig. 19).

Comparison of the models where the stratigraphic location of the anhydrite layer is varied shows that initially horizontally embedded anhydrite layers can be entrained highest if it is located in the middle of the salt layer (Fig. 20). This is because the velocity gradient acting on the upper and lower boundaries of the anhydrite layer is proportional when the anhydrite is located in the middle of the salt layer. On the other hand, in case where the anhydrite layer is embedded in the upper half of the salt layer, time for initiation of the instabilities between the lower salt and the anhydrite layers is longer.

When the anhydrite layer is embedded within the upper half of the salt layer, it acts as a retardant layer for the salt flow beneath it. In the very early stages, the diapir grows by relatively slow salt withdrawal within the thin salt layer above the anhydrite layer. However, shortly after the deposition of the first overburden layer, the lower segment of the salt layer (beneath the anhydrite) is mobilized. As the overburden thickens and loads the salt layer, an increased velocity gradient of salt flow bends the anhydrite layer upward and lifts it. The entrainment starts by bending the anhydrite layer upward into the stem, where it is detached and entrained as a separate block by the upward-flowing salt to the stem of the diapir.

When the anhydrite layer is located in the lower part of the salt layer, the main salt flow is initiated within the upper thicker
5.1 Entrainment of the anhydrite layer

Numerical models with salt viscosity $10^{17}$ Pa s predict that diapirs can potentially grow with an embedded anhydrite layer, and deplete their source layer in a very short time ranging from 3 to as little as 0.7 Myr. That natural diapirs typically grow more slowly and for much longer time than the above predictions, clearly suggesting that salt does not flow freely and continuously throughout the growth history of the diapir. However, as it is shown in this article, many parameters such as sedimentation rate, salt viscosity, perturbation width and the stratigraphic location of the anhydrite layer can retard or speed up the development of the diapir. Burial of a diapir during intermediate stages of its evolution slows the rise rate of the diapir. On the other hand, adding erosion in the models will result in removing overburden units that rest on the diapir and hence may activate the diapir.

The effect of erosion depends on when it takes place relative to the onset of diapirism (i.e. pre-, syn- or post-diapirism). By removing overburden units that rest on the diapir crest, erosion influences the rise rate of the diapir and rate of sediment accumulation, and, hence, has a direct impact on the entrainment process. Pre-diapiric erosion thins overburden units which, in the presence of other triggering mechanisms (e.g. extension, differential loading), may assist in the formation of a diapir and potentially entrain any embedded denser layers. Syn-diapiric erosion removes overburden units and salt from
a rising diapir. Consequently, erosion may influence the entrainment of the diapir as it forms because it reduces sedimentation rate. Post-diapiric erosion, which occurs during a period when the diapiric growth is very slow or insignificant (inactive diapirs), can reactivate the diapir that in turn entrains denser blocks.

The negative buoyancy force acting on an anhydrite layer, which is embedded within a layer of salt, causes this layer to sink. The descent rate of the anhydrite is controlled by the density difference between the anhydrite and the salt, viscosity of salt and the size/geometry of the anhydrite layer. If the anhydrite layer sinks faster than the rate at which the salt rises within the diapir, an overall sinking of the anhydrite layer takes place. However, if the rise rate of the diapir exceeds the descent rate of the anhydrite blocks then the latter can be carried upward by the salt flow (Weinberg 1993; Koyi & Schott 2000; Koyi 2001).

Rapid salt flow is progressively countered by thinning of the source layer due to salt withdrawal towards the diapir, which simultaneously entrain the initially embedded anhydrite layer. However, if the diapir is buried by a stiff overburden layer, models presented here suggest that such blocks sink within the diapir. No entrainment is observed in models where the diapir is continually covered by overburden layers (Fig. 2). Sedimentation rate and viscosity of salt are the main parameters controlling the burial of the diapir. Diapirs of low-viscosity salt ($10^{16}$ Pa s) survive even for high sedimentation rate (e.g. 15 mm a$^{-1}$) whereas increasing the salt viscosity requires a decrease of the sedimentation rate for the diapir to rise without being buried (Fig. 21). Increase of viscosity by an order of magnitude and decrease of sedimentation rate by the same order often result in diapirs of similar geometry.

In order to simulate the entrainment of the anhydrite layer by the Gorleben diapir, we run one model with a relatively high viscosity of salt ($2 \times 10^{19}$ Pa s), slow sedimentation rate (0.025 mm a$^{-1}$), wide perturbation width (800 m) and an anhydrite layer placed in the middle of the source layer (800 m level). A slow sedimentation rate down-builds the diapir that grows 3.6 km tall in 45.26 Ma (Fig. 22). The entrained anhydrite layer remains in place even after 50 Ma (Fig. 22). We attribute this to the high viscosity salt which ‘holds’ the anhydrite layer by viscous drag. Unlike in models where the viscosity of the salt is one, two or three orders of magnitude less than the viscosity of the anhydrite layer, in this model the anhydrite layer is thickened before it starts to fold which is characteristic for a competent layer embedded within a viscous media (salt layer with the same viscosity as the anhydrite layer). The deformation style of the anhydrite layer differs in models with high viscosity of the salt. This model shows some similarity with the Gorleben diapir (Fig. 22). However, this model does not simulate the evolution history of the Gorleben diapir, nor does it take into account parameters like erosion and discrete sedimentation rate likely to have occurred during the evolution of the Gorleben diapir.

Models presented in this work confirm that a denser anhydrite layer can be entrained by the diapiric flow and entrainment is controlled by sedimentation rate, viscosity of salt, perturbation width, and stratigraphic location of the denser layer. These parameters along with the entrained anhydrite layer affect the stability of a diapir, which is considered as a repository for radioactive waste or as a storage facility. The viscosity of salt is an important parameter as it controls the rate at which entrained blocks sink within the diapir. Our models show that a high viscous salt entrains less amount of the anhydrite layer but to higher stratigraphic levels. In such cases with blocks entrained to high stratigraphic levels, when the denser blocks sink back, they disturb the whole diapir along their path. In less viscous salt diapir, on the other hand, only the lower part of the diapir will be disturbed, because in such a diapir the anhydrite blocks are entrained to lower stratigraphic levels but in larger amounts. The perturbation width is also an important parameter, which leads to formation of the diapir with a wide stem. Anhydrite blocks sink easier within diapirs with a wider stem as they do not clog up within the diapir stem.

![Plot of the height versus time for the trace point A (x = 40 m, y = 840 m) in the anhydrite layer for models with the same viscosity ($10^{18}$ Pa s) and sedimentation rate (1 mm a$^{-1}$). The anhydrite layer is placed at different stratigraphic location in these three models (upper half-800 m, middle-480 m and lower half-200 m).](image-url)
6 CONCLUSIONS

2-D numerical models of salt diapirs are used to quantify flow rates and elucidate how inclusions can be lifted and then sink during diapirism. The models presented here suggest that entrainment of denser blocks into a salt diapir is controlled by the following parameters:

(i) Sedimentation rate: Fast sedimentation suppresses the rate of diapiric rise. Denser embedded layers are likely to sink within the salt layer left beneath the thick overburden before forming a diapir. However, sedimentation rate slower than the rate of diapiric rise, can down-build a diapir that entrains and deforms the anhydrite layer.

(ii) Salt viscosity: High viscosity salt significantly influences and controls the entrainment by retarding the evolution of the diapir and thus diminishing its likelihood of lifting detached blocks to high levels. However, once initiated, a more viscous diapir entrains anhydrite blocks to high stratigraphic levels. On the other hand, the drag provided by salt of low viscosity is less capable of lifting anhydrite blocks. Instead, the entrained blocks are transported sideways into the widening overhang. Diapirs with relatively low viscosity salt are characterized by folding of the anhydrite layer as it is transported into the overhang.

(iii) Perturbation width: The width of the perturbation influences rate of diapiric rise by increasing the amount of salt that flows into the diapir through the perturbation. An increase in salt supply has a direct impact on the entrainment of the embedded anhydrite layer.

(iv) Stratigraphic location: The stratigraphic position of an embedded dense layer in a salt layer is an important control on the amount and distribution of entrainment. An anhydrite layer
embedded in the middle of a salt layer is entrained more effectively than a layer embedded within the upper or lower half of the salt layer.

(v) Presence of dense and viscous layers within a salt layer has a significant impact on the overall evolution of any diapir that initiate from this salt layer; such denser layers impede the rise rate of the diapir and thus govern its geometry.

Model results show that it is the combined effect of these four parameters (sedimentation rate, viscosity of the salt, perturbation width, and stratigraphic location of a dense layer) that shape a diapir and the mode of entrainment rather than the net value of each parameter individually.

Our model results support earlier studies (Koyi & Schott 2000; Koyi 2001) that diapirs containing denser blocks can be active internally even though they might be considered inactive externally. The Gorleben diapir in Germany, which has been considered as a repository for radioactive waste is such an example.

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