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**The Influence of Shortening and Sedimentation on Rejuvenation of Salt
Diapirs: a new Discrete-Element Modelling Approach**

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ABSTRACT

This study employs a novel Discrete-Element Modelling approach to investigate the interplay of sedimentation with rejuvenation of diapirs by shortening. The inherent complexity of salt tectonics, the complications encountered when imaging structures beneath salt, and the lack of outcrop analogues, coupled with its importance to petroleum systems, make salt tectonics one of the most interesting and debated topics in basin studies. Model results successfully reproduce the geometric and dynamic behaviour of active diapirism and show the effects of sedimentation thickness, rate and timing on the generation of distinct diapir geometries, including i) salt tongues and ii) squeezed upright diapirs. Models with late sedimentation or a lower sedimentation rate relative to salt mobility show development of asymmetric diapirs with allochthonous salt tongues; whereas models with earlier sedimentation or a faster sedimentation rate generate upright squeezed diapirs. Early sedimentation at a moderate rate results in a symmetrical hour-glass shaped structure, resembling a tear-drop diapir. Results are fully reproducible and comparable with many natural examples, and include overburden deformation which is difficult to simulate using other numerical techniques. Extending this approach to different problems and basinal contexts could improve our understanding of deformation mechanisms and sediment distribution around salt structures.

1. Introduction

Salt is an incompressible material with negligible yield strength that behaves as a viscous fluid under typical geological strain rates (e.g. Turcotte and Schubert, 2002; Hudec and Jackson, 2007). The mechanical instability of evaporites, herein referred to as salt, allows it to be more easily deformed than any other rock and to produce some of the most spectacular structures found in sedimentary basins (Fig. 1a and b). Salt tectonics acts as a major control on the geological and structural evolution of more than 120 basins around the world (Hudec and Jackson, 2007). Most of these basins are prolific hydrocarbon provinces e.g. the Gulf of Mexico (e.g. Schuster, 1995; Rowan 1995; Rowan et al., 2000; Hudec and Jackson, 2009; Hudec et al., 2013), the North Sea (e.g. Trusheim, 1960; Davison, et al 2000; Van Gent et al., 2010; Jackson and Lewis, 2014; Harding and Huuse, 2015), the Mediterranean (e.g. Gaullier et al., 2000; Cartwright et al., 2012), the South Atlantic (e.g. Mohriak et al., 1995, 2012; Cramez and Jackson, 2000; Hudec and Jackson, 2004; Fort and Brun, 2004; Jackson et al., 2008; Davison *et al.*, 2012; Fiduk and Rowan, 2012; Quirk et al., 2012; Jackson et al., 2015) and Nova Scotia (e.g. Alberty et al., 2010). In these basins, the mobility of salt affects reservoir distribution, migration pathways and trap formation and, due to its low permeability salt acts as the most efficient seal-rock for petroleum systems, therefore being a critical factor for hydrocarbon exploration (Hudec and Jackson 2007; Mohriak et al., 2009; Tari and Jabour, 2013; Harding and Huuse, 2015).

Rejuvenation of diapirs is a common phenomenon of salt basins around the world and is commonly driven by regional shortening. On continental margins, regional shortening can be caused by gravity-driven salt tectonics, such as in Angola (Hudec and Jackson, 2004), Brazil (Quirk et al., 2012; Fiduk and Rowan, 2012), Nova Scotia

(Albertz et al., 2010) and the Gulf of Mexico (Rowan et al., 2000; Hudec et al., 2013) or by its combination with thick-skinned crustal tectonics as in NW Africa (Davison, 2005; Tari and Jabour, 2013; Tari et al., 2017), the North Sea (Davison et al., 2000; Harding and Huuse, 2015), the Parentis Basin (Ferrer, et al., 2012), and the Gulf of Cadiz (Matias et al., 2011) Some of the most successful salt-related hydrocarbon plays along these margins occur associated with salt structures that were reactivated by shortening, such as the flank-of-diapir play in the Central Graben in the North Sea, examples including Banff, Mashar, Monan, Pierce and many other discoveries in the flanks of squeezed upright diapirs worldwide (Davison et al., 2000; Birch and Haynes, 2003), and sub-salt plays beneath allochthonous salt tongues and sheets, such as the Ship Shoal and Mahogany oil fields in the Gulf of Mexico, plays that host considerable volumes of hydrocarbons, and are becoming increasingly important as seismic imaging methods improve (Montgomery and Moore, 1997).

Shortening of salt stocks and walls displaces salt, and can result in pinching-off of their necks with complete exhaustion of salt supply and the development of sub-vertical salt-welds and dramatic structures such as tear-drop diapirs and allochthonous salt tongues (Fig. 1a-b; Hudec and Jackson, 2007, 2011). Tear-drop diapirs (Fig. 1b) have an hourglass shape in which a symmetric salt bulb is separated from its pedestal and source-layer by a (sub) vertical salt weld (Nilsen and Vendeville, 1995; Hudec and Jackson, 2007). Salt tongues (Wang, 1988; Hudec and Jackson, 2007; Tari and Jabour, 2013) may also have a squeezed sub-vertical feeder but differ from tear-drop diapirs, mainly because their asymmetric upper salt body has a larger seaward overhang compared to a smaller or non-existent landward overhang which results in emplacement of allochthonous salt at a higher stratigraphic level (Fig 1a and 4b). Allochthonous salt tongues may also develop due

to differential loading (Schuster, 1995; Rowan, 1995) whereas tear-drop diapirs form exclusively by lateral shortening.

Figure 1 here

Although the development of tear-drop and squeezed diapirs is relatively well-known, the evolution of salt tongues and sheets and their interaction with sedimentation is still poorly understood. Some authors (McGuinness and Hossack, 1993; Talbot, 1993; Fletcher et al., 1995; Rowan and Inmann, 2011) consider they form due to salt extrusion at the paleo sea-floor, whereas others argue that they are formed by contractional reactivation of buried salt structures and thrust piercement of salt (Nelson and Fairchild, 1989; Wu et al., 1990; Tari et al., 2003; Hudec and Jackson, 2007; Tari and Jabour, 2013; Jackson et al., 2015). The impact of sedimentation on the rejuvenation of diapirs and on the generation of these distinct geometries (e.g. symmetric diapirs and salt tongues) is still not fully understood.

The lack of good and accessible outcrop analogues of salt structures at the scale of an entire diapir, problems with seismic imaging linked with the high velocities associated with salt, the complex geometries encountered (Fig. 1a and b) and its unique mechanical behaviour make the interpretation of salt tectonics and its interaction with surrounding sediments and basement structures challenging. In this context, physical and numerical forward modelling techniques are useful tools that help improve understanding of the kinematic and mechanical behaviour of salt.

The latest finite-element models (FEM), based on arbitrary Lagrangian-Eulerian formulations (Gemmer et al., 2004, 2005; Albertz and Ings, 2012; Gradmann et al., 2009; Gradmann and Beaumont, 2016) provide successful and numerically accurate results of local and regional scale salt tectonics (Fig. 1c). Their reproducibility and

more precise control on numerical parameters have significant advantages over physical models, but they prevent observation of realistic deformational processes in the overburden, such as brittle deformation, as they treat it as a continuous frictional-plastic and often viscous-plastic material (Fig.1c). Other limitations of FEM are that points are fixed in their respective temporal and spatial positions while the grid moves and it requires regular re-meshing (Schultz-Ela et al., 1993; Fullsack, 1995), a relatively computationally intense process necessary within deformed areas.

Physical models typically using silicone polymers and sand to simulate salt and overburden and have been very efficient in modelling salt tectonics at regional and small scales in both 2D and 3D (Fig. 1d), increasing our current knowledge of salt tectonics by producing geometrically accurate and naturalistic results. There are few drawbacks, however, with this technique due to the amount of time and financial investment required for each experiment and, even though they are reasonably reproducible on a large scale, repeated experiments are not exactly identical in a finer scale as in numerical methods (Botter et al., 2014), which involve more control on physical parameters and can allow tracking of individual particles and forces in the system through time.

Due to the predominant focus of the hydrocarbon industry in understanding reservoir distribution and compartmentalization around salt structures, a novel approach has been applied in this study. A Discrete-Element Modelling (DEM) technique has been developed to investigate the interplay between rejuvenation of diapirs by shortening and deep-water sedimentation. The ultimate goals of this study are: i) to evaluate how active diapirism controls sediment distribution and overburden deformation; ii) to assess how aggradation affects diapir geometry on a slope setting; and ii) to test the

feasibility of DEM for salt studies, by comparing results with natural examples and commonly used physical and numerical analogues.

DEM is a discontinuous method in which the viscous behaviour of salt is approximated. Here, it is considered a complementary solution to other modelling techniques as it produces physically realistic and relatively fast results that provide new and valuable insights of the sequential evolution of salt diapirs and how they interact with sedimentation and deformation in the overburden.

2. Methodology

2.1. Discrete-Element Modelling Principles

The Discrete-Element Modelling (DEM) applied here is a discontinuous numerical method derived from the Lattice Solid Model (LSM) from Mora and Place (1993, 1994) and Place et al. (2002) and the Particle Dynamics Method. This technique has been used extensively in physics and chemistry to simulate liquid and gas behaviours (Allen and Tildesley, 1987; Hardy and Finch, 2006). Most recently, it has been successfully applied in simulation and modelling of the dynamic evolution of natural geological systems (Donzé et al., 1993; Place et al., 2002), and to investigate faulting and folding processes (Finch *et al.*, 2003, 2004; Hardy and Finch 2005, 2006, 2007; Schöpfer, 2006) as well as viscous flow of rock matrices (Abe and Urai, 2012).

As with any other modelling approach, DEM has limitations, such as the limited number of particles and duration of simulations (Zhu et al., 2008) and the need of meticulous calibration of particle parameters (Botter et al., 2014), but it offers the following advantages over other methods: 1) scale is not a restriction, 2) results are

easily reproducible, 3) it does not require complex re-meshing and extraction of temporal and spatial information to track individual elements since each computing step registers position and velocities of elements within the system; and 4) it is intrinsically discontinuous and each element simulates the physical properties of a rock. These factors make DEM an ideal method to quantitatively study overburden deformation.

DEM treats the rock mass as an assemblage of circular elements that interact in pairs connected by breakable elastic springs through a 'repulsive-attractive' force obeying Newton's Laws of motion (Mora and Place, 1993, 1994; Finch *et al.*, 2004; Hardy and Finch, 2006). The relative strength of the assemblage is defined by its breaking separation so the particles remain bonded until this threshold is exceeded (Donzé *et al.*, 1994; Finch *et al.*, 2004). The force acting on a bond at this threshold corresponds to the force necessary for failing or yielding of the bond, representing the stress acting on a particle at failure (Hardy and Finch, 2005). Once a bond is broken, the elements that it connects experience no further attractive force. If the elements return to a compressive contact however, a repulsive force acts between them. Thus, healing of bonds is not allowed in this methodology (Finch *et al.*, 2003, 2004; Hardy and Finch, 2006). The motion of elements is assumed to be frictionless and cohesionless with elasto-plastic behaviour (Finch *et al.*, 2003; Hardy and Finch, 2007).

The circular elements in these models have four different radii of 0.2, 0.3, 0.4 and 0.5 units which are randomly distributed to reduce failure in preferential orientations within the matrix. A viscous term ($\dot{v}$) is added to counteract the elastic behaviour of the springs and the build-up of kinetic energy within a closed system. This viscosity rapidly dissipates energy and damps reflected waves from the model boundaries,

reducing dynamic phenomena and thermal vibrations, and enabling the stabilization of the model (Finch et al., 2004), making it ideal for the study of tectonic processes.

Forces are resolved in both x and y directions and, as the elements are also subjected to gravitational forces, F_g , the equations that define the inter-relationship of all forces acting on the DEM are:

$$F_x = F_{i,n} - v\dot{x} \quad (1)$$

$$F_y = F_{i,n} - v\dot{y} + F_g \quad (2)$$

Where $F_{i,n}$ corresponds to the total elastic force acting on a particle, v represents the dynamic viscosity and $\dot{x}$ and $\dot{y}$ correspond to the velocity of the particle. For a complete and more detailed description of scaling of parameters and the equations governing DEM, see Mora and Place (1994), Finch et al. (2004) and Hardy and Finch (2005, 2006).

2.2. Discrete-Element Modelling of Salt Tectonics

Because of its discontinuous nature, DEM has not yet been used to analyse salt-related deformation. Nevertheless, Abe and Urai (2012) applied it successfully to reproduce the viscous behaviour of boudinage matrix flow, showing that the methodology can be efficient to model viscous-plastic materials. In order to make DEM applicable to salt tectonics, the properties of the elements representing salt are adjusted so they behave macroscopically as a viscous-plastic material and deform microscopically by an approximation of dislocation-creep, which is expected for dry rock-salt (Urai et al., 1986; Spiers et al., 1990). This does not reproduce entirely the mechanical behaviour of salt in nature, which usually contains traces of brine (Urai et al., 1986) and deforms on the threshold of diffusion and dislocation creep (Spiers et

al., 1990; Jackson and Hudec, 2017) but, based on the stress-strain response obtained in our study (Fig. 2), it works as a good first-order approximation.

Figure 2 here

This approximation of the mechanical behaviour of rock-salt is achieved by reducing the breaking separation of particles representing salt to the point that they deform plastically and are controlled entirely by the viscosity and gravity of the system, thus exhibiting macroscopic viscous-plastic behaviour. In order to achieve this, a range of breaking separations was tested using biaxial compressional tests and extracted differential stress-strain plots. Here, the results from experiments with materials that reproduced the expected mechanical behaviour of salt and the overburden are presented, which have 0.001 and 0.05 of separation threshold respectively (Fig. 2).

The tests show that a media with a separation threshold of 0.05 is relatively weak but still develops well-defined fault segments (Fig. 2a and b) and produces a stress-strain response typical of brittle materials with an initial elastic (upward segment) and a later brittle component (downward segment) (Fig. 2c); whereas materials with breaking separation of 0.001 react with non-localized and pervasive breaking of bonds (Fig. 2a and b), and generate a linear and horizontal response with insignificant elastic component, representative of ductile viscous-plastic materials that accumulate strain without significant variations of stress (Fig. 2c). This response pattern of materials representing rock-salt is very similar to the curves produced by physical (Spiers et al., 1990) and numerical (Li and Urai, 2016) experiments of salt deformation, demonstrating rheological similarity (Weijermars and Schmeling, 1985; Weijermars et al., 1993).

Since the breaking separation of salt and, consequently, its elastic force component are negligible (e.g. $F_{i,\alpha} \approx 0$), the forces acting on the salt are dependent on its viscosity and the gravity of the system. Hence, the real-world scale viscosity of the salt is 1.14×10^9 Pa.s, which is lower than its real world viscosity (10^{17} - 10^{18} Pa.s – Turcotte and Schubert, 1982; Hudec and Jackson, 2007) but is still a reasonable approximation when compared with physical models, in which scaling is applied but salt is modelled using silicon polymers with viscosities in the range of 10^4 Pa.s (Vendeville et al., 1995; Ge et al., 1997; Dooley et al., 2009, 2012; Brun and Fort, 2011; Adam and Krezsek, 2012).

2.3. Modelling Scenario and Experimental Parameters

A series of experiments on the rejuvenation of buried diapirs by regional shortening in a deep-water setting were conducted with the following objectives: i) to analyse the effects of sedimentation on the rejuvenation of salt structures driven by shortening; and, ii) to understand how salt movement controls depocentre distribution and deformation. It is not intended in this work to investigate the initial stages of evolution of diapirs as this has been already extensively studied (Trusheim, 1960; Vendeville and Jackson, 1992; Vendeville, 2002; Hudec and Jackson, 2007).

The modelled media consists of a box (Fig. 3) with a rigid and undeformable base and free side-walls and 10894 elements with varying radii. The media represents a length of 9.8 km and height of 1.5 km with a 3° basinward dip to simulate margin tilting due to post-rift thermal subsidence. This dip fits within the spectrum of salt detachment slopes at deep-water segments of many continental margins salt basins (Tari et al., 2003; Peel 2014) and is within the range used in previous models of salt tectonics (Brun and Fort, 2011; Dooley et al. 2007; Dooley et al., 2015).

Figure 3 here

It is assumed that an earlier phase of diapirism is responsible for the emplacement of a wide and symmetric salt stock with relatively little deformation of the adjacent minibasins as expected for a passive mode of diapirism (Vendeville and Jackson, 1992a; Hudec and Jackson, 2007; Weijermars et al., 2015). Thus, the salt stock is 1.25 km wide and 1.25 km (10 layers) high, with steep flat walls and un-deformed pre-kinematic overburden, the autochthonous salt and the diapir roof are 2 layers (250 m) thick and pre-kinematic sediments are 10 layers thick (1.25 km). A different colour is assigned to each pre- and syn-kinematic layer so overburden deformation can be easily tracked. Four markers were included within the stock and 2 markers in the source-layer to investigate intra-salt flow (Fig. 3).

The flat crest in cross-section reproduces dissolution effects prior to its burial, a common characteristic of many natural examples of buried diapirs (Schultz-Ela et al., 1993; Jackson et al., 2015). Although variations of source-layer thickness in the peripheral sinks of passive diapirs occur (Vendeville and Jackson, 1992a, Hudec and Jackson, 2007), for design simplicity and because the focus of this paper is on the late evolution and rejuvenation of diapirs, this interval is modelled as initially isopachous, similar to previous physical models studies (Dooley et al., 2009, 2015, models 5-7).

For simplicity, an homogeneous overburden is assumed, with density of 2300 kg m^{-3} , representative of sediments not heavily compacted, and salt density of 2160 kg m^{-3} , representative of mobile salt, i.e. halite (Albertz and Ings, 2012; Gradmann and Beaumont, 2016), which is the main component of diapirs since the less mobile evaporites are preferentially left behind in the autochthonous layer as the structure

develops (Kupfer, 1968; Wagner and Jackson, 2011; Albertz and Ings, 2012; Cartwright et al., 2012; Dooley et al., 2015). Both densities are in agreement with previous physical and numerical analogues and natural examples (Gemmer et al., 2005; Ings and Shimmeld, 2006; Dooley et al., 2009, 2012, Albertz and Ings, 2012; Gradmann and Beaumont, 2016). As both the thickness and density ratios of our models and natural prototypes are similar, stress in the elasto-plastic overburden are dynamically scaled (Weijermars et al., 1993).

The Poisson's ratio (ν) for 2D DEM models is 0.33 and the Young Modulus (E) of salt and overburden are 3.65 and 13.5 GPa respectively, which are in the range of natural examples of salt and an overburden formed by sandstones and mudstones (Johnson and DeGraff, 1988; Liang et al., 2007).

Contacts at the boundary walls are exclusively compressional. Experiments are run for a total of 5 million time-steps divided equally into 5 phases (I to V). The model run-time has been scaled to simulate strain and sedimentation rates that are compatible to natural examples. Thus, in this case each time-step is equivalent to 2 years and each phase corresponds to 2 Ma. Regional compression is simulated by inward movement of both end-walls at a constant displacement rate of 0.39 mm/year and 8% compression per 2 Ma phase. Hence, compression generates a total displacement of 3.9 km or 40% of compression at a strain rate of $2.5 \times 10^{-5} \text{ s}^{-1}$, in the range of ductile strain rates of salt deformation in nature (Weijermars et al., 1993; Jackson and Hudec 2017). The amount of shortening of deep-water contractional domains in passive margins varies considerably from 5-6 km in the Mississippi Fan and Perdido Fold-Belt, Gulf of Mexico, 27-30 km in the Kwanza Basin, Angola, to 100 km in the Campos Basin with shortening rates in the range of 0.1 – 0.5 mm/year (Rowan et al., 2004).

A series of 5 experiments were conducted where the timing, thickness and rate of sedimentation were varied to investigate the interplay of sediment input with the rejuvenation of diapirs. Sediments are added to the system following a fill-to-spill methodology relative to a base-level that progressively rises 50 m during the sedimentation interval, simulating pelagic aggradation. Sedimentation frequency has been defined at a constant rate of 0.125 m/ka for models 1 to 3 and 0.1 and 0.15 m/ka for models 4 and 5, respectively, which are within the range of Cenozoic sedimentation rates for the Atlantic Ocean (Whitman and Davies, 1979) and previous numerical models of salt tectonics (Hardy and Cohen, 1996; Gemmer et al., 2005). Syn-kinematic material consists of smaller elements with variable radii size to prevent development of unrealistic holes and facilitate visualization of structures. All other properties are the same as the pre-kinematic material.

3. Model Results

Table 1 summarizes differences in sedimentation patterns and resultant diapir geometries for each model. Model 1 is run without syn-kinematic sedimentation whereas for models 2 and 3, syn-kinematic sedimentation occurs at a constant rate of 0.125 m/Ka (250 m/phase). In model 2, sedimentation starts late (beginning of phase IV) and reaches a total thickness of 500 m and in model 3, sedimentation starts earlier (beginning of phase II), reaching a thickness of 1000 m (Table 1). Thus, by comparing models 1-3, the effects of the timing and thickness of sedimentation on diapir evolution are evaluated (section 3.1).

For models 4 and 5, the rate of sedimentation is changed to 0.1 m/Ka (200 m/phase) and 0.15 m/ka (300 m/phase), respectively. All other parameters remain the same as

model 3 to allow comparison of the effects of sedimentation rates on active diapirism driven by shortening.

Table 1 here

3.1. Influence of Timing and Thickness of Sedimentation on Salt Mobilization and Geometry (Models 1 – 3)

3.1.1. Model 1: No Syn-kinematic Sedimentation

During Phase I, the experiment shows incipient squeezing of the diapir with minor salt upwelling generating gentle uplift and arching of the roof. Salt anticlines develop at the edges of the model folding the overburden (Fig. 4a). During Phase II (Fig. 4b), salt anticlines are amplified, the diapir gets progressively thinner and taller. Small reverse faults appear in the form of symmetric pop-up structures (PP1-PP3) towards the top of the pre-kinematic cover, which are attributed to free-surface effects. Due to continuous salt inflation, a basinward-vergent thrust (RT1) forms on the roof of the diapir favouring upward and basinward salt flow along the base of the hanging-wall.

Figure 4 here

In Phase III (Fig. 4c), the diapir continues to inflate and push its roof upwards due to increasing upward salt flow driven by shortening. Movement is accommodated by the development of roof-thrusts, which occur mainly at the diapir margins (ET 1-2) but also immediately above the diapir's centre (RT1). The downdip thrust (ET1) allows basinward salt movement and the formation of an immature salt tongue by thrust advance. Amplification of the distal salt pillow culminated with the formation of a large front-thrust (FT1) at its crest and thrust piercement of salt (sensu Hudec and Jackson, 2007) at the base of its hanging wall as in the source-fed thrust mechanism

(sensu Hudec and Jackson, 2006), in which salt is carried up along the fault plane, conformably to hanging-wall strata and unconformably to the footwall (Hudec and Jackson 2007). The development of this structure is partly due to edge-effects from the downdip end-wall but also to continuous inflation and shortening of the salt pillow. New reverse faults, such as FT2 and back-thrust (BT1) developed while previous faults enlarged and rotated (Phase III, fig. 4c).

During Phase IV, the diapir's roof started to undergo outer-arc extension in response to increasing salt upwelling progressively pushing the roof upwards (Fig 4d). Uplift was preferentially accommodated along the basinward roof-edge thrust (ET1) in response to the basinward tilting of the margin, while there was only minor salt flow on the hanging-wall of the landward-vergent roof-edge thrust (ET2) on the opposite flank of the diapir.

In Phase V (Fig. 4e), the stock was laterally shortened to 280 m, equivalent to 22% of its original width, leading to further asymmetric upwelling and inflation of the salt tongue. The final salt structure is 2 km high, 750 m taller than its initial configuration, and has a small basinward salt tongue 750 m wide, similar to examples from West Africa continental margins (e.g. Tari and Jabour 2013; Tari et al., 2017). An imbricate thrust-system (ITS), similar to Hudec and Jackson (2009), formed immediately basinward of the salt tongue as it spread horizontally and reached a buttress formed by the uplifted and rotated pop-up block (PP1, Fig. 4e).

This model shows that as salt was squeezed from the stock, it became pressurized and rose, initially arching and elevating its roof above the regional datum (Fig. 4a, b) and then, dismembering and rotating it outwards (Fig. 4c-e) with the development of normal keystone faults by outer-arc stretching. This is the pattern expected for

forceful intrusion or active diapirism driven by regional shortening (Schultz-Ela et al., 1993; Hudec and Jackson, 2007; Dooley et al., 2015; Rowan et al., 2016). In our model, however, piercement was asymmetric and resulted in basinward advance of salt forming a small salt tongue similar to the plug-fed mechanism (sensu Hudec and Jackson, 2006) due to: a) the lack of syn-kinematic sediments; b) the topographic slope of the system generating an elevation head on top of the diapir (Weijermars et al., 2015; Dooley et al., 2015); and c) the position of the diapir slightly close to the updip end-wall (although this is of secondary importance). This asymmetric piercement caused the basinward flap to be more intensely uplifted, rotated and completely shouldered aside (Fig. 4e). The landward flap was initially rotated outward (Fig. 4b-c) but began to rotate inward as salt started to flow on the hanging-wall of the roof-edge thrusts ET1-2 (Fig. 4d-e).

The overall thickness of the source-layer did not change considerably as there was no sedimentation to impose differential sedimentary loading onto it and regional shortening balanced localized salt expulsion by thickening the salt layer (Jackson and Hudec, 2017) and by promoting minor inward salt flow from the diapir into the source-layer as proposed by Dooley et al., (2009).

3.1.2. Model 2: Influence of Late Sedimentation

In the second experiment, syn-kinematic sedimentation occurs during the two last phases (IV-V) and is equivalent to a maximum of 500m of sediment aggrading around the diapir. During Phases I-III, model evolution is identical to Model 1 (Fig. 4a-c) and it changes only at the moment that sedimentation commences (Fig. 5b-c). To avoid repetition, only images of the final three phases are presented: Phase III, where evolution is identical to Model 1 (Fig. 5a) and Phases IV and V, in which

system evolution is different (Fig. 5b-c). Due to the basinward tilting of the margin, and the relief at the sea-floor produced by the diapir at the end of Phase III, an earlier and thicker depocentre is generated on its basinward flank which retards basinward salt flow and results in a more symmetric structure with a narrower basinward tongue of 485m (Fig. 5c) compared with 750m when sedimentation is not present (Fig. 4e).

Figure 5 here

The addition of sediment around the salt structure gently increases differential loading, enhancing salt expulsion from the source-layer and inflation of the diapir. The final structure is 950 m or 76% taller than its initial geometry and 200 m taller with a feeder 20 m wider than the diapir in Model 1 without sedimentation (compare Figs. 4e and 5c). The source-layer in Model 2 is, on average, only 15m thinner than in Model 1 (white tick on the source-layer landward of the diapirs in Models 1 and 2, Figs. 4e and 5e), and is locally thicker at the basinward side due to higher structural loading in Model 1 by the imbricate thrust-system and the upturn of the hanging-wall block above FT2 (Fig. 4e).

A greater depocentre thickness and salt inflation allowed the development of a second basinward roof-edge thrust (ET3, Fig. 5c) immediately above ET1. As the lower part of the sheet was being buttressed by a thicker and stronger overburden (relative to Model 1) salt was forced to climb higher, resulting in stronger basinward flow towards the top of the inflating salt tongue. The flaps rotate less than in Model 1 although arching and rotation were still enough to stretch the roof horizontally and produce a set of keystone normal faults (Fig. 5c). As sediments were deposited they were folded and faulted by the propagation of roof-edge thrusts (ET1 and ET3) and

the formation of new faults around the tongue. These results suggest that the basinward depocentre is more intensely deformed because: a) it formed earlier than the landward depocentre and b) its local stresses were higher in response to the basinward thrust-advance of salt.

The front-thrusts FT 1-2 and pop-up fault systems PP 1-3 developed similarly to Model 1. A new pop-up, PP 4, nucleated above the backward thrust BT1 in the updip side of the system during Phase V (Fig. 5c). Syn-kinematic sedimentation reduced rotation of the front-thrust blocks (FT 1-2) on the basinward flank of the diapir, so they rotate less than those observed in Model 1 (Fig. 5b-c). No peripheral thrust system is developed in this model, which can be explained by the presence of a stronger depocentre at the basinward flank of the diapir buttressing downdip salt flow.

3.1.3. Model 3: Influence of Early Sedimentation

In Model 3, 1000m of sediment is deposited during Phases II to V and the evolution of the system is notably different because sedimentation starts before major inflation of the diapir and roof uplift occurred. Evolution during Phase I is identical to previous models (Fig. 4a), with initial squeezing of the stock, salt upwelling and minor arching of the roof and development of salt anticlines. In Phase II (Fig. 6a), a wide depocentre is formed on the basinward side of the diapir partially burying its basinward edge while the diapir continues to be squeezed and arch its roof. Pop-up structures form preferentially in the landward flank, presumably because of its thinner and weaker cover while smaller thrusts form in the opposite flank (Fig. 6a). The pop-up sets (PP1-2) formed during Phase II in Models 1 and 2 with less

sediment input are suppressed in this model due to the greater sediment load on the basinward flank.

Figure 6 here

During Phase III (Fig. 6b), the roof is uplifted and arched further than previous models (Figs. 4c and 5a) with symmetric outward rotation around a central hinge generating earlier normal faulting at the hinge and smaller roof-edge thrusts (ET 1 and ET2) in comparison to Models 1 and 2. The syn-kinematic interval gets folded around the diapir and above topographic highs associated with uplifted fault blocks producing thinning and onlapping of sediments (Fig. 6b). In Phase IV (Fig. 6c), the roof is completely dismembered as more salt is expelled from the centre of the diapir and forcefully pierces the overburden, an evolution pattern characteristic of active diapirism driven by regional shortening (Vendeville and Jackson, 1992, Schultz-Ela et al., 1993 and Hudec and Jackson, 2007). After Phase V the diapir breaks through its roof, further rotating and shouldering aside its flaps. The basinward side is disrupted by a major basinward roof-edge thrust (ET3) which makes its lower block rotate and become overturned (Fig. 6d).

The final diapir geometry varies dramatically relative to Models I and II, being considerably more symmetric, taller and thinner. Its feeder is almost completely pinched-out, having a minimum width of 120 m, which represents 9.5% of its initial dimension and it would most likely be visualized on seismic datasets as a weld. Its final height is 3 km, equivalent to 240% of its original height, and its overhangs have virtually the same width (280 and 285 m on the basinward and landward margins) without forming any asymmetric tongue as in previous experiments.

This geometry is characteristic of upright tear-drop diapirs (Hudec and Jackson, 2007) and is very distinctive compared with Models 1-2 in which asymmetric structures with a basinward-leaning salt tongue developed. In these models (Figs. 4-6), shortening is the main driver of diapirism and the amount of shortening is constant. Thus, the development of a much taller and symmetric squeezed diapir in Model 3 must be explained by the higher sediment input, which: i) generates a thicker basinward depocentre that buffers basinward salt flow to a point where it only moves upward and, ii) mildly increases differential loading, pumping more salt from the source-layer to the diapir forcing it to rise further. This is evidenced by a reduced thickness of the salt layer of 190m (Fig. 6d, white tick on the source-layer).

In this model, faulting is dominated by front-thrusts (FT 2-4) in the updip edge of the system (FT 3-4, Fig. 5d). The large front-thrust FT1 associated with the source-fed salt advance and the pop-up set equivalent to PP2 in Models 1-2 (Figs. 4-5) do not develop in Model 3, whereas all other pop-up blocks (PP1, 3 and 4) are formed (Fig. 6b). These differences are related to the higher sediment input and consequent burial of the diapir's basinward flank in Model 3 (Fig. 6), which causes strain in the overburden to be preferentially accommodated on the landward side where sedimentation is less intense. No roof-thrust (RT1) is formed and salt upwelling is accommodated mainly by roof-edge thrusts (ET1-3). ET3 is much larger in Model 3 and generates considerable displacement and folding of the syn-kinematic interval (Fig. 6d).

To demonstrate complete welding of the diapir, this experiment was run for an additional phase (Phase VI, Fig. 6e) to higher strains (48% of shortening) with consistent shortening and sedimentation rates. The landward block is translated

basinward, overthrusting and decapitating the diapir at mid-level (Fig. 6e), resulting in a basinward-vergent thrust weld.

3.2. Influence of Sedimentation Rate on Salt Mobilisation and Geometry

In this set of experiments, the effects of variable sedimentation rates on the evolution of active diapirs are evaluated. Model 3 is chosen as a reference model for comparison due to its longer and higher sediment input, which results in a significant influence of sedimentation on diapir evolution (Table 1). The rate of sedimentation was varied while keeping all other parameters (e.g. timing, duration, strain rate) identical to Model 3. In Models 4 and 5, the effects of a reduced (0.1m/ka or 200m/Phase) and increased (0.15m/ka or 300m/Phase) sedimentation rate on diapir evolution are tested.

3.2.1. Model 4: Reduced Sedimentation Rate (0.1m/ka or 200m/phase)

Model 4 has no sedimentation in Phase I and a reduced sedimentation rate relative to Model 3 in Phases II-V (Fig. 7a). In this model, an asymmetric basinward-vergent diapir is formed by basinward thrust advance of salt at the top of the diapir. The lower sedimentation rate on Model 4 relative to Model 3 results in a weaker and thinner basinward overburden, which does not generate a downdip barrier capable of lateral salt flow. Thus, a small basinward-leaning overhang (540 m, Fig. 7a) is formed.

Figure 7 here

The final diapir height is smaller (2.15km, Fig 7a) compared to Model 3 (3km, Fig. 6d) and this can be explained by the fact that more salt moves laterally in Model 4 than in Model 3 and, secondarily, by less differential loading on the source-layer in

Model 4, evidenced by a slightly thicker salt layer at the updip side. The higher sedimentary loading of Model 3 is balanced by a higher structural loading around the diapir in Model 4 (see stacked fault blocks on the updip side of Model 4, Fig. 7a) and by a considerable amount of salt being carried away along the large basinward-vergent front-thrust FT 1 (Fig. 7a). Thus, the difference in differential loading and average of source-layer thickness are only minor (15m) between these two models (compare Fig. 6d and 7a) and shows that differential loading and salt expulsion from the source-layer acts only as a secondary control on the development of these distinct diapir geometries.

The roof is only partially dismembered by the formation of a keystone graben at the hinge, and it rotates considerably less in Model 4 due to reduced salt upwelling and roof uplift (compare Fig. 6d and 7a). No roof-thrust (RT1) is formed, but roof-edge thrusts (ET 1-3) are generated similar to other models where a salt tongue developed but with a more intricate pattern in Model 4 (Fig. 7a). The basinward syn-kinematic interval is more deformed with strong overturning and shearing of the pre-kinematic flap immediately beneath the salt tongue (Fig. 7a). This overturning is more intense in Model 4 than Model 3 due to the asymmetric advance of salt (Fig. 7a). In Model 4, the thinner and weaker basinward depocentre allows the development of PP2 and FT1 with basinward thrust advance of salt (Fig. 7a) whereas in Model 3 these faults do not form (Fig. 6d).

3.2.2. Model 5: Increased Sedimentation Rate (0.15m/ka or 300m/phase)

In Model 5, aggradation occurs during phase II to V with an increased sedimentation rate relative to Models 3 and 4. Even though shortening is active and deforming the system throughout the experiment, the faster aggradation rate outpaces the salt rise

rate and progressively buries the structure, impeding overall salt movement and overburden deformation. Therefore, the changes observed compared with the original diapir geometry are relatively minor (Fig. 7b).

The diapir is still squeezed and salt is pushed upward arching its roof but it is not able to completely pierce and dismember the pre-shortening flaps. Both basinward and landward roof-edge thrusts (ET1 and ET2) develop without any intra-roof thrust (RT1). The resultant structure is a squeezed upright diapir with very little asymmetry between its overhangs and a final height of 1.8 km, only 550 m higher than its original size, with a feeder width of 480 m (Fig. 7b). Fewer and smaller faults form in this model, especially in its basinward flank where sedimentation is more intense. Still, PP3 and a larger and asymmetric pop-up (PP4) develop in the landward flank (Fig. 7b).

3.3. Summary and Comparison of Diapir Geometries

Table 1 summarizes the variations of sedimentation patterns for each model and final dimensions of their salt structures. In the first set of models (Models 1-3), an increase in diapir height is directly proportional to the amount of sediment and differential loading around the diapir, whereas asymmetry and horizontal salt advance are inversely proportional to the amount and duration of aggradation. There is no relationship evident between stock width and sedimentation for these experiments.

For the second set of experiments (Models 3-5), an increase in aggradation rate is inversely proportional to the amount of horizontal salt advance and asymmetry of the diapir. Nevertheless, vertical salt movement is higher for the model with intermediate sedimentation rate and volume (Model 3), in which loading kept pace with diapir rise

and suppressed lateral expansion of the diapir, similar to data shown by Weijermars et al. (2015). However, in the model with the slowest sedimentation rate (Model 4), salt was allowed to expand basinward, which, combined with a slightly smaller differential loading, induced less upward salt flow. In Model 5, the aggradation rate was faster than salt rise driven by shortening resulting in less diapirism and overburden deformation than previous models.

Despite the existence of a topographic slope in our models, active diapirism resulted in a relatively symmetric structure in Model 3. Conversely, in models of passive diapirism on a slope, diapirs invariably develop an asymmetric shape due to gravity flow downdip (Weijermars et al., 2015). This difference is due to the fact that in our examples, gravity flow on a basinward-dipping surface is skewed by shortening and higher sedimentary loading on the downdip side of the diapir where there is higher accommodation space due to the dip of the margin. This higher loading in Model 3 hinders basinward salt flow and allows the structure to grow taller than in any other models.

3.4. Intra-Diapir Salt Flow

Four marker-elements (A-D from top to bottom) were located at the centre of the stock for each model to analyse flow within the diapir (Fig. 8). Two marker-elements (elements E and F) were also situated on the basal-salt layer on each flank of the diapir to investigate salt flow within the source-layer and into the diapir (Fig. 9). The trajectories of all elements are identical until the beginning of sedimentation for all models (Figs. 8-9).

Figure 8 here

3.4.1. Intra-Salt Flow for Models 1-3

Elements A and B from the uppermost and mid-upper central parts of the stock respectively present a similar trend (Fig. 8b-c) with increase in vertical displacement and decrease of horizontal displacement as sedimentation thickness increases. Thus, in Model 1, the elements move farther basinward (1.45 km and 1.2 km) and less upward (1 km) relative to Model 3, in which they rise further (1.5 km) with lesser basinward translation (0.5 km). For each model, the proportion of horizontal and vertical motion is broadly equal (slope of the curve $\sim 45^\circ$) until sedimentation begins and movement becomes predominantly vertical (blue and green curves, fig 8a).

Element C (Fig. 8d) represents flow in the lower-mid portion of the stock and shows a decrease in both horizontal and vertical movement and increase in complexity of movement as sedimentation becomes more intense. In Model 3, with increased sedimentation, element C moves only 0.75km upward and 0.6km basinward; whereas in Model 1 it moves 1.1km in both axes (Fig. 8d). Element D at the lower portion of the stock shows an even more erratic flow pattern later in its history (Fig. 8e). This is associated with the thinning of the stock and to the increasing pressure of sediments on the remaining salt pedestal at the landward flank (Fig. 8a) pushing salt downward and inward towards the pedestal and the source-layer, as observed and predicted from the latest physical models (Dooley et al., 2009). This inward movement component is stronger in Model 3 where sedimentary loading is higher, pushing salt further into the pedestal. In these lower parts of the stock, the trajectories become more unstable as the feeder is significantly thinned (61.6% in Model 2 to 90.4% in Model 3, Fig. 8a) and, consequently, interaction with the sides of the diapir impose additional stresses that interfere with salt movement and generate a complex flow pattern (Fig. 8 d-e). This instability is higher in Model 3

where narrowing of the diapir is more intense and results in its almost complete pinch-out (Fig. 8a, d-e).

3.3.2. Intra-Salt Flow for Models 3-5

The amount of movement for all markers in Model 5 (with the highest sedimentation rate and volume) is considerably smaller than in Models 3 and 4 as the structure is rapidly buried and overall salt movement is impeded (Fig. 8f-i). The two uppermost elements (A and B, Fig. 8f-g) show higher basinward movement for Model 4 (lower sedimentation rate) and higher vertical movement for Model 3 (intermediate sedimentation rate). Vertical movement is favoured in Model 3 as the thicker basinward depocentre prevents horizontal spreading and the higher sedimentation rate relative to Model 4 generates more loading of the source-layer, expelling more salt towards the diapir (Fig 8a).

The mid-lower marker (Element C, Fig. 8h) shows a similar pattern to the previous set of experiments with a higher amount of vertical and basinward motion for Model 4, in which sedimentation rate and thickness are lower and the diapir is wider than in Model 3, resulting in less interference from the diapir walls. In the case of Model 5 where the structure gets rapidly buried in phase II, motion at this part of the stock is minor with a late component of inward flow as the diapir becomes less capable of pushing its progressively thicker roof.

The lower marker (Element D, Fig. 8i) shows an oscillatory flow pattern due to thinning of the stock and interactions with the side-walls, and a strong component of inward flow for all experiments. This inward flow is caused, firstly, by thinning of the feeder, which reduces salt motion from the lower portions towards the top of the diapir, and, secondly, by the pressure of the overriding landward block onto the

remaining salt pushing elements back into the pedestal and source-layer (Fig. 8a). Thus, inward flow is higher for Model 4, where the feeder is almost completely pinched-out and salt in the lower portions of the diapir can no longer ascend effectively.

Figure 9 here

3.3.3. Source-Layer Markers

For the first set of models (Models 1-3), Element E shows a significant variation from early basinward movement to late landward flow towards the diapir (Fig. 9a). The amount of updip flow is directly proportional to sediment input where in Model 3 movement is focussed towards the diapir as sediment input was greater and started earlier (Fig. 9a). Despite the lack of sedimentation in Model 1, structural loading due to the propagation and imbrication of thrust blocks in the last two phases (Figs. 4d-e) results in additional differential loading of the source-layer in this area, pushing salt towards the diapir. Models 1 and 2 have identical early phases showing 106 m of basinward motion followed by 60 and 67 m of landward flow, respectively. In Model 3, only 10 m of early basinward flow occurs during the first phase followed by 365 m of landward and 40 m of upward movements (Fig. 9a).

Element F for Models 1-3 demonstrates that an increase in sediment input and loading is inversely proportional to the amount of basinward flow (Fig. 9b). This is due to the fact that sedimentation is more intense on the basinward flank of the diapir generating a stronger sedimentary cover downdip that reduces flow from the source-layer on the landward side of the diapir.

For the second set of experiments, movement of Element E on the basinward flank is predominantly landwards, i.e. towards the diapir (Fig. 9c). In Model 3, in which differential loading is more effective and the diapir becomes taller, movement is stronger, whereas in Model 4 where sedimentation rate is reduced, flow towards the diapir is minor (110 m landward, Fig. 9c). Model 5 has a higher sedimentation rate than Model 4 but because the diapir becomes progressively buried, salt pumping into the diapir is arrested and landward flow is less than in Model 3 (300 m landward, Fig. 9c).

For Models 3-5, Element F demonstrates a similar relationship to the first set of experiments, where basinward movement and sedimentation rate are inversely proportional (Fig. 9d). In Model 5, Element F doesn't conform to the observed trend from Model 3 and 4 because as the diapir is progressively buried, upwelling and inflation is hindered forcing salt to move mainly horizontally and downdip (Fig. 9d). In the last phase there is a minor component of inward flow updip due to greater burial of the structure (Figs. 7b and 9d).

The early basinward flow of Element E reflects downdip movement due to gravity and shear forces within the system and it can be regarded as a dominant Couette type of flow (Weijermars et al., 1993; Rowan et al., 2004) in stages prior to major differential loading acting on the source-layer. Later updip salt movement towards the diapir is diagnostic of a dominant Pouiseuille-type of flow (Weijermars et al., 1993; Rowan et al., 2004) in response to the increasing differential pressure of the overburden on the salt layer.

4. Discussion

4.1. Applicability of DEM

The experiments show that buried diapirs rejuvenated by regional shortening result in lateral squeezing and forceful piercement of salt, confirming previous studies using sand-box experiments (Vendeville and Jackson, 1992; Schultz-Ela et al., 1993; Rowan and Vendeville, 2006; Dooley et al., 2009; Dooley et al., 2015) and FEM (Schultz-Ela et al., 1993). Unless overwhelmed by extreme sedimentation rates, the diapir initially inflates and arches its roof, progressively rotating it outward until it becomes completely dismembered and shouldered aside in more advanced stages, in common with previous models (Vendeville and Jackson, 1992; Schultz-Ela et al., 1993; Dooley et al., 2015). A general upward movement is favoured by the development of reverse faults at the roof and edges of the diapir. This geometric evolution is notably similar to previous models of active diapirism driven by shortening (Vendeville and Jackson, 1992; Schultz-Ela et al., 1993; Jackson et al., 1994; Hudec and Jackson, 2007; Dooley et al., 2009) and to natural examples observed in seismic data (Fig. 10, see also Davison et al., 2000; Jackson et al., 2008 Albertz et al., 2010, Tari and Jabour, 2013; Rowan et al., 2016).

In models of salt flow, which involve solid-state creep and negligible inertial forces (i.e. Reynolds number $\ll 1$), geometric congruence ensures kinematic and dynamic similarity; despite the fact that numerical parameters are not identical to the real world (Weijermars and Schmeling, 1986; Weijermars et al., 1993; Schultz-Ela et al., 1993). The experiments presented in this study accurately simulate the geometric and dynamic evolution of diapirs rejuvenated by shortening supporting the feasibility of this technique when analysing diapirism driven by regional stresses.

Nevertheless, we emphasize that DEM is not the ultimate solution for modelling salt tectonics. Since it is based in a discontinuous numerical method, DEM may not be able to fully represent the complete mechanical behaviour of salt and model salt

deformation driven exclusively by buoyancy. However, the resemblance of our models to real-world geometries (Figs. 10 and 11) and physical experiments (Figs. 1d and 11c) and FEM (Fig. 1c) suggest that DEM is a valuable modelling technique to evaluate the sequential evolution of diapirs and test and analyse the interplay between diapirism, regional stresses, overburden deformation and sedimentation (Fig. 12). The advantage of the DEM technique in modelling salt tectonics is that it combines positive aspects of FEM and of physical models, such as the easy reproducibility and numerical control of the former and the natural and more realistic aspect of rock-deformation and sedimentation of the latter. It generates quick analytical and scaled models of the sequential evolution of salt structures and depocentres, allowing tracking of individual elements through time and space. Furthermore, DEM can be also applied for 3D studies, as physical models, to produce time-slices and multi-directional cross-sections that can aid in the analysis of the variation of salt-related structural styles along-strike.

Figure 10 here

Figure 11 here

4.2. Effects of Sedimentation on the Rejuvenation of Diapirs

The results confirm that during rejuvenation of buried diapirs by shortening in a slope setting, sedimentation acts as the main control on the development of upright squeezed diapirs or asymmetric salt tongues (Fig. 12). The figure is sketch representation of model results summarizing differences in diapir geometries relative exclusively to variations in sedimentation. All parameters apart from sedimentation are constant for all models so Fig. 12 illustrates how varying the timing (Fig. 12a) and rate of sedimentation (Fig. 12b) can result in distinct styles of active diapirism.

Examples of similar structures found in worldwide salt basins are also listed for comparison to each model (Fig. 12).

Figure 12 here

In models with low sediment input controlled either by timing (Models 1 and 2, fig. 12a) or rate of sedimentation (Model 4, fig. 12b) salt flows not only upward but also basinward due to the absence of a strong basinward buttress. The resultant structures are asymmetric and characterized by an allochthonous tongue formed by basinward thrust advance of salt over a thin cover, similar to various seismic examples (Fig. 1a, 10a and 13), such as in the NW Africa continental margin (e.g. Tari and Jabour, 2013, Tari et al., 2017), Nova Scotia (e.g. see Albertz et al., 2010, Deptuck and Kendell, 2017), Gabon (e.g. Jackson et al., 2008), Gulf of Mexico (e.g. see Schuster, 1995; Rowan, 1995; Rowan and Vendeville, 2006; Rowan et al., 2016), North German (Hudec and Jackson, 2011) and even intra-salt tongues in the Santos Basin, Brazil (see Jackson et al., 2015; Dooley et al., 2015).

In experiments with larger sediment volumes (e.g. Model 3, Fig. 12b), the thicker and stronger overburden buffers horizontal spreading of salt, especially in the basinward direction where the overburden is thicker, resulting in symmetric and upright diapirs. In Model 3, the rate of sedimentation is not high enough to completely bury the diapir as in Model 5, so the final structure is a typical tear-drop diapir such as the ones found in the North Sea (Davison et al., 2000), the Moroccan margin (Tari and Jabour, 2013), Nova Scotia (Albertz et al., 2010), Angola (Fig. 1b, Duval et al., 1993) and many other salt basins (Fig. 10b, 11 and 13a). Additional shortening of Model 3 results in complete pinch-out of the feeder and development of a basinward-vergent

weld by overthrusting of the landward block, similar to examples found in the Lower Congo and Kwanza Basin (Fig. 11).

Figure 13 here

Basinward tilting of the margin is another factor that influences the evolution of diapirs (Dooley et al., 2015; Weijermars et al., 2015). When pelagic aggradation is absent or mild (Models 1, 2 and 4), basinward tilting favours downdip translation of salt due to the elevation head gradient along the top of the diapir (Weijermars et al., 2014; Hudec and Jackson 2007). When aggradation starts earlier or is more severe, however, (Models 3 and 5); this tilting hinders downdip translation of salt because it allows the development of a thicker and stronger depocentre in the basinward flank of the diapir. This suggests that allochthonous sheetlike structures formed by thrust advance, such as small salt tongues, occur preferentially associated with periods of relative sediment starvation in deep-water areas. In our models, the diapir roof does not become as heavily fragmented as in other physical models without syn-kinematic sedimentation (Dooley et al., 2015) because sedimentation acts as a barrier for lateral expansion of the diapir and roof extension.

The geometries of our models are notably similar to seismic examples (Fig. 10a-b and 11) and physical analogues (Fig. 10c), where results show the development of the notable features from natural examples such as diapir geometry, squeezed subvertical feeders, overhangs, thicker basinward depocentres, roof uplift and dismembering (e.g. Figs. 10 and 11). In some natural examples, differential salt thickness and overburden uplift across the diapir are comparable to model results (Fig. 11) whereas in others these can contrast with our experiments (Fig. 10b). These differences could be due to limitations of this model to reproduce natural

irregularities on early salt geometries and other variables that may act in these systems, such as basement topography and 3D variations in sediment input and salt flow; or could also be related to difficulty in successfully imaging deep autochthonous salt layers and strata below or at the flanks of diapirs (Fig. 1a).

These results contribute to understanding the diversity of salt-related structural styles on various continental margin salt basins. Typical along-strike variations from segments dominated by upright symmetric diapirs (Fig. 10b) to others characterized by asymmetric and basinward-leaning diapirs and tongues (Fig. 10a) can be related to lateral changes of sedimentation rates and input to deep-water systems along these margins. Areas that experience higher sediment input will preferentially develop more symmetric structures whereas those receiving reduced sedimentation will favour the generation of asymmetric diapirs and salt sheets (Fig. 12, e.g. Tari and Jabour, 2013; Albertz et al., 2010; Deptuck and Kendell, 2017).

Moreover, similar along-dip shifts in diapirism style from symmetric structures updip to asymmetric diapirs, tongues and sheets downdip are common in many margins (e.g. Tari and Jabour, 2013; Deptuck and Kendell, 2017; Tari et al., 2017; Lentini et al., 2010; Jackson and Hudec, 2017, see their figs. 10.71 and 10.73) with both syn- (Fig. 13a) and post-rift salt (Fig. 13b) can also be partially associated with variations in sediment input and rates as these are usually higher updip than further downdip. This is not true everywhere, as salt tectonics is also affected by many other factors such as basement topography (Dooley et al., 2016), intra-salt variability (Cartwright et al., 2012; Jackson et al., 2015), out-of-plane salt flow (Demercian et al., 1993; Rowan et al., 1993) and initial diapir geometries (Dooley et al., 2015) where our models involve only diapirism driven by shortening.

The Central Louisiana segment of the Gulf of Mexico salt basin is an example of a more complex scenario where asymmetric basinward-leaning structures, i.e. counter-regional systems (Schuster 1995), predominate near the shelf passing downdip to symmetric systems, i.e. salt-stocks, at the upper slope and further downdip to another asymmetric domain referred to as the Sigsbee canopy system (Diegel et al., 1995; Peel 1995; Rowan 1995; Hudec et al., 2013). This variation may be associated to differences in early diapir geometries, i.e. basinward-leaning diapirs due to early progradation (Diegel et al., 1995).

4.3. Thrust-Advance of Allochthonous Salt

The experiments confirm that allochthonous salt tongues can also develop without salt extrusion (Figs. 4, 5 and 12a). In scenarios where a previously buried salt stock is squeezed without a thick basinward buttress, salt is pushed up and basinward carrying a thin carapace of pre-kinematic sediments across a thick footwall, similar to models of thrust advance and the plug-fed-thrusts lineage of Hudec and Jackson (2006). As more salt is squeezed from the stock by progressive shortening and, secondarily, expelled from the source-layer by differential loading, it continues to rise and pierce the overburden above a basinward-vergent thrust, inflating the salt tongue while its thin roof is rotated and deformed, similar to physical model examples (Figs. 1-d and 10c, see also Dooley et al., 2015).

This type of generation of allochthonous salt sheets is expected to occur in areas where stresses are high enough to deform the diapir's roof (Hudec and Jackson, 2006), such as in the toe-of-slope and salt pinch-out in passive margin settings and in salt basins affected by thick-skinned shortening such as Morocco (Hafid et al., 2000; Hafid et al., 2006; Tari and Jabour, 2013), the North Sea (Davison et al., 2000)

Central European basins (Graham et al., 2012; Ferrer et al., 2012), the Great Kavir (Jackson et al., 1990; Talbot and Alftabi, 2004; Hudec and Jackson, 2011) and in the Flinders Range in Australia (Rowan and Vendeville, 2006). In many cases, due to difficulties in subsalt seismic imaging, limited vertical resolution and the highly strained nature of sediments adjacent to salt structures, accurate identification of the mechanism responsible for the emplacement of allochthonous features can be problematic in seismic data. Thus forward modelling techniques such as the one used in this study can contribute to improving understanding of the processes and evolution of these structures.

4.4. Deformational Styles within the Overburden

The results shed light into deformational processes on the overburden related to active diapirism driven by shortening that are observed in seismic data (Fig. 11) and physical model examples (Fig. 1d and 10c) but not produced by FEM techniques. Even though diapirs localize most of the strain (Weijermars et al., 1993; Rowan and Vendeville, 2006), in both cases of symmetric upright diapirs and asymmetric diapirs with salt tongues formed by shortening, roof-thrusts and roof-edge thrusts develop as the roof gets dismembered and rotated outward over adjacent depocentres (Fig. 12), similar to results presented in Schultz-Ela (1993), Nilsen and Vendeville (1995) and Dooley et al. (2009, 2015). Active piercement and inflation of a buried salt tongue is also accommodated by imbricate thrust systems immediately basinward of the edge of the advancing sheet (Figs. 5 and 10c) similar to physical models (Dooley et al., 2009; Hudec and Jackson, 2011).

In nature, these faults can occur at or below the limit of seismic resolution or in highly strained or sub-salt areas, thus being usually visualized through core or well data

(Davison et al., 2000), although in some circumstances they can be large enough to be resolved by seismic imaging as in the Banff Diapir in the Central Graben (Fig. 1b), the Cegonha Diapir, offshore Angola (Duval et al., 1993) and at the Astrid fold-thrust belt offshore Gabon (Jackson and Hudec, 2008). The recognition of faults around salt structures is important as they can act as both conduit or seal for hydrocarbons depending on their depth and lithology.

5. Conclusions

DEM is a very efficient and inexpensive tool to analyse the structural and stratigraphic evolution of sedimentary basins. Although it has limitations in modelling certain scenarios of salt tectonics, i.e. purely buoyancy-driven deformation, this novel approach is a useful tool to guide seismic interpretation and to assess the interplay of salt tectonics and sedimentation due to: i) results are easily reproducible, ii) it allows analysis of the sequential evolution of the structures and tracking of individual elements in the system; and, especially because, iii) it produces more realistic and natural deformation of the overburden, as opposed to other numerical models, thus being capable of improving our current knowledge of deformation styles and sedimentation processes around diapirs.

Modelling results confirm that shortening of buried diapirs on a slope setting can generate two end-member salt geometries according to sedimentation patterns: i) asymmetric diapirs with basinward-vergent salt tongues and ii) upright squeezed diapirs. When the sedimentation rate is low or sedimentation starts late relative to rejuvenation of the diapir, salt movement is asymmetric resulting in basinward-vergent structures. When the sedimentation rate is higher or occurs earlier, resultant structures are symmetric and defined as upright squeezed or tear-drop diapirs.

Although diapirs with strong asymmetry occur in most of our models (Fig. 12, Models 1, 2 and 4) due to the basinward dip of the margin and the position of the diapir slightly closer to the updip moving wall, early and intense sedimentation can counter-act this effect and generate relatively symmetric and upright structures (Fig. 12, Models 3 and 5).

The key structures in our results are comparable to salt and respective overburden geometries of many diapirs around the world showing the applicability of DEM to reproduce accurately the geometric and dynamic behaviour of salt deformation driven by regional stresses.

The models presented in this paper contribute to the understanding of variations in salt-related structural styles along continental margins due to lateral changes of sedimentation rates and input to deep-water systems. They also explain downdip variations of structural styles observed in passive margins salt basins, where more symmetric structures prevail in the updip domains due to higher sediment input and sedimentation rates whereas asymmetric diapirs and tongues develop further downdip where sedimentation is less intense.

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MODEL	Thickness of syn-kinematic sediments (m)	Beggining of aggradation	Sedimentation rate (m/ka)	Height (km)	Width (m)	Seaward overhang (m)	Landward overhang (m)
1	0	-	-	2	280	750	300
2	500	Phase IV	0.125	2.2	300	485	360
3	1000	Phase II	0.125	3	120	280	285
4	1000	Phase II	0.100	2.15	290	540	265
5	1000	Phase II	0.150	1.8	480	130	110

Table 1: Summary of initial parameters and final response of each model presented.

Figure 1: Examples of different scales of study and modelling of salt tectonics: (a) Regional seismic transect offshore Morocco showing allochthonous salt tongues (numbered from 1-4) and sheets, squeezed diapirs, a salt nappe and related sub-salt imaging problems; (b) example of squeezed tear-drop diapir with intense roof arching and upturning, extracted from Hudec and Jackson (2011); (c); FEM of active salt piercement with salt in pink and zones of high-strain in green to red colours (Schultz-Ela et al., 1993); and (d) model of rejuvenation of buried salt stocks by shortening extracted from Dooley et al. (2009).

Figure 2: Biaxial compressional tests of materials used to model overburden (breaking separation of 0.05) and salt (breaking separation of 0.001). (a) Broken-bond plot after 15% shortening where white indicates elements with no broken-bonds and black indicates elements with 9 broken-bonds. (b) The media after 15% of shortening. The white numbers on the upper plate represent the breaking separations. (c) The differential stress-strain relationship for this test showing a typical brittle response for the material used to model the overburden and a linear response of the material used for salt, which is representative of viscous-plastic behaviour.

Figure 3: Initial input of the model with elements representing salt in brown. The box dips 3° basinward and has a rectangular salt stock. For visualization purposes, the pre-kinematic cover has been divided into 10 coloured layers (oranges, yellows and greens) with no mechanical contrast between layers. Intra-salt markers are coloured in yellow and lettered A-D from top to bottom and E and F downdip and updip in the source-layer.

Figure 4: Results from Model 1 showing the sequential evolution of the system. Phases: (a) I, (b) II, (c) III, (d) IV and (e) V. Salt is coloured in brown, pre-kinematic layers are oranges, yellows and greens. Faults are represented by black lines and their sense of motion presented by a black arrow on the larger faults. Letters represent structures outlined in the text where: (RT) roof-thrusts; (ET) roof-edge-thrusts; (PP) pop-ups; (FT) front-thrusts; (BT) back-thrusts; and (ITS) imbricate thrust-systems.

Figure 5: Results from Model 2 with the sequential evolution of the system after (a) Phase III, (b) IV and (c) V. Salt is coloured in brown and pre-kinematic layers are oranges, yellows and greens. Syn-kinematic sediments are represented by smaller radii elements and coloured in shades of pink, blue and white. Faults are represented by black lines and their sense of motion is represented by black arrows for the larger faults. Letters represent structures outlined in the text where: (RT) roof-thrusts; (ET) roof-edge-thrusts; (PP) pop-ups; (FT) front-thrusts; and (BT) back-thrusts.

Figure 6: Results from model 3 with the sequential evolution of the system after Phases (a) II, (b) III, (c) IV, (d) V and an extra phase (e) VI. Salt is coloured in brown and pre-kinematic layers in oranges, yellows and greens. Syn-kinematic sediments are represented by smaller radii elements and coloured in shades of pink, blue and white. Faults are represented by black lines and their sense of motion is presented by black arrows on the larger faults. Letters denote structures outlined in the text where: (ET) roof-edge-thrusts; (PP) pop-ups; and (FT) front-thrusts.

Figure 7: Final results (Phase V) with sedimentation added from Phases II-V for sedimentation rates of (a) 0.1m/ka (Model 4) and (b) 0.15m/ka (Model 5). Salt is coloured in brown and pre-kinematic layers are oranges, yellows and greens. Syn-kinematic sediments are represented by smaller radii elements and coloured in shades of pink, blue and white. Faults are represented by black lines and their sense of motion is represented by black arrows for the larger faults. Letters represent structures contained in the text where: (ET) roof-edge-thrusts; (PP) pop-ups; and (FT) front-thrusts.

Figure 9: Trajectory of elements within the source-layer; Elements E and F (inset of original salt stock). The trajectories of elements E and F for Models 1-3 are shown in (a) and (b), respectively, and in (c) and (d) for Models 3-5.

Figure 10: Comparison of model results with structures interpreted in seismic data and physical models. (a) Salt tongues with sub-vertical welded feeders offshore Morocco (left, courtesy of Chevron and ONHYM) and small salt tongues offshore Mauritania, adapted from Tari et al., 2017 (right) compare well to the salt and overburden geometries developed in Model 2 (centre); and (b) Upright squeezed diapirs offshore Morocco (left) and tear-drop diapir offshore Kwanza basin, adapted from Hudec and Jackson, 2011 (right), both similar to the diapir developed in Model 3 (centre). (c) Close-up of salt tongue at Model 1 (left) showing similar faulting styles to a physical model of thrust-advance of a salt sheet extracted from Hudec and Jackson (2011), with roof uplift and rotation, and development of roof-edge thrusts and an imbricate thrust system at the downdip side of the structure.

Figure 11: Interpreted seismic section of the Kwanza Basin, offshore Angola, extracted from Hudec and Jackson (2011), illustrating two squeezed and symmetric diapirs with intense roof overturn and considerable roof thrusting due to regional contraction. The tear-drop diapir to the west is separated from its pedestal by a basinward-vergent thrust-weld while the squeezed diapir to the east is still partially connected to its pedestal by a very thin feeder. Inset: Sketch of the additional phase of Model 3 (Fig. 6e) presented for comparison with the westernmost diapir.

a)

Timing and Volume of Sedimentation

Model 1: No sedimentation

- Lack of sedimentation allows seaward salt advance
- Allochthonous salt tongue and strong asymmetry
- Shorter structure due to less differential loading around diapir
- E.g. Saït Haute Mer (Morocco) and Lower Congo Basin (Gabon)

Model 2: Late Sedimentation - 500m

- Late sedimentation still allows seaward salt advance
- Salt tongue is less asymmetric due to stronger distal buttress
- Slightly taller structure due to higher loading around diapir
- E.g. Atwater fold-belt (Gulf of Mexico), Lower Congo fold-belt (Angola & Gabon), Talfeney Plateau (Morocco) and Sable Basin (Nova Scotia)

Model 3: Early Sedimentation - 1000m

- Early sedimentation prevents horizontal salt advance
- Symmetric and upright squeezed diapir (tear-drop)
- Tallest structure (3km), complete roof dismembering and higher flap rotation due to higher differential loading
- E.g. Central Graben diapiers (North Sea), Cegonha diapir (Kwanza Basin), Agadir Basin (Morocco), Nordkapp Basin (Barents Sea)

b)

Sedimentation Rate

Model 4: Rate - 0.1m/ka

- Salt rise-rate higher > sedimentation rate and weak seaward buttress allow minor seaward salt flow
- Subtle asymmetry and narrow salt tongue
- E.g. Agadir Basin and Talfeney Plateau (Morocco), Nova Scotia and Meissendorf Diapir (Germany)

Model 3: Rate - 0.125m/ka

- Salt rise-rate >> sedimentation rate but no seaward salt advance due to thick distal buttress
- Symmetric and upright squeezed diapir (tear-drop)
- E.g. Central Graben diapiers (North Sea), Cegonha diapir (Kwanza Basin), Agadir Basin (Morocco) and Nordkapp Basin (Barents Sea)

Model 5: Rate - 0.15m/ka

- Salt rise-rate < sedimentation rate (diapir burial)
- Very little salt movement and change of geometry
- Common in most basins in areas where sedimentation outpaces salt movement

1km

Figure 12: Summary sketches showing progressive variation of diapir and depocentre geometries related to increase in: (a) thickness and time of sedimentation and (b) sedimentation rate. Salt is coloured pink, pre-kinematic intervals in green and syn-kinematic sediments in blue. Faults are in black with their sense of motion illustrated by a black arrow for major faults.

Figure 13: Seismic examples of variations of diapiric structural style along continental margins. (a) Line drawing cross-section offshore Essaouira Basin in Morocco showing symmetric and upright diapir geometries updip passing downdip into asymmetric and basinward-vergent diapirs and salt tongues (from Tari and Jabour, 2013). (b) Regional seismic section of the Santos Basin, offshore Brazil illustrating similar downdip variations of structural style, with symmetric upright diapirs and salt walls in a zone of thick and inflated salt, passing downdip to a zone characterized by basinward leaning diapirs and tongues (from Lentini et al., 2010).

Highlights

Discrete-Element Modelling (DEM) of diapir shortening exhibit kinematics and geometries of active diapirism

Results attest efficiency of technique to model salt deformation driven by shortening

Time, rate and volume of sedimentation result in distinct squeezed diapir geometries

Results explain variations in salt-related structural styles of continental margins

Method works as analytical guide to interplay of sedimentation and active diapirism