Numerical modelling of gravitational sinking of anhydrite stringers in salt (at rest)

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ABSTRACT

A large number of salt bodies contain layers of anhydrite material which is generally referred to as “stringers”. The movement and deformation of embedded anhydrite bodies are processes which are not yet fully understood. It is observed that stringers tend to sink towards the bottom of salt bodies at velocities highly dependent on the mechanical properties of both salt and anhydrites, with given density contrast between salt and denser anhydrites. The rheological differences between salt and the embedded anhydrites are a major issue, contributing to the complexity of the problem. On a geological timescale, the salt behaves as a Newtonian or a power-law fluid. The anhydrite stringers present elastic or brittle properties under certain conditions. Finite Element Modelling (FEM) has been employed in this study by using the FEM package ABAQUS (SIMULIA, Dassault Systems) in order to numerically simulate the sinking of an anhydrite stringer embedded in the salt. Furthermore, numerical modelling of isolated anhydrite stringers in salt at rest is compared with observations of stringers in seismic data. FEM simulation of the anhydrite stringer sinking and the gravitational sinking of anhydrite blocks embedded in the salt will be studied and demonstrated with two different methods of rheology, respectively. The study results indicate that sinking velocity is closely related to several factors, including the viscosity, the thickness of the stringer, as well as the density contrast between stringer and salt for a given viscosity. The results also prove that anhydrite stringer fragments do not sink significantly over the geological timescale if the halite is deformed by non-Newtonian viscosity. But, when Newtonian viscosity is dominant, the fragments are likely to sink hundreds of metres through the Zechstein salt during a few Ma. In conclusion, the modelling of the sinking of anhydrite or anhydrite inclusions provides an important scope for understanding the movement and deformation of embedded stringers.

Key words: stringer, rheology, Newtonian, power-law, sinking velocity, FEM.

1. Introduction

Anhydrite body inclusions are common in salt diapirs. However, the movement and deformation of those embedded anhydrite or anhydrite bodies are not yet fully understood. Evaporites containing thick layers of anhydrite (“stringers”) have been explored by many researchers (Weinberg, 1993; van der Bogert, 1997, 1998; Chemia and Koyi, 2008; Chemia et al., 2008, 2009). These studies
demonstrate that, due to the density contrast between salt and denser anhydrite or anhydrite, the stringers tend to move downwards in the salt at velocities which are highly dependent on the mechanical properties of the salt and the geometrical properties of the embedded stringers. In contrast to the Newtonian or power-law fluid behavior of the halite, the stringers can exhibit elastic to brittle behavior or fold and flow at much higher viscosity than the surrounding salt. In these studies, the rise and fall of a dense layer in salt diapirs is modelled in a numerical way, and the upward transport of inclusions in Newtonian and power-law salt diapirs is also explored. Some reports focus on the in situ stress model of the stringer in salt. Physical models were used to study the deformation of intra-stringers, which is related to halokinesis and inversion tectonics (Eleman, 1997). In addition, some research on the deformation of salt diapirs has been published. Examples include the following: mechanics of active salt diapirism (Schultz-Ela and Jackson, 1993), a numerical model set up for the initiation of salt diapirs with frictional overburdens (Podladchikov et al., 1993; Poliakov et al., 1993), the modelling of the salt flow by overburden (Koyi, 1996), the shaping of the salt diapirs explored by Koyi (1998), the salt minbasins investigated by Ings and Beaumont (2010), the effective viscosity of rocksalt discussed by van Keken et al. (1993), whose research is also concerned with the program of radioactive waste management. Physical models (Koyi, 2001) and numerical models (Chemia et al., 2008, 2009) were applied to study the whole process in which anhydrite blocks are entrained by salt and then descend as a whole within the structure. Numerical models were used to quantify the descent rate of entrained anhydrite blocks within a salt diapir (Koyi, 2001). Other related issues were also systematically studied, such as the effects of viscosity [Newtonian and nonlinear: Chemia et al. (2008)], position of the anhydrite layer (Chemia and Koyi, 2008), the different rising rate of salt diapirs in connection with the inclusion of anhydrite layers/blocks and their descent within a salt structure (Chemia et al., 2009), the effect of size/aspect ratio and orientation of denser blocks on sinking rate and mode (Burchardt et al., 2011, 2012a, 2012b).

In this paper, the sinking of stringers or stringer fragments in salt blocks or domes is discussed. The researchers investigate how the sinking velocity of stringers is influenced by material conditions and geometrical properties through numerical simulation. For the validation of the numerical modelling approach, two sets of simulations have been applied. First in Li et al. (2008) and Li (2013), relations between strain rate and stress obtained from simulation and experimental measurement were compared with each other. The relation between strain rate and stress can be obtained by either simulation or experimental measurement. For the former method, Finite Element Modelling (FEM) is used to simulate the cylindrical salt body under uniaxial compression. As for the latter method, the relation between strain rate and stress is obtained by varying and measuring rheological parameters (Urai and Spiers, 2007).

Second, researchers tested a simulation of the flow of a power-law fluid between two flat plates. The numerical solution for the flow velocity is compared to the analytical solution of Turcotte and Schubert (1982). Finally, comparison of simulated power-law creep with a theoretical result was completed in Li (2013). In the study, a sinking velocity formula [i.e., Stokes law: Lamb (1994)] was used to evaluate the numerical results in the model in which the velocity of a ball sinking in a steady-state Newtonian fluid (n=1) was simulated.

In recent years, the deformation mechanisms and rheology of rock salt have been investigated in a large number of studies, including laboratory experiments and microstructural investigations (Carter and Hansen, 1983; Heard and Ryerson, 1986; Urai et al., 1986; Wawersik and Zeuch,
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1986; Aubertin et al., 1989; Senseny et al., 1992; Carter et al., 1993; Peach and Spiers, 1996; Weidinger et al., 1997; Cristescu and Hunsche, 1998; Spiers and Carter, 1998; Hunsche and Hampel, 1999; Martin et al., 1999; Ter Heege et al., 2005a, 2005b; Urai and Spiers, 2007; Urai et al., 2008). During dynamic recrystallization at geological strain rate, salt is in the transition regime where both dislocation creep, related to Newtonian flow, and solution-precipitation creep, related to non-Newtonian flow, operate (Urai et al., 2008). If the dislocation creep and pressure solution act in parallel, the steady-state flow of a rock salt can be expressed as the summation of the strain rate from dislocation creep processes and the strain rate from pressure solution (Urai et al., 2008). In power-law creep, the strain rate is related to the flow stress using the equation:

$$\dot{\varepsilon} = A(\Delta \sigma)^n = A_0 \exp\left(-\frac{Q}{RT}\right)(\sigma_1 - \sigma_3)^n$$

where $\varepsilon$ is the strain rate, $\Delta \sigma = \sigma_1 - \sigma_3$ is the differential stress, and $A = A_0 \exp(-Q/RT)$ is the viscosity of the salt. Within the viscosity described above, $A_0$ is a material-dependent parameter, $Q$ is the specific activation energy, while $R$ is the gas constant ($R=8.314 \text{ J mol}^{-1} \text{K}^{-1}$) and $T$ is the temperature. The other mechanism is solution-precipitation creep:

$$\dot{\varepsilon} = B(\Delta \sigma) = B_0 \exp\left(-\frac{Q}{RT}\right)\left(\frac{\sigma_1 - \sigma_3}{TD^m}\right).$$

The strain rate is dependent on the strain size $D$, $\Delta \sigma = \sigma_1 - \sigma_3$ is the differential stress, and $B = B_0 \exp(-Q/RT)/(1/TD^m)$ is the viscosity of the salt. Within the viscosity described above, $B_0$ is a material-dependent parameter, $Q$ is the specific activation energy, while $R$ is the gas constant ($R=8.314 \text{ J mol}^{-1} \text{K}^{-1}$), and $T$ is the temperature. The order $m$ influences strain rate dependent on the grain size.

Fig. 1 summarizes low-temperature laboratory data for a wide range of halite based on experiments by Sandia, BGR, Utrecht University, and other laboratories. The dashed line represents an extrapolation of the dislocation creep with $n=5$ (30-50 °C). The solid lines are room-temperature solution-precipitation creep laws for different grain sizes. During active salt tectonics (differential stress in the order of a few MPa as shown by subgrain size piezometry), the two kinds of rheology have similar strain rates, and both are interpreted to be important in coarse-grained diapiric salt (Schléder and Urai, 2005). In this study, numerical experiments were designed to be sensitive to salt rheology, geometry, and density of stringer or fragment. The purpose and interest of the research is to investigate the sinking velocity of stringers as influenced by salt rheology, density contrast, and geometrical properties. In recent years, Koyi (2001) studied the effect of thickness on descending rate. The experimental results indicated that thicker blocks sink faster in the Newtonian salt. Chemia et al. (2008, 2009) studied the effect of differences in the rheology of salt. The same geometry as that of the Gorleben salt diapir and the anhydrite layers was simulated to study the interaction between these two rock units. These studies investigated the effect of including different salt rheology within the same model in order to simulate the different subgroups of Zechstein formation. In our study, we changed the value of thickness, density contrasts, and the rheology of the salt within which the embedded stringer descends. A generic model and a case from Zechstein salt in the northern Netherlands were chosen. Cases obtained from seismic data tend to produce results which later can be compared with observations in real fields. In this way, more insights are likely to be provided for further studies. Different from Chemia et al. (2008),
the salt tectonics in our models is not active and the stringer sinks after salt tectonics. The study is similar to the research of Burchardt et al. (2011, 2012a, 2012b), who used extensive numerical modelling to study sinking anhydrite blocks within a Newtonian salt body. In our model, the stringer is brittle rather than viscous, and salt flow presents the property of both Newtonian and non-Newtonian fluid. In this way, the stringers tend to sink due to gravitational loading and the density contrast between itself and surrounding salt. The relation between sinking velocity and material or geometrical properties can be clearly observed.

2. Methods and models

2.1. Gravitational sinking of a single stringer in salt block (a generic model)

As for the simplest, generic model for the sinking of an anhydrite stringer embedded in a salt body, we have chosen a setup consisting of a single rectangular stringer inside a rectangular salt block (Fig. 2). The geometry of the model is described by the width and height of the salt body, which are respectively set to be 8 and 4 km in all of the following models; \( h \) stands for the thickness of the stringer, \( w \) is the width, and \( D \) is the initial depth, which is measured from the top of the stringer. The model consists of a salt block, the geometry of which is 8 km wide and 4 km high.

For the case of Newtonian flow, the rheology is presented with \( A_0=4.70\times10^{-10} \text{ Pa}^{-1}\text{s}^{-1}, Q=24530 \text{ J/mol}, m=3, n=1, D=0.01 \text{ m}, R=8.314 \text{ J/(mol·k)} \) (Spiers et al., 1990). For the case of non-Newtonian flow, the rheology is presented with \( A_0=1.82\times10^{-39} \text{ Pa}^{-5}\text{s}^{-1}, Q=32400 \text{ J/mol}, n=5, R=8.314 \text{ J/(mol·k)} \)
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Schoenherr et al., 2007. The surface temperature is set to be 50 °C and, at the depth of 4 km, the temperature is set to be 140 °C (i.e., the lower limit of the model). 2D plane strain conditions are applied. Using this model, we observed that the sinking velocity of the central point in the stringer depends on the following factors: a) thickness and aspect ratio of the stringer, b) the density contrast between the stringer and the surrounding salt.

2.2. Gravitational sinking of 30-to-80 m-thick Zechstein intra-salt stringers

The concept is based on seismic observations from the Zechstein salt (van Gent et al., 2011; Strozyk et al., 2012). During salt tectonics, many Zechstein intra-salt stringer fragments appear due to breakage, the thickness of which ranges from 30 to 80 m. The fragments are located in the upper part of the salt section. The width of the fragments ranges from 100 to 1000 m (Fig. 3). The Mesozoic is the main phase of salt tectonics and tectonics stopped from the Paleogene (Geluk, 2000, 2005). In our study, adaptive remeshing techniques in FEM were applied (Li et al., 2012a, 2012b). The models calculate the sinking velocity and trajectory of fragment geometries for the two different kinds of salt rheology after salt tectonics stopped. The calculation results can be very useful. On the one hand, we can evaluate the relation between sinking velocity of stringer fragments and viscosity for the two different kinds of salt rheology. On the other hand, we can also evaluate the relation between sinking velocity and the geometrical properties of the stringer fragment. Besides, by comparing the modelling results with the observations of seismic data, salt rheology can be further studied to facilitate other research (Li et al., 2012b).

Modelling and calculation involve two major steps (Li et al., 2012b). First, a vertical displacement of the top salt boundary should be applied to simulate the down-building of overburden sediments and formation of a salt pillow (Li et al., 2012a). Second, gravitational loading is applied to the salt section after tectonics and the sinking velocity and trajectory of stringer fragments are surveyed.
Two models with different dominant salt rheology are applied: model A is performed with pressure-solution creep \((n=1)\), and model \(B\) is performed with dislocation creep \((n=5; \text{Table 1})\). In addition, the geometry and configuration of stringer fragments in the two models are also different. We compared the sinking velocity of fragments in two models which have different salt deformation mechanisms. Table 1 shows the rheological and mechanical properties of both the salt layer and the stringer fragments used for the two models.

![Fig. 3 - 3D seismic data (left) and 2D seismic profile (right) with interpreted, physically isolated Zechstein 3 stringer fragments embedded in the deformed salt sections, northern Netherlands (by courtesy of NAM).](image)

![Fig. 4 - Model width is 18 km and initial model thickness 1 km. A: initial model setup before salt tectonics without differential stresses.](image)

![Table 1 - Material parameters for anhydrite and rock salt [following the two different deformation mechanisms at 50° C (i.e., lower limit of the model)].](table)

<table>
<thead>
<tr>
<th></th>
<th>Salt A: pressure-solution creep (Newtonian flow)</th>
<th>Salt B: dislocation creep (Non-Newtonian flow)</th>
<th>Anhydrite blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_0)</td>
<td>(4.70 \times 10^{-10} \text{ Pa}^{-1} \text{ s}^{-1})</td>
<td>(1.802 \times 10^{-39} \text{ Pa}^{-5} \text{ s}^{-1})</td>
<td>-</td>
</tr>
<tr>
<td>(Q \ [\text{J/mol}])</td>
<td>24530</td>
<td>53920</td>
<td>-</td>
</tr>
<tr>
<td>(R \ [\text{J/(mol·K)}])</td>
<td>8.314</td>
<td>8.314</td>
<td>-</td>
</tr>
<tr>
<td>(m,n)</td>
<td>3/1</td>
<td>0/5</td>
<td>-</td>
</tr>
<tr>
<td>(\mu \text{/density [kg/m}^3)]</td>
<td>2200</td>
<td>2200</td>
<td>2900</td>
</tr>
<tr>
<td>(E)/Youngs Modulus [GPa]</td>
<td>10</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>(\nu) Poisson’s ratio</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>
A simplified model of the Zechstein salt section (Fig. 7) was applied. This model included seven stringer fragments which are elongated, broken, and isolated. The width of each fragment is chosen from 100, 600, and 1000 m, while thickness is chosen from 30, 60, and 80 m. All fragments are embedded in a rectangular salt section 1 km thick and 18 m long, which is a plane strain model based on seismic observations from van Gent et al. (2011). The boundary condition for the model is displacement equals zero when it is perpendicular to the bottom and both sides of the model. The top of the salt surface is fixed in x and y direction after salt tectonics lasting for 4 Ma. When salt tectonics stops, a model with a time span of 60 Ma is performed to simulate the Zechstein salt at rest in the Tertiary. Table 2 is a summarization which presents the geometric parameters of stringer fragments and salt section as well as the time duration of each experimental phase.

Table 2 - Geometrical and temporal model setup.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of salt body</td>
<td>18000 m</td>
</tr>
<tr>
<td>Height of salt body</td>
<td>1000 m</td>
</tr>
<tr>
<td>Stringer fragment thicknesses</td>
<td>30, 60, 80 m</td>
</tr>
<tr>
<td>Stringer fragment widths</td>
<td>100, 600, 1000 m</td>
</tr>
<tr>
<td>Amplitude down-building</td>
<td>300 m</td>
</tr>
<tr>
<td>Duration salt tectonics</td>
<td>4 Ma</td>
</tr>
<tr>
<td>Duration salt at rest</td>
<td>60 Ma</td>
</tr>
</tbody>
</table>

3. Results

3.1. Gravitational sinking of a simple stringer in salt block

3.1.1. Stringer thickness

First we investigate the influence of the variations in the thickness, and therefore mass, of the stringer. In this part, the width of the stringer $w$ is a constant value and the height of the stringer $h$ is various. The boundary conditions are zero displacement perpendicular to the boundary at the bottom and at the sides. The material properties of the stringer are Young’s modulus $E=40$ GPa, Poisson ratio $\nu=0.3$, and density $\rho=2400$ kg/m$^3$ (Sayers, 2008). This geostatic state is used as the initial stress condition for the next step.

![Graph showing sinking velocity vs. thickness](image)

Fig. 5 - Sinking velocity of the stringer vs. stringer thickness. The variation in stringer thickness (140, 160, 180, 200, 220, and 240 m) results in aspect ratios of 8.6, 7.5, 6.7, 6.0, 5.4, and 5.0 respectively due to the constant length of the stringer (1200 m). a) The salt rheology is Newtonian ($n=1$); b) the salt rheology is non-Newtonian ($n=5$).
Fig. 5 illustrates the relation between the sinking velocity and the thickness of the stringer, separately for \( n=1 \) and \( n=5 \). The stringer thickness \( h \) is 140, 160, 180, 200, 220, and 240 m, and therefore the aspect ratio is 8.6, 7.5, 6.7, 6.0, 5.4, and 5.0, respectively. The variation of the size, and thereby the mass, of the stringer influences the differential stress \( \Delta \sigma \) linearly. The sinking velocity of the stringer are determined by the strain rate on the differential stress when \( n=1 \) and 5\(^{th} \) order relation when \( n=5 \). The displacement and velocity of the stringer have the same trend as the strain rate. Moreover, from the result, we can know that the stringer with the same size in both \( n=1 \) and \( n=5 \) rheological salt has similar differential stress \( \Delta \sigma \) distribution around it because of the same mass, and the peak differential stress around the stringer changes from 100 to 150 kPa with various stringer size.

### 3.1.2. Density contrast

The second parameter influencing the sinking velocity we discuss is the density contrast between the salt and the stringer. A single stringer 1200 m wide and 160 m thick is located in the salt. The material properties of the stringer are Young’s modulus \( E=40 \) GPa, Poisson ratio \( \nu=0.3 \), and density \( \rho=2400 \) kg/m\(^3\). The salt density is 2040 kg/m\(^3\), and the stringer density is 2200, 2300, 2400, 2500, 2600, 2700, and 2800 kg/m\(^3\), respectively. The initial location of the stringer is in the centre of the salt block.

The results of the simulations confirm the expectations. The numerical solution shows that for Newtonian fluid flow (\( n=1 \)), the sinking velocity of the stringer in the salt follows a linear relation depending on the density contrast (Fig. 6a). For non-Newtonian fluid flow (\( n=5 \)), the sinking velocity of the stringer follow a nonlinear relation with 5\(^{th} \) power order (Fig. 6b). The variation of the density influences the differential stress \( \Delta \sigma \) in the salt linearly. The strain rate varies from the density contrast due to the relation \( \dot{\varepsilon}=A(\Delta \sigma)^n \) and \( \dot{\varepsilon}=B(\Delta \sigma) \).

#### 3.2. Gravitational sinking of 30-to-80 m-thick Zechstein 2 intra-salt stringers

Figs. 7a and 8a show the initial model setup with the stringer fragments Nos. 1-7 in salt section. Figs. 7b and 8b show that the stringer fragments rotate during salt tectonics when Newtonian law
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Fig. 7 - Results of Model A using salt rheology of \( n=1 \). Model width is 18 km and initial model thickness 1 km: a) initial model setup before salt tectonics without differential stresses; b) Model A during salt tectonics (-62 Ma); c-g) Model A after salt tectonics (-60, -40, -20 Ma, and today).

Fig. 8 - Results of Model B (right) using salt rheologies of \( n=5 \). Model width is 18 km and initial model thickness 1 km: a) initial model setup before salt tectonics without differential stresses; b) Model B during salt tectonics (-62 Ma); c-g) Model B after salt tectonics (-60, -40, -20 Ma, and today).
dominates, while the fragments in the salt with \( n=5 \) (Model B; Figs. 8b and 8c) almost do not sink. Furthermore, we detect average sinking velocity and differential stresses around the stringer fragments in both Model A and Model B, depending strongly on the geometry and location of the fragments in the salt body (Table 3). Finally, the bending deformation of stringer fragments can be clearly seen in Model A during the sinking process and the bending deformation also increases the internal stress of the stringer fragment.

From Table 3, we can figure out the relation between the sinking velocity and the thickness of the stringer, both for Model A (\( n=1 \)) and Model B (\( n=5 \)). Here average sinking velocity in the central point of a stringer fragment is investigated because of rotation or deformation. And the sinking velocity of a stringer fragment will decrease when it gets close to the bottom of the salt section.

The variation of the size and mass of the stringer linearly influences the differential stress, and the velocity of the stringer is determined by the strain rate, depending on the thickness of the stringer in the salt which is linearly dependent on the differential stress when \( n=1 \) and has nonlinear relation when \( n=5 \). The differential stress of a stringer fragment keeps stable and does not change with salt rheology. The stringer fragments Nos. 3, 4, and 5 share the same width of 1000 m, but have different thicknesses of 30, 60, and 80 m, respectively. For Model A, the average sinking velocities of the three stringer fragments are 28.4, 49.8, and 101.7 m/Ma separately, while the differential stresses around stringers are 133, 146 and 154 kPa. For Model B, the average sinking velocities are 0.45, 0.72, and 0.90 m/Ma, while the differential stresses around the stringers are 131, 146, and 154 kPa. Moreover, the stringer fragments Nos. 1, 4, and 6 have the same width of 80 m but different thicknesses of 100, 500, and 1000 m, respectively. For Model A, the average sinking velocities are 40.5, 75.8, and 101.7 m/Ma, while the differential stresses around stringers are 136, 148, and 154 kPa. In Model B, the average sinking velocities are 0.63, 0.84, and 0.90 m/Ma, while the differential stresses around stringers are 132, 147, and 154 kPa.

Furthermore, the stringer fragments Nos. 2, 6, and 7 have the same width of 600 m but different thicknesses of 30, 60, and 80 m, respectively. For Model A, the average sinking velocities are 27.4, 49.8, and 75.8 m/Ma, while the differential stresses around stringers are 134, 138, and

### Table 3 - Results of average sinking velocity, sinking displacement and differential stress of the stringer fragments 1-7 in Model A with the rheology \( n=1 \) (pressure-solution creep) and Model B with the rheology \( n=5 \) (dislocation creep).  

<table>
<thead>
<tr>
<th>Stringer fragment No. (see Fig. 3a)</th>
<th>Fragment width/thickness [m]</th>
<th>Model A ( (n=1) )</th>
<th>Model B ( (n=5) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average sinking velocity [m/M]</td>
<td>Sinking displacement in 10 Ma [m]</td>
</tr>
<tr>
<td>1</td>
<td>100/80</td>
<td>40.5</td>
<td>405</td>
</tr>
<tr>
<td>2</td>
<td>600/30</td>
<td>27.4</td>
<td>274</td>
</tr>
<tr>
<td>3</td>
<td>1000/30</td>
<td>28.4</td>
<td>284</td>
</tr>
<tr>
<td>4</td>
<td>1000/80</td>
<td>101.7</td>
<td>1017</td>
</tr>
<tr>
<td>5</td>
<td>1000/60</td>
<td>49.8</td>
<td>498</td>
</tr>
<tr>
<td>6</td>
<td>600/80</td>
<td>75.8</td>
<td>758</td>
</tr>
<tr>
<td>7</td>
<td>600/60</td>
<td>49.8</td>
<td>49.8</td>
</tr>
</tbody>
</table>

148 kPa. For Model B, the average sinking velocities are 0.44, 0.63, and 0.84 m/Ma, while the differential stresses around stringers are 130, 136, and 147 kPa. Here one thing we should pay attention to is that the linear relation is not obvious in this example for Model A (n=1), because the movement of stringer fragments with large width and thickness is sometimes restricted by the boundary effect.

4. Discussion

Simulation is used to evaluate the effect of model geometry and material parameters on the movement of anhydrite stringers which are embedded in salt. Whether using the generic model or the model based on the Zechstein salt, results indicate that the sinking velocity of the stringer varies linearly with parameter $A$ and parameter $B$ [$A=A_0 \exp(-Q/RT)$, $B=B_0 \exp(-Q/RT)(1/TD^n)$], both of which are derived from the flow law $\dot{\varepsilon}=A(\Delta \sigma)^n$ and $\dot{\varepsilon}=B(\Delta \sigma)$. However, any change in the differential stress $\Delta \sigma$ leads to either linear change in the sinking velocity for Newtonian rheology ($n=1$) or nonlinear change for power law rheology ($n>1$) (the differential stress $\Delta \sigma$ is caused by varying the size of the stringer or the density contrast between the stringer and the salt). In this case, the non-linear change of the sinking velocity follows a power law with the same exponent $n$. Density and geometry change of the stringer is related to its own gravity that affects the differential stress $\Delta \sigma$.

The calculation result of the single stringer in the generic model shows that the velocity of the sinking anhydrite stringer is greater than 1000 m/Ma, which indicates that if the salt follows the rule of Newtonian rheology and the viscosity $B$ is 10-20 Pa·s, the stringer will get close to the bottom of the salt body in a time range of about 10 Ma. The velocity of the sinking anhydrite stringer is similar to that of the anhydrite blocks which are embedded in Newtonian salt (Burchardt et al., 2011). Besides, the velocity of stringer fragments varies from 15 to 100 m/Ma if anhydrite blocks are embedded in Zechstein salt at rest (effective stress decreases after relaxation) which follows the Newtonian law and has a salt viscosity of around $10^{-19}$ Pa·s. All of the stringer fragments would get close to the base of the salt section within a time span of the entire Tertiary. However, it is observed in seismic data (van Gent et al., 2011; Strozyk et al., 2012) that some stringers are still located close to the top or in the upper part of the salt body after a longer time (~ 60 Ma). This discrepancy suggests that the long-term rheological behavior of the salt is, at least in some cases, quite different from what we expected from the rheological parameters which are obtained in the laboratory. When the salt follows power-law rheology, the sinking velocities are rather slow. The explanation for this situation is that due to the gravitational sinking stringer in long-term rheological salt, the peak differential stress around the stringer is 100-150 kPa, which leads to a rather low strain rate of around $10^{-20}$-$10^{-19}$ s$^{-1}$. It is clear that stringers do not significantly sink over geologic times.

Other issues discussed here include that the initial location (depth) of the stringer also has a big impact on the salt flow and its own descent (Chemia et al., 2008). In our study, this factor seems to be not as important as salt rheology, density contrast, and geometrical properties of the stringer, because the method employed in this study is gravitational sinking stringer in salt at rest (after tectonics) since we focus on the relation between sinking velocity and factors including salt rheology, density contrast, and geometrical properties of the stringer due to gravitational
loading. Salt tectonic process or the movement of salt diapir can have a direct impact on the rise and fall of stringers or stringer fragments. The complex model which includes salt tectonic movement and gravitational loading could be taken into account in further research of movement and deformation of embedded stringers.

5. Conclusion

This study has demonstrated that salt rheology and model geometry of stringers (fragments) are the dominant factors affecting the sinking velocity of anhydrite stringers in the generic model or anhydrite blocks in Zechstein salt at rest (the stress in Zechstein salt is released after tectonic movement). The study has also indicated that the sinking velocity of the stringer linearly changes with the rheological parameters $A$, $B$, and $n$. Moreover, as is shown in the results of the generic model, the factors affecting sinking velocity at a given rheology are stringer thickness and density contrast. Thickness and width of stringer fragment are also factors that control sinking velocity in Zechstein salt. The velocity changes nonlinearly for power-law rheology ($n>1$) and changes linearly for Newtonian rheology when the value of stress $\Delta\sigma$ changes. In this case, the nonlinear change of the sinking velocity follows a power law with the same exponent $n$.

In contrast to the Newtonian rheology leading to high sinking speed (>15~100 m/Ma), the power-law rheology results in stringers presents no significant sinking over the geologic timescale, which is consistent with the seismic data observations. These large differences in sinking velocity are due to the very low differential stress around the stringers, on the order of 0.1 MPa, after salt tectonics stopped. Finally, we can conclude that the simulation of gravitational sinking of a simple anhydrite stringer in the generic model and anhydrite blocks in rock salt based on observations from natural settings enables a profound understanding of movement and deformation of embedded stringers or fragments.

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