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How do salt withdrawal minibasins form? Insights from forward modelling, and implications for hydrocarbon migration

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ABSTRACT

Existing models for the initiation of salt withdrawal minibasins focus on the role of triggers that exist within the minibasin, either stratigraphic (e.g. differential deposition) or tectonic (extension, translation or contraction). Existing studies tend to focus on complex settings, such as continental margins, which contain many different potential triggering mechanisms. It can be difficult in these settings to identify which process is responsible for minibasin initiation, or the influence of individual factors on their subsequent development.

Salt withdrawal minibasins also exist in simpler settings, without any obvious intrinsic trigger; the region of the North German Basin used by Trusheim (1960) in the classic definition of salt withdrawal geometries was of this nature. There is no overall basal or surface slope, no major lateral movement, and there is no depositional heterogeneity. Previously recognized trigger processes for minibasin initiation do not apply in this benign setting, suggesting that other, potentially more fundamental, influences may be at work.

A simple forward-modelling approach shows how, in the absence of any other mechanism, a new minibasin can develop as the consequence of salt movement driven by its neighbour, and families of withdrawal minibasins can propagate across a region from a single seed point.

This new mechanism may explain how some minibasins appear to initiate before the sediment density has exceeded that of the underlying salt. The forward modelling also indicates that some minibasins begin to invert to form turtle anticlines before the underlying salt has been evacuated, so that the timing of turtle formation may not be diagnostic of weld formation. This mechanism may also give rise to salt-cored turtles that have a lens of salt trapped beneath their cores. These new findings have implications for hydrocarbon migration and trapping.

1. Introduction to salt withdrawal minibasins

Salt withdrawal minibasins are important economically because they contain significant hydrocarbon resources: the processes which govern the architecture and evolution of the minibasins control the development of traps, the distribution of reservoir units, the distribution of source rocks and the timing of migration pathways. They form an economically and volumetrically significant component of many basins and passive margins, yet they are comparatively poorly studied relative to an immense body of literature that focusses on the salt bodies. Where they have been studied, the principal focus has been on systems with high complexity (active extension/translation/contraction, significant surface and basal slopes, depositional systems with complex geometries, prograding margins, etc.) As a result, the fundamental processes that operate in the absence of any of these complications remain poorly understood, to such an extent that it is commonly believed that systems of salt withdrawal minibasins cannot initiate in a setting free of any of these triggers.

Salt withdrawal minibasins are relatively small (typically 1–10 km across), sediment-filled regions of subsidence into a larger salt body (Jackson and Talbot, 1991; for review, see Hudec et al., 2009). The energy that drives the subsidence, and the movement of salt which accommodates it, derives from net lowering of the centre of mass, as denser sediments move downwards, and less dense salt moves upwards (Kehle, 1988; Ramberg, 1967, 1981; Trusheim, 1960). They are common in many salt provinces around the world, and are easily recognized in settings where the larger basin in which they formed still retains its original configuration, for example in passive margins such as the US Gulf of Mexico (Worrall and Snelson, 1989), the Angola margin (Marton et al., 2000), offshore Brazil (Demercian et al., 1993), and in intracontinental basins such as the South Oman Salt Basin (Al-Marjeby and Nash, 1986; Li et al, 2012a), the Pricaspian basin (Volozh et al., 2003) and the UK Central North Sea (Hodgson et al., 1992). They have been variously called “sinks” and “rim synclines” (Trusheim, 1960), “withdrawal basins” (Jackson and Talbot, 1991), “minibasins” (Worrall and Snelson, 1989), and “pods” (Hodgson et al., 1992); regardless of terminology, the principle is the same.

Minibasins created by salt withdrawal can also be identified from their distinctive geology and architecture even when the system in

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which they developed has been uplifted and restructured, such as the Sivas region of Turkey (Callot et al., 2014), the Neoproterozoic Roan Supergroup of central Africa (Jackson et al., 2003), and the Amadeus Basin (Dyson and Marshall, 2005) and the Flinders Range (Dyson and Rowan, 2004; Kernen et al., 2011) of Australia.

Development of a minibasin by salt withdrawal is accommodated by movement of the salt out from under the subsiding region, most commonly into an adjacent rising region (Fig. 1).

The adjacent rising region of salt is known by different names, including “diapir”, “salt high”, “salt wall”, “salt pillow”, etc., depending on the author, context and 3D shape (e.g. Jackson and Talbot, 1991). The majority of the published studies focus on the development of the salt high, and the subsiding minibasin has been relatively neglected; yet it is the subsiding minibasin that contains the majority of the economic resource in the form of hydrocarbons, and it is the weight of the accumulating sediments that powers the movement. Therefore this article focusses on the geometry of the minibasin itself, and what we can learn about the minibasin initiation and development from a simple numerical forward model.

Withdrawal minibasins are seen in a variety of geological settings. Those seen in intracontinental basins commonly develop in the absence of significant extension or contraction, without significant surface or basal slope, and deposition commonly forms a blanket filling them up to a near-horizontal base level. Examples of this type include the minibasins developed on the Zechstein of the Central North Sea (Hodgson et al., 1992) and North Germany (Trusheim, 1960) and on the Ara salt of Oman (Al-Marjeby and Nash, 1986). A simple system of this type is rendered schematically in Fig. 2a.

In contrast, withdrawal minibasins on passive continental margins are subject to a range of additional variables, which may significantly modify both the mechanisms and the resulting geometries. These variables include surface and basal slope, extension, contraction and lateral translation over ramps, progradation of the shelf and incised valley formation on the shelf. A complex system of this type is rendered schematically in Fig. 2b. Most publications on the subject of salt withdrawal basins consider scenarios, natural examples, numerical or analogue (sand/silicone) models which reflect the behaviour of systems on passive margins (Fig. 2b) with all their associated complexities.

Existing literature on the subject of gravity-driven salt tectonics is too abundant to summarize here. The reader is directed to reviews of salt tectonics on real and modelled passive margins which are dominated by slope and by lateral movement (e.g. Brun and Fort, 2011; Gemmer et al., 2004, 2005; Marton et al., 2000; Mauduit et al., 1997; Pilcher et al., 2011; and references cited within these); systems controlled by a prograding sediment load (e.g. Ge et al., 1997; Koyi, 1996; McClay et al., 1998; Gaullier and Vendeville, 2005; Vendeville, 2005); systems in which salt movement is triggered and controlled by thin- or thick-skinned extension (e.g. Jackson and Vendeville, 1994; Vendeville and Jackson, 1992a); and systems in which the onset of salt withdrawal minibasin formation may be controlled by contraction

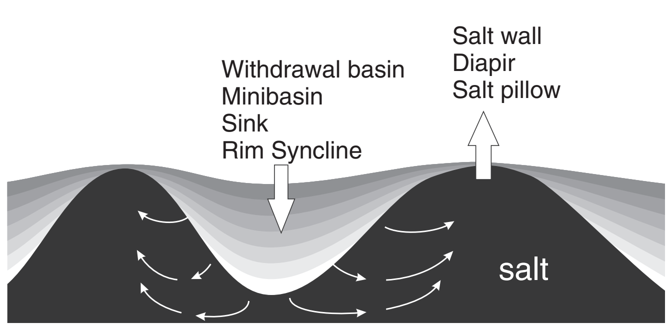

Fig. 1. The basic elements of a salt-withdrawal basin, showing alternative names for the region of salt depletion (minibasin) and the region of salt accumulation.

(e.g. Humphris, 1979; Ings and Beaumont, 2010; Rowan, 2002; Rowan and Vendeville, 2006).

These are undoubtedly significant and important contributions, which correctly emphasize the role that these additional factors play in the initiation and development of salt withdrawal minibasins. However, the presence of multiple degrees of freedom and many independent controlling variables means that these complex multivariate systems are perhaps not the best place to begin a study of salt withdrawal; analysis of complex systems is best begun by reducing the number of independent variables.

In the case of salt withdrawal minibasins, this can be achieved by studying minibasins which develop in the absence of extension and contraction, and with no overall slope on either the sediment surface or on the base of salt, and no lateral or vertical changes in sediment density. In this reduced-complexity scenario, it is possible to investigate the effect of changing a single variable. This approach has been applied by using analogue (sandbox) models (Warsitzka et al., 2013), and is here applied by using a simple numerical model approach.

2. The evolution of salt withdrawal minibasins in tectonically passive regions

2.1. The historical view of salt withdrawal minibasins

The geological evolution of salt withdrawal minibasins was elegantly described by Trusheim (1960) in a landmark publication, which provided a complete evolutionary model, reproduced here in redrafted form (Fig. 3). Trusheim showed the evolution of a salt withdrawal minibasin developing in an environment without applied extension or contraction, without a significant slope on the base of the system or on the surface topography, and without any significant initial heterogeneity in the suprasalt sediment layer.

The minibasin begins as a more or less symmetrical depocentre, with subsidence concentrated in its centre (Fig. 3d). Trusheim (1960) described this as the primary peripheral sink. It is now more commonly referred to as a basin-centred, salt-floored withdrawal minibasin.

During this stage, there is a significant thickness of salt (>hundreds of metres) still present under the minibasin centre. This accommodates subsidence of the minibasin centre as salt is driven from under the minibasin into the salt on either side, causing growth and potential uplift of the salt high.

Basin-centred subsidence continues until a critical point (Fig. 3c) at which the subsidence pattern changes radically: the minibasin centre ceases to subside, and subsidence shifts to the flanks of the basin. Trusheim referred to this change as the transformation of structural relief: it is also known as minibasin inversion.

This transition occurs when the salt layer beneath the minibasin centre becomes so reduced in thickness that further subsidence is drastically slowed; the salt layer may become welded out, at which point no further withdrawal is possible at that location.

Onset of flank subsidence may be more or less symmetrical (both flanks subside equally), or, as shown in this example, the flanks may start subsiding at different times, and at different rates (Mauduit et al., 1997).

The flanks of the minibasin continue to subside as the underlying salt is evacuated into the adjacent salt body (Fig. 3b). Trusheim (1960) named the new depocentre the rim syncline, or secondary peripheral sink. Continuing flank subsidence inverts the structure of the minibasin, creating a turtle anticline.

During this stage, the deeper part of the minibasin fill still has a synclinal form, while the shallower section becomes anticlinal. As the turtle develops, the basin fill deforms; the boundary between deep syncline and shallow anticline shifts downwards through the sediments, and this deformation is commonly associated with crestal faulting over the core of the growing turtle.

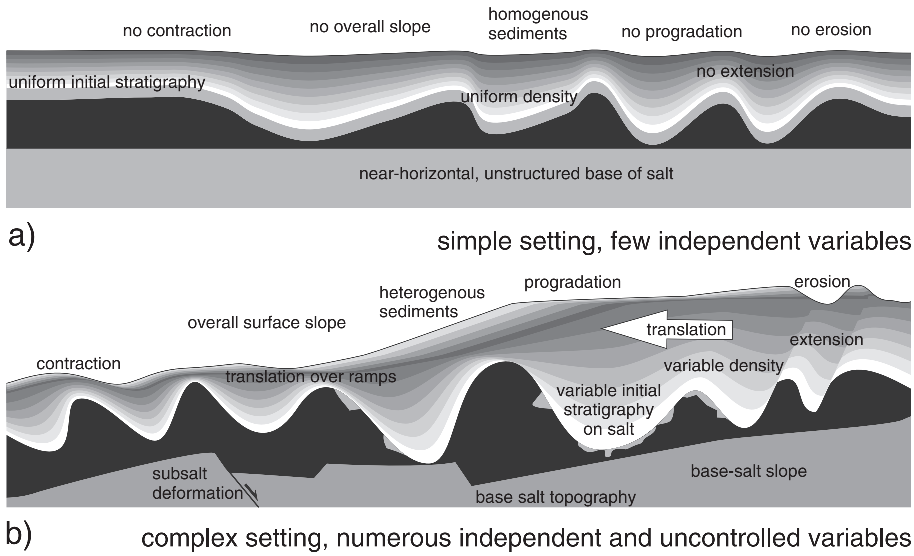

Fig. 2. Comparison of an idealized salt withdrawal minibasin system (a) in a simple intracontinental basin and (b) in a complex passive-margin setting, showing the tendency for the intracontinental basin to have fewer degrees of freedom.

As salt is evacuated from under the minibasin flanks, the extent of the welded area progressively grows (annotated by black dots in Fig. 3) and the locus of flank subsidence correspondingly shifts progressively outwards (white arrows in Fig. 3).

The minibasin continues to develop in this way until the minibasin runs out of space to grow (Fig. 3a). At this point, the turtle anticline is fully mature and the intra-basinal structure is fully inverted.

The engine driving salt into the salt high is now effectively switched off, so the rate of salt flow is drastically reduced. This does not necessarily end the structural development; the salt in the high may be redistributed in the plane of section, focussing into a narrow diapir; or the salt may be removed from the plane of section by concentration along strike into a circular diapir, or it may be reduced by salt dissolution. Lowering of the flank of the salt high by any of these means permits deposition over the former ridge. Trusheim (1960) named this the "third-order peripheral sink".

Trusheim's terminology for the stages of minibasin formation (primary, secondary and third-order peripheral sink) is no longer in widespread use, but his palinspastic reconstructions clearly demonstrate that these concepts are equivalent to the stages of subsidence

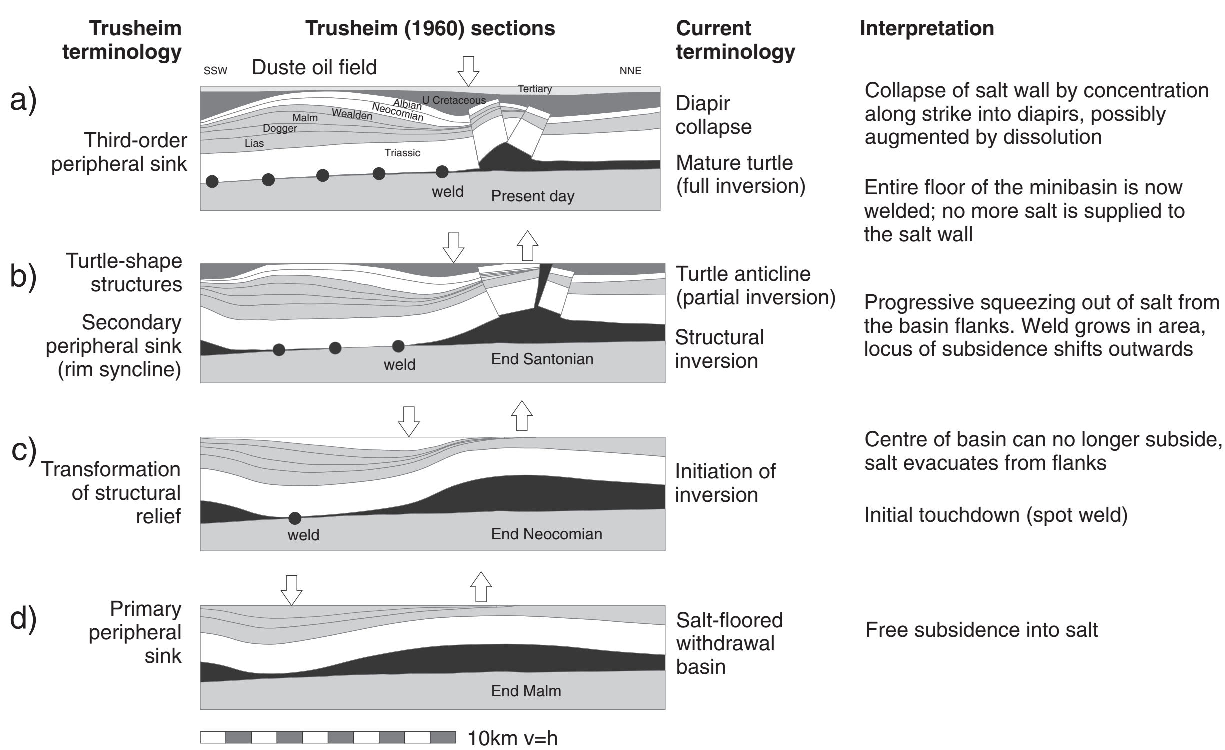

Fig. 3. Redrafted Trusheim (1960) restoration through the Duste anticline showing the sequential development of a salt withdrawal minibasin. The sections are redrawn without modification from Fig. 18 of Trusheim (1960); the annotation shown here is not that of the original figure. Salt is shown in solid black, and welded regions are marked with black dots. Arrows show location of active subsidence and relative uplift at each stage.

associated with salt-floored withdrawal minibasins, the structural inversion associated with turtle anticline development, and with collapse of the salt wall by out-of-plane movement or by dissolution.

As shown here, the original model of Trusheim (1960) calls for the minibasins to form on top of a more or less uniform layer of post-salt Triassic sediment, with a subhorizontal base of salt and an effectively horizontal top-sediment surface, without any extension or contraction. This leaves several mysteries: how did these minibasins initiate? Why is there a basal post-salt section of almost uniform thickness?

2.2. Salt-centred vs. minibasin-centred viewpoint

Subsequent considerations of the Trusheim (1960) model focus on the role played by the diapir rather than the role played by the salt, by placing the diapir at the centre of the diagram (Fig. 4a, adapted from Vendeville, 2002). The visual impression that the process of minibasin formation is governed by the development of the diapir is reinforced by the original choice of words (peripheral sinks appear to be defined by a salt body in whose periphery they sit). Fig. 4b shows a simple graphical exercise (mirroring the same section in the middle of the minibasin rather than in the middle of the salt), emphasizing that these are two views of the same process, with different perspective. Comparison with a forward-modelled salt withdrawal system (Fig. 4c) demonstrates how these two views merely reflect the observer's centre of attention.

2.3. Three-dimensional perspective: minibasins surrounded by salt, or salt surrounded by minibasins

Another issue of perspective is illustrated by consideration of the 3D geometry. The block diagrams shown in Fig. 5 have identical end-wall geometries, compatible with minibasins surrounded by salt (Fig. 5a) or salt bodies surrounded by continuous basin (Fig. 5c). An intermediate state is a hub-and-spoke geometry (Fig. 5b) in which the withdrawal minibasins are surrounded by salt ridges with spaced diapirs. Although these are geometrically distinct scenarios, they may represent the same system seen at different stages in its development, with an initial basin-centred system (Fig. 5a) evolving through time to a more salt-centred system (Fig. 5c) with the hub-and-spoke scenario representing an intermediate stage in its development.

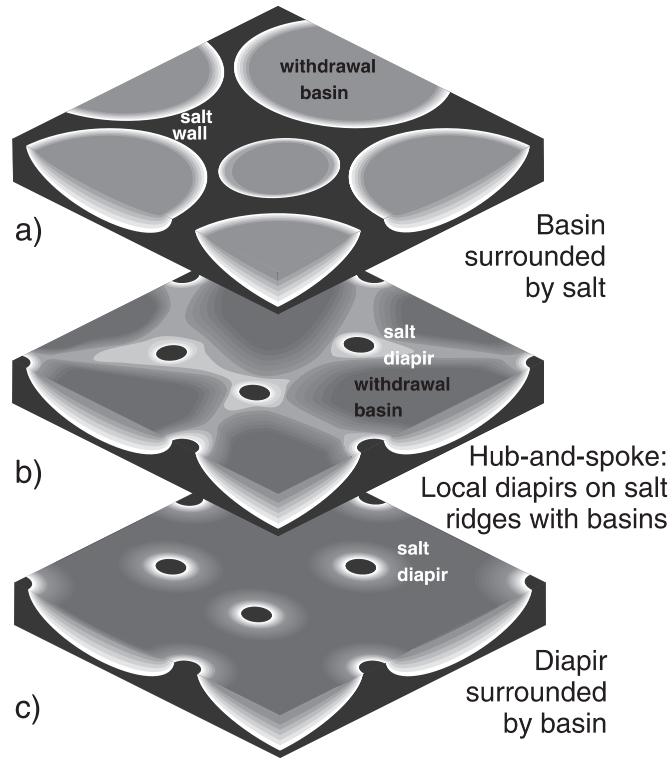

Fig. 5. Three-dimensional perspective, showing that an identical 2D section on the end walls of the model may represent the following: a, minibasins surrounded by salt; b, an intermediate scenario with minibasins surrounded by lower salt walls upon which some diapirs are developed; c, salt bodies surrounded by sediment.

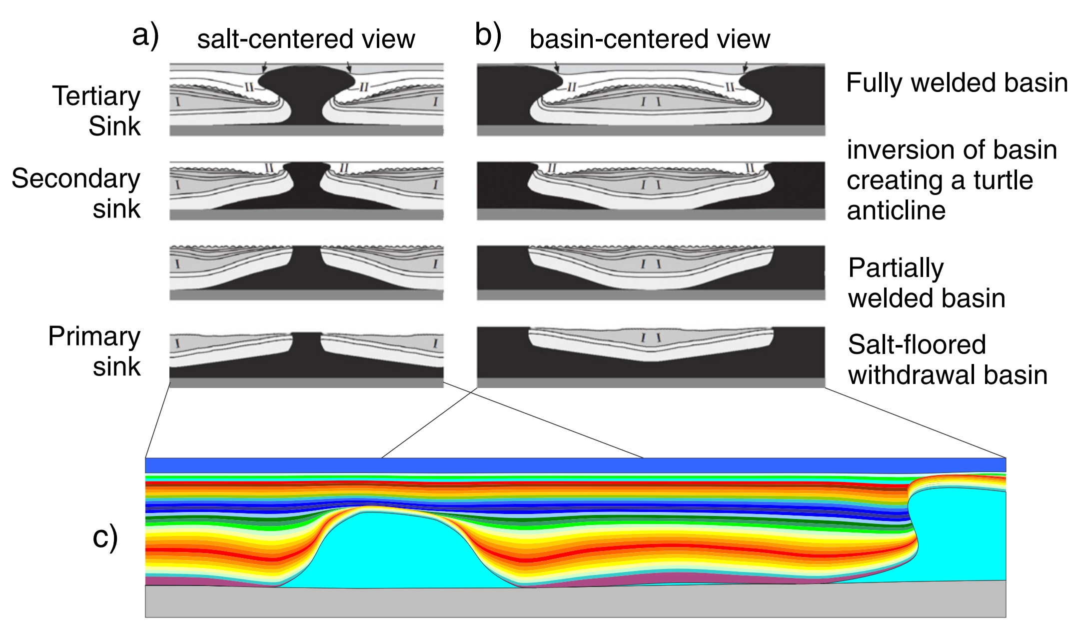

Fig. 4. Salt withdrawal minibasins, in concept and forward models. a, Trusheim (1960) model of formation of synclines and sinks related to lateral salt movement, after Vendeville (2002). Salt is shown in solid black. b, the same figure, recentred on the basin, to show how Trusheim's stages are identical to the distinct stages of evolution of a salt-withdrawal basin. c, numerical forward model of salt withdrawal minibasins, created using DRAWL. The model is dimensionless but is appropriate to a section of the order 10 km × 50 km.

3. Simulation of salt withdrawal using DRAWL

"All models are wrong, but some are useful... the practical question is how wrong do they have to be to not be useful". (Box and Draper, 1987). DRAWL is a simple arithmetic simulation, created in Microsoft Excel® to investigate the initiation and growth of salt withdrawal minibasins and the effect of changing initial conditions. It is intentionally designed with minimum complexity, using the smallest number of input variables and the simplest algorithm that still delivers a reasonable approximation of geological structure. It is computationally minimal (42 spatial points × 36 layers × 32 time steps) permitting instantaneous calculation.

It does not attempt to simulate the full physics of salt flow or sediment deformation; instead it applies a basic flow law for salt driven by differential sediment loading. Deposition follows a simple rule, filling accommodation space up to a base level, which rises relative to basement at a controlled rate.

The user can change the following initial conditions:

- Depth and structure of the base of the initial salt layer
- Thickness and structure of an initial suprasalt seed layer
- Density contrast between the salt and the suprasalt sediments
- The rate of rise of sediment base level
- The effective viscosity of the salt.

The simulation follows the following basic rules (Fig. 6):

1. The model is two-dimensional; there is no flow in or out of the plane, the area of salt is conserved.
2. The model starts with a flat, horizontal sediment surface.
3. The initial model includes a layer of sediments on top of the salt. The user can vary the thickness of this initial layer, creating the seed geometry. The geometry of the base of salt is also user-defined, so that it can be flat, dipping or structured.
4. Lateral variations in the thickness of the sediment overburden and the sea floor topography create a potential gradient within the salt layer, which is expressed as a pressure gradient on a horizontal section through the salt.
5. The salt layer moves laterally in response to the pressure gradient.
6. The sediments move vertically to accommodate the salt movement: they are dropped down where there is net loss of salt, and are raised up where there is a net gain of salt.
7. The resultant sea floor topography is calculated, and a new layer of sediments is added, filling the topography up to the new sediment base level.
8. The new geometry is used as input to the next iteration, and the process is repeated for 32 time steps.

The simulation makes the following assumptions:

1. Sediments have uniform, user-defined density. No sediment compaction is considered.
2. The sediment sequence has no strength: it deforms by vertical shear to accommodate the salt movement.
3. The salt has uniform viscosity, which is selected by the user.

While none of these assumptions are true representations of nature, they vastly simplify the process, allowing simple coding, rapid model building and instantaneous calculation. The model results are geologically realistic in appearance, indicating that the simplifications have not severely compromised the usefulness of the simulation.

3.1. Calculation of salt pressure head and salt flux

The model consists of a layer of sediment overlying a layer of salt. The total thickness of water, total sediment, and salt down to a reference datum are $t_{(water)}$, $t_{(sed)}$ and $t_{(salt)}$ respectively. The seawater, sediment and salt are assumed to be of uniform density, $\rho_{(water)}$, $\rho_{(sed)}$ and $\rho_{(salt)}$. The model calculates the static pressure at a fixed reference depth within the salt for every cell in the model (Fig. 7a), calculated as though each column is an isolated cell:

$$P(static) = g\left(\left(t_{(water)}*\rho_{(water)}\right) + \left(t_{(sed)}*\rho_{(sed)}\right) + \left(t_{(salt)}*\rho_{(salt)}\right)\right)$$

where g is the acceleration due to gravity, $t_{(water)}$ and $t_{(sed)}{}^*$ are the thicknesses of water and supra-salt sediment, and $t_{(salt)}$ is the elevation of the top of salt above a reference datum (Bishop, 1978; Hudec and Jackson, 2007; Vendeville and Jackson, 1992a). The salt is not assumed to be in equilibrium across the model, and the pressure varies from point to point depending on the overburden.

The pressure within the salt at a reference depth defines the pressure head for the salt at that point, which in turn determines the direction and amount of salt flux (Kehle, 1988). The horizontal salt flux is proportional to the horizontal potentiometric gradient and it increases as some function of the thickness of the salt. The salt flux between adjacent cells (e.g. cell 1 and cell 2) is given by:

$$Q_1 = (P_2 - P_1)*(H_1)^k/(d*\eta)$$

where Q_1 is the flux from cell 1 to cell 2, P_1 and P_2 are pressure heads at cells 1 and 2, H_1 is the total thickness of the salt at an intermediate point

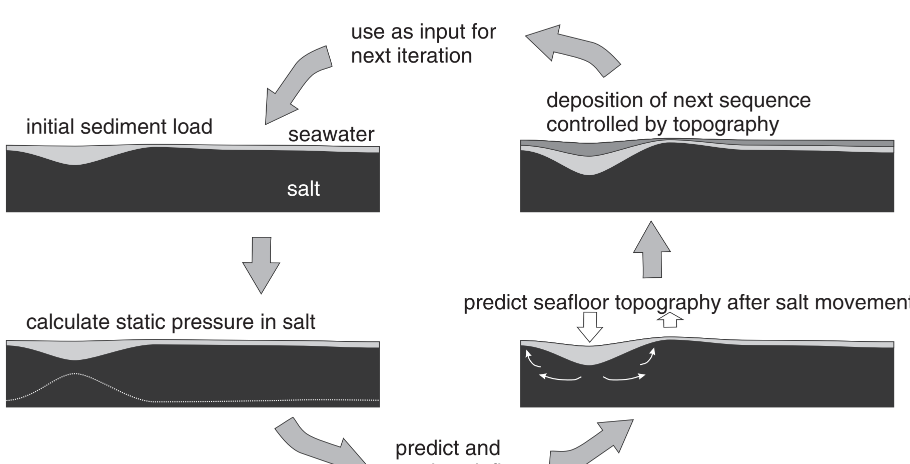

Fig. 6. The iterative process used in the simulation of salt withdrawal minibasins using DRAWL.

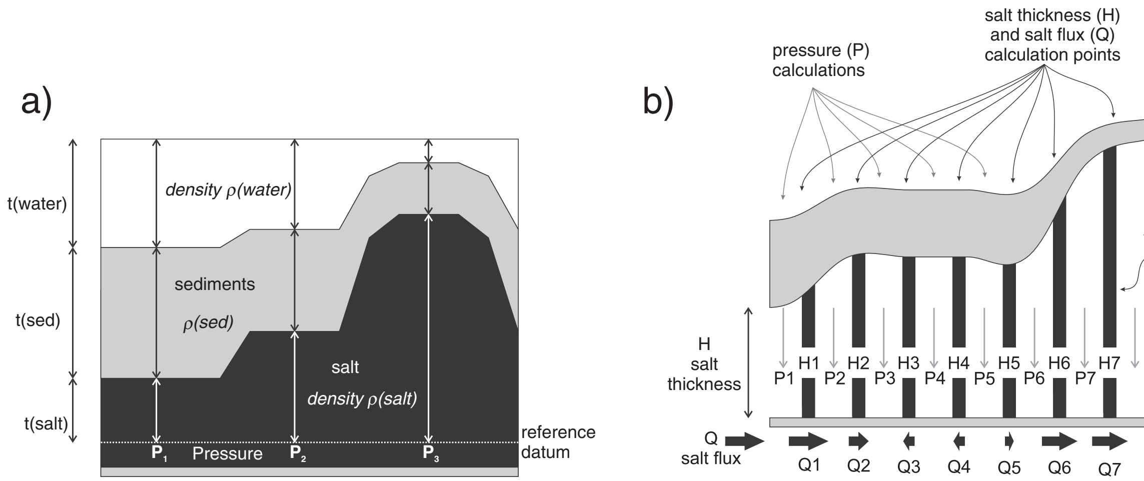

Fig. 7. Calculation of salt flux: a, static pressure determination; b, calculation of salt flow between points at which pressure is calculated. Key: P, pressure; H, thickness of the salt layer; Q, salt flux.

between cell 1 and cell 2, d is the horizontal spacing between cells, and η is the viscosity of the salt (Fig. 7b).

The standard model representing laminar flow of a Newtonian viscous fluid between two parallel plates driven by a potentiometric gradient is plane Poiseuille flow (Fig. 8), for which the flux Q is proportional to the third power of thickness of the salt layer ($Q = (dP/dx)*H^{3}*/12\eta$). Modelling salt withdrawal systems using third-power dependency on salt thickness gave geologically unrealistic results, in which basins initially subside too fast, but then slow down and never weld (see Appendix A and Fig. A.1). Why Newtonian viscous behaviour does not provide the optimum description of salt flow lies outside the scope of this paper, but there is some evidence that salt may behave as a non-Newtonian, shear-thinning fluid in natural conditions (Li et al., 2012b), for which the dependency of salt flux on the salt layer thickness is less than third-order. Simulation using a range of exponents showed that geologically reasonable results were achieved only for exponents close to 1; consequently all other DRAWL simulations presented here use first-order dependence, $Q = (dP/dx)*H/12\eta$.

A typical forward-model result (Fig. 9a) demonstrates that the overall geometry achieved in this way is quite realistic in appearance. Comparison of a single synthetic withdrawal minibasin (Fig. 9b) with a real-world example (Fig. 9c, redrawn from Trusheim, 1960), shows that they have the same overall appearance and the same sequence of development.

This level of realism suggests that the overall simulation is a reasonable approximation of geological processes, and that lessons learned from the simulation may be applicable to the real world.

The extreme simplicity of the simulation method means that it is quite limited in application, since it is two-dimensional, purely arithmetical in approach and it involves neither a full fluid-mechanical model of the salt nor a mechanical model of the sediments. However, it is of value for several reasons:

(i) The model set-up is simple and rapid.
(ii) It calculates the model instantaneously, so that the results of every change to the starting geometry or parameters can be seen immediately.
(iii) The effects of minor changes in starting geometry or parameters are easily and rapidly investigated.
(iv) It provides a full sequential animation showing how the simulated diapirs and minibasins develop through time.

In summary, DRAWL provides a method of rapid reconnaissance, allowing very rapid investigation of hundreds of different scenarios, thereby highlighting critical problems and geometries which may be investigated by more rigorous methods (such as full fluid-mechanical simulations, finite-element models, 3D numeric models, and analogue experiments).

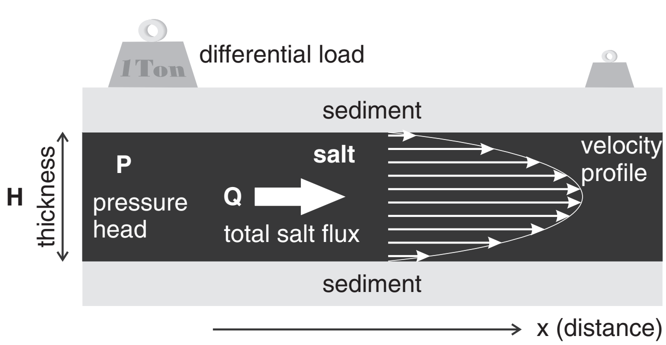

Fig. 8. Theoretical plane Poiseuille flow.

4. How do salt withdrawal minibasins initiate?

4.1. Previous models for withdrawal basin initiation

In order for natural salt withdrawal minibasins to initiate and develop, there needs to be a local cause which allows sediments to accumulate preferentially at a point until a critical thickness is achieved, at which point the weight of the incipient minibasin exceeds the weight of an equivalent volume of salt, and runaway subsidence can occur.

Two problems need to be addressed:

(i) What triggers the development of a withdrawal minibasin at a particular point – does this require an intrinsic heterogeneity at that location, and if so, what is the nature of the initial heterogeneity?
(ii) How can we explain the development of early-formed basins, which start developing while the sediments within them are thin, and in theory less dense than salt? This paradox of minibasin subsidence is reviewed by Hudec et al. (2009) and Ings and Beaumont (2010).

Some previously suggested mechanisms which could provide an initial heterogeneity as well as a mechanism for initial subsidence include lateral contraction or extension, decay of a dynamic salt bulge, differential sedimentary loading, the shallow expression of subsalt deformation processes (Hudec et al., 2009), viscous pressure ridge

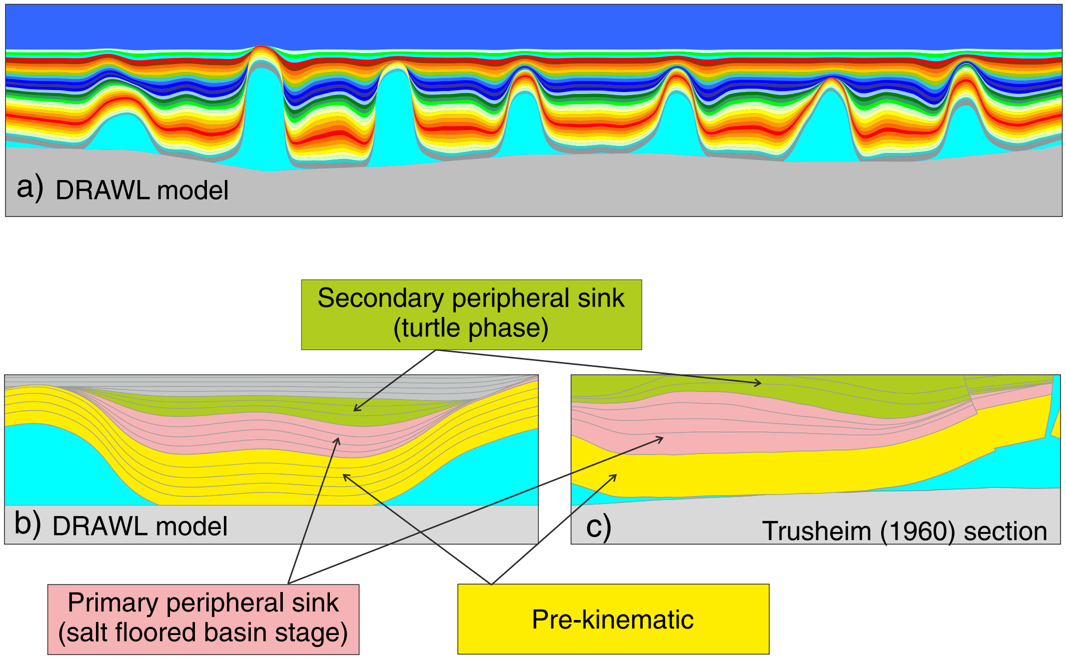

Fig. 9. a, Typical DRAWL output section, showing the final model after after 32 iterations. This simulation investigates the effect of base-salt topography; b, detail view of one salt-withdrawal minibasin created in DRAWL, showing internal stratal architecture and major stages of development; c, geological section through the Duste basin at Santonian time (Trusheim, 1960).

development (Ings and Beaumont, 2010), and the drag effect of movement of a competent overburden over a salt layer of varying thickness (Waltham, 1997).

4.2. Propagation of multiple generations of minibasin

Results presented here suggest an additional potential mechanism, related to the propagation of a suite of minibasins: in the absence of any initial heterogeneity, and where there is no lateral tectonic movement of any type (either extension or contraction), a minibasin may initiate in hitherto uniform stratigraphy as the daughter of an adjacent basin. Successive generations of diapirs and minibasins are not triggered by some intrinsic anomaly within the minibasin, but instead are a response to the development of a neighbouring parent basin/diapir.

This echoes the observation of Trusheim (1960) that first-generation "mother" diapirs spawn second-generation "daughter" diapirs on their periphery, which in turn spawn third-generation "grandchild" diapirs, and that each generation of diapirs is associated with its own set of withdrawal basins.

4.3. Propagating generations of minibasins in numerical simulations

In order to investigate this process, a series of DRAWL simulations were created in which the initial model consists of a uniform horizontal layer of sediment above a uniform horizontal salt (Fig. 10). Introduction

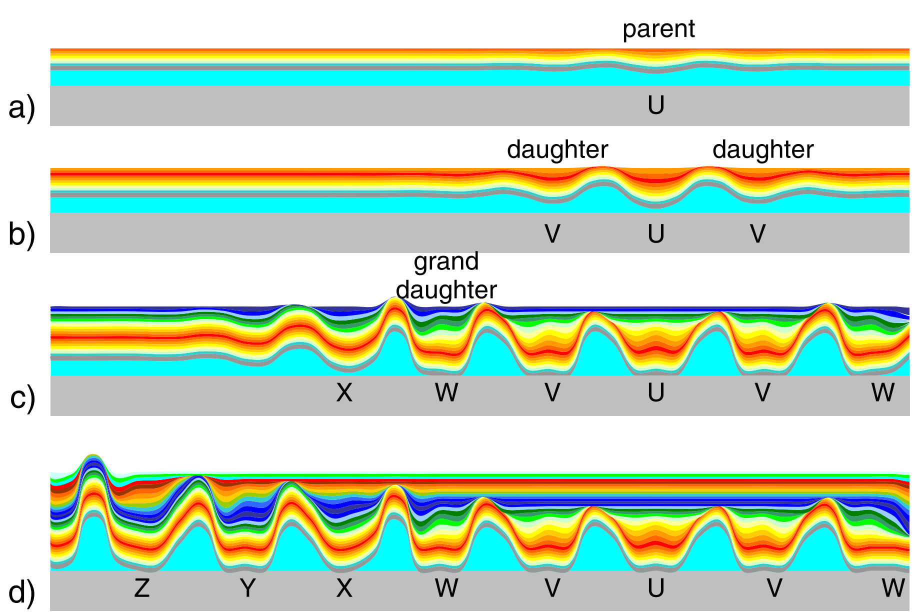

Fig. 10. Numerical model produced in DRAWL showing propagation of six generations of daughter minibasins away from an initial parent minibasin at U. The initial condition consisted of a completely uniform salt and sediment stratigraphy, apart from a single seed point at point U. This seed was sufficient to trigger the cascading process.

of a single thickness anomaly causes a suite of withdrawal minibasins to propagate across the entire region, in the manner described by Trusheim (1960).

The model was built with a single seed point in the middle of minibasin U, at which the initial suprasalt cover is 6% thicker than in the rest of the model. The overall behaviour of the model is not sensitive to the magnitude of the initial seed perturbation; reducing or enlarging the magnitude slows or accelerates the rate at which the initial parent basin forms, but beyond that the model proceeds in an essentially identical manner.

At the first stage shown here (Fig. 10a), the seed has developed into a parent minibasin at point U, displacing salt into two flanking salt pillows. As the model progresses (Fig. 10b), a pair of new daughter minibasins (V) forms on either side. By the third stage shown here (Fig. 10c), the first-formed minibasins (V) have already welded out, and new minibasins are developing (W and X). This process continues through six successive generations (Fig. 10d), by which time withdrawal basins populate the entire model.

4.4. Propagating generations of minibasins in analogue models

Strikingly similar results are obtained by sandbox modelling of withdrawal minibasins produced by differential loadings in the absence of imposed lateral movement (Fig. 11, redrawn from Warsitzka et al., 2013). In these experiments, a suite of withdrawal minibasins and diapiric highs propagates away from an initial seed across a uniform, horizontal sand–silicone stratigraphy. Initiation of the daughter basins is triggered by the influence of the neighbouring parent basin.

4.5. A mechanism for minibasin propagation

A proposed mechanism for the propagation of minibasins is illustrated in Fig. 12. An initial minibasin (Fig. 12a) drives salt laterally outwards, creating a relative low centred on the minibasin, and a sea floor high on both flanks (Fig. 12b). In the absence of sedimentation (right hand sequence), the flanking high spreads out with time, and no new minibasins develop. However, in the presence of sedimentation (left hand sequence), the flanking high is fixed in position, and a positive feedback process creates new minibasins.

The flanking high receives less sediment than the area further outboard, fixing it in position. (Fig. 12c, left). This differential load creates a potential gradient, so that a small amount of leftwards salt flow occurs (Fig. 12d) resulting in the formation of a new minibasin. The process can continue (12e, 12f) creating successive generations of new basins.

4.6. Is this concept applicable to natural examples in the North German Basin?

The observation, made in numerous basins around the world, that minibasin initiation is commonly triggered by extension, contraction,

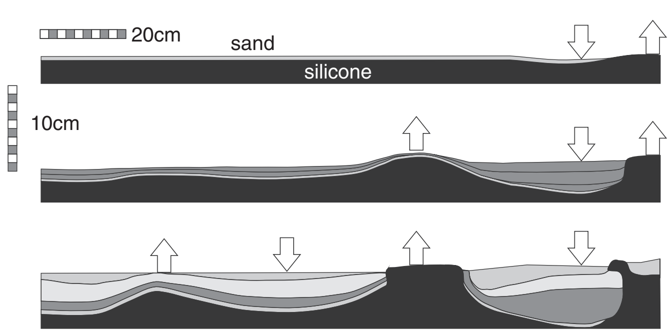

Fig. 11. Three successive stages in the development of experimentally produced withdrawal basins, redrawn from Warsitzka et al. (2013), showing propagation of a suite of minibasins across an initially uniform sand/silicone stratigraphy.

or differential deposition, has led some to conclude that some such mechanism is a necessary condition for minibasin initiation (e.g. Gaullier and Vendeville, 2005; Ge et al., 1997; Hudec et al., 2009; Jackson et al., 2010; Vendeville and Jackson, 1992a). The salt structures of the North German Basin (the type area for salt withdrawal) are a good test of this because the basin is relatively simple, and the structures are well defined, with good data and detailed studies.

Trusheim (1960) did not propose a mechanism for the initiation of the salt-withdrawal systems in north Germany, but his sections indicate that this occurred, in at least some instances, in the absence of triggering extension or contraction. These classic sections have been re-interpreted by some workers, suggesting that they are triggered by sediment progradation (Ge et al., 1997), despite evidence that the basin floor had little topography, or that they were triggered by extension (Vendeville, 2002), despite evidence to the contrary (Zirngast, 1996). Warsitzka et al. (2013) noted that although some of the salt structures in the basin were probably initiated by regional extension (Jaritz, 1987; Jaritz, 1994; Mohr et al., 2005; Scheck and Bayer, 1999), others show no evidence of any such extensional trigger (Zirngast, 1996), occurring at times and locations where no extension is seen. A similar scenario is described in the Central North Sea (Hodgson et al., 1992).

We can deduce that in this region, minibasin initiation does not require extension or contraction, (either thin-skinned, or involving the subsalt section), and the regional setting eliminates mechanisms related to regional slope or sediment progradation. In the absence of these triggers, it is a reasonable hypothesis that the basins were triggered by the mother–daughter propagation mechanism described above. It is the nature of this hypothesis that it is difficult to find positive evidence for it: instead the best lines of evidence are the absence of other candidate mechanisms.

The following observations may provide evidence that minibasins have initiated by mother–daughter propagation rather than local triggering:

(i) Absence of local or regional extension, compression or thin-skinned translation
(ii) Absence of basin floor slopes and sediment progradation
(iii) Identification of a uniform pre-kinematic layer on top of the salt within some minibasins
(iv) Initiation of subsidence occurring at different times in different minibasins
(v) A consistent spatial pattern of the timing, with minibasins developing progressively later in time away from a parent minibasin

We may conclude that deposition of denser sediments on top of salt creates a situation that is intrinsically metastable. Any local trigger is likely to initiate minibasin subsidence, but in the absence of a local trigger, and even in an area with uniform initial suprasalt stratigraphy, families of withdrawal minibasins are likely to propagate across a region; given enough time, it may only take one local seed at one point to populate the entire region with withdrawal basins.

4.7. A potential solution to the paradox of minibasin formation in sediments less dense than salt

The mechanism described above for the lateral propagation of generations of minibasins may also provide an alternative solution to the density paradox, by which new withdrawal minibasins appear to initiate in thin sediment sequences even before a critical thickness is achieved at which the sediments become more dense than salt (Hudec et al., 2009).

Fig. 13 illustrates the evolution of a system in which the sediments are initially less dense than salt, but become denser due to burial and compaction. In the first frame (Fig. 13a) an initial parent minibasin, subsiding under its own weight, drives salt into a flanking high with a relative low beyond it. The sediments in this incipient daughter minibasin are at this stage less dense than the salt. Burial of the whole section

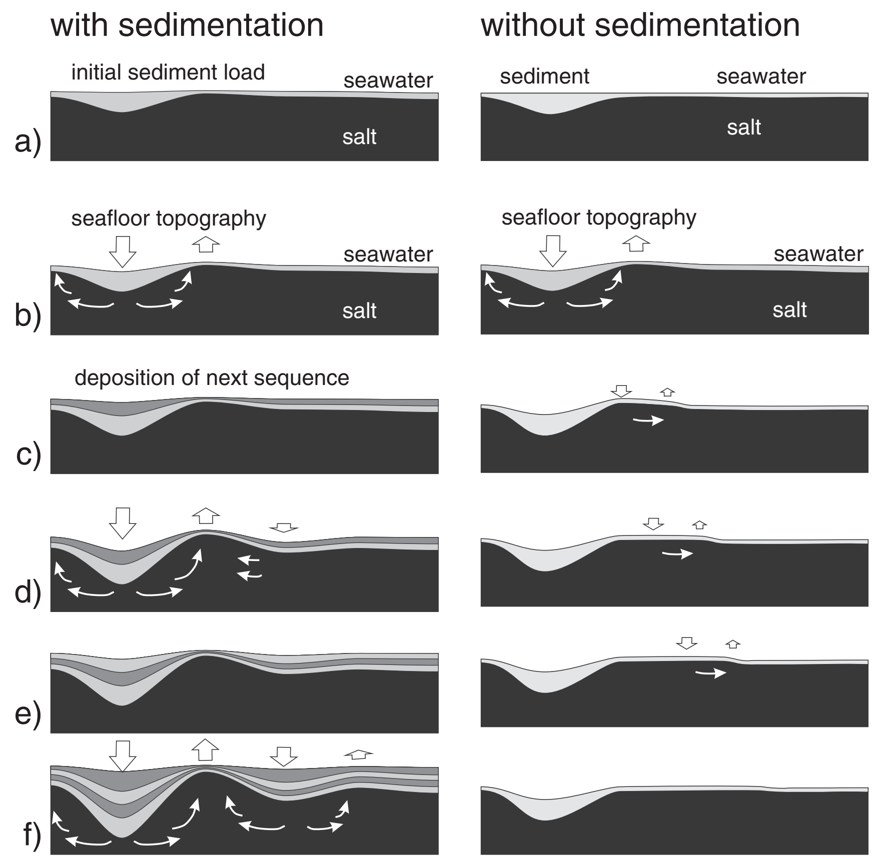

Fig. 12. A mechanism for the lateral propagation of successive generations of salt highs and withdrawal minibasins away from an initial parent minibasin or parent diapir, comparing the effect predicted with sedimentation (left) and without sedimentation (right).

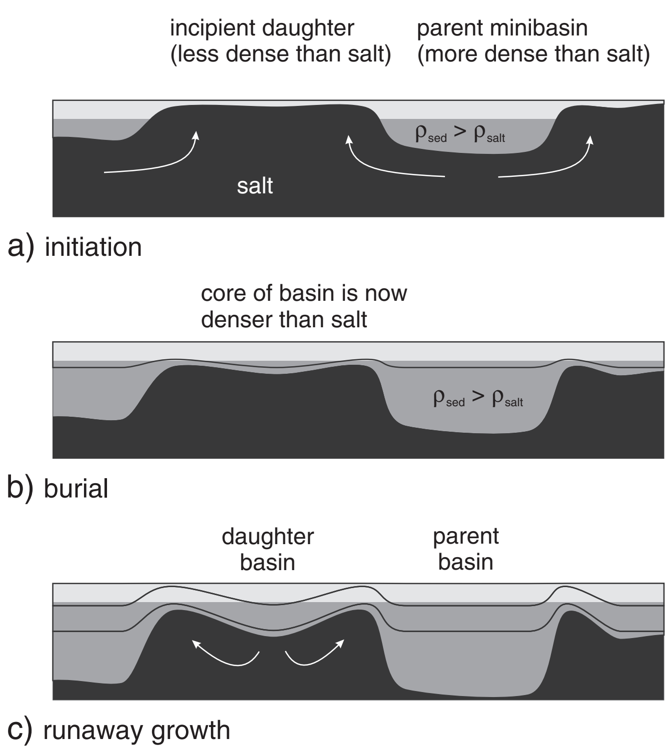

Fig. 13. A mechanism for development of a daughter basin by the lateral propagation mechanism, in a section with depth-dependent density. Darker grey sediment is denser than salt; lighter grey is less dense than salt. a, initiation (incipient daughter is less dense than salt); b, burial (core of daughter basin becomes denser than salt; c, runaway growth (density-driven subsidence of daughter minibasin).

causes the core of the incipient daughter to become denser than salt (Fig. 13b). This enables the daughter minibasin to subside under its own weight (Fig. 13c).

The stratal architecture within the daughter minibasin will record relative subsidence even before the critical density threshold is reached, because this is the effect of salt movement driven by the neighbouring minibasin, rather than a process intrinsic to the daughter basin. This mechanism only requires one seed point to populate an entire region with withdrawal basins, even where the suprasalt section is initially less dense than salt. Although this greatly diminishes the scale of the "density paradox", it does not eliminate the problem entirely, because there still needs to be some mechanism for the birth of the first parent minibasin.

5. Is the timing of turtle formation a reliable guide to the timing of minibasin welding?

An important stage in the maturation of a hydrocarbon exploration prospect is the identification of a viable migration path for the hydrocarbons to pass from the source interval to the prospect.

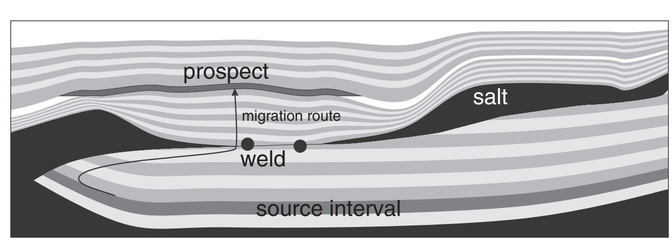

Fig. 14. The impact of welding on hydrocarbon migration.

In the case of a prospect which is separated from the source rock by a salt layer, as shown in Fig. 14, the two most important considerations are (i) to determine whether there is a weld through which hydrocarbons can pass (Guardado et al., 2000; Jackson and Cramez, 1989; Rowan, 2004; Wagner, 2010; Wagner and Jackson, 2011), and (ii) if a weld exists, has it been in place long enough to allow for migration to reach the prospect.

Structural inversion of a minibasin to form a turtle anticline is commonly taken to be evidence that welding has occurred, and the timing of onset of minibasin inversion (deduced from the stratal architecture) is commonly considered to indicate the onset of welding. These assumptions are difficult to test in natural examples, where we only have the present-day geometry, and it can be difficult to identify whether a basin has welded on the basis of seismic data (Wagner and Jackson, 2011).

A series of forward models was created in DRAWL to investigate the validity of these assumptions (Figs. 15 and 16). For small basins, modelling does indeed suggest that minibasin inversion (turtle formation) occurs only if the minibasin is welded, and in these cases the timing corresponds to the onset of welding. However, this is not a universal observation. For broader basins, such as the example shown in Fig. 15, the minibasin began the process of inversion above a significant thickness of salt (Fig. 15c), and true welding occurred significantly later (Fig. 15e).

This is an expression of the lubrication paradox of Lipscomb and Denn (1984). Two parallel plates separated by a viscous fluid can be pushed together, squeezing out the fluid; as the layer becomes thinner, it becomes progressively harder to expel the remaining fluid. If a constant force is applied, the rate of convergence decreases, to such and extent that it is difficult to explain how true welds can form by this mechanism (Cohen and Hardy, 1996; Wagner, 2010; Wagner and Jackson, 2011).

This result indicates that the presence and age of formation of turtle anticlines are not necessarily a reliable indicator of the presence or timing of salt welding.

The influence of minibasin size on the relative timing of welding, inversion and turtle anticline formation was investigated in a model (Fig. 16), with two wide minibasins (U and W) built into the starting geometry and a narrower daughter minibasin V developing as the model progressed.

These models indicate that

(a) For narrow basins, welding and turtle inversion appear to be synchronous.
(b) For wider basins, the onset of inversion occurs before weld formation, and the presence of a turtle does not necessarily indicate the presence of a weld.
(c) The time difference between inversion and welding increases with the width of the basin.
(d) Welding and inversion are separated not only in time, but also in space. Narrower basins tend to weld under the middle of the basin, under the turtle anticline axis; wider basins tend to weld under the basin flanks, not under the turtle anticline axis. Consequently, inversion to form a turtle anticline is not conclusive evidence of welding; if welding has in fact occurred, the timing of inversion is not neccessarily equivalent to the timing of welding; and the location of the turtle core is not neccessarily the same as the location of the weld.

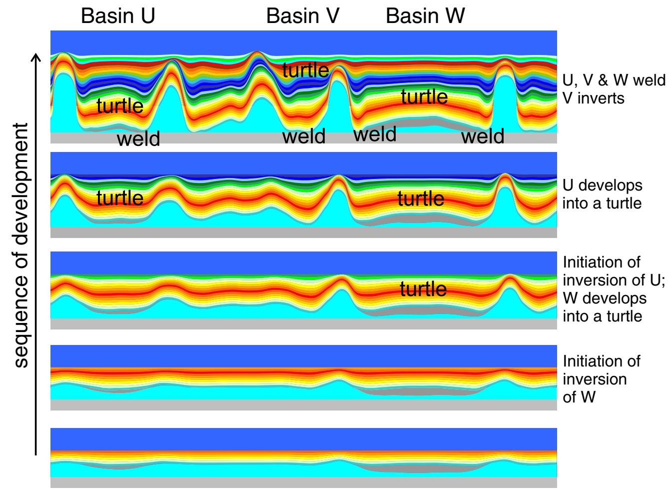

Fig. 16. A DRAWL model showing how the relative timing of the initiation of inversion, development of a turtle anticline, and welding depend on the scale of a basin. Larger minibasins (U and W) invert and develop into turtles significantly in advance of welding. For smaller minibasins (V), welding may be synchronous with the initiation of inversion, and may predate turtle formation. Larger minibasins such as U and W also tend to the initial develop welds around the minibasin margins, whereas for smaller minibasins such as V, the initial weld point is located in the minibasin centre.

6. Salt-cored turtle anticlines and hydrocarbon migration

This study indicates that in some circumstances, a new class of turtle anticlines may develop, with subtly different character, and potentially significant differences for the hydrocarbon system. These are salt-cored turtles, formed where the turtle anticline starts to develop before the salt weld has formed, exemplified by minibasins U and W in Fig. 16. A schematic representation of salt-cored turtles, based on observations from multiple forward models, is shown in Fig. 17. The key difference is that in the conventional turtle (left) the inversion does not begin until a weld has formed in the middle of the basin, and then the weld spreads laterally, squeezing out the salt like toothpaste from a tube. Preferential subsidence of the minibasin flanks occurs because the centre of the minibasin is supported by a weld.

In the salt-cored turtle, inversion begins prior to welding due to difficulty of removing salt from the middle of the basin. Enhanced subsidence of the minibasin flanks occurs not because the centre is supported by a weld, but because the salt under the flanks has an easier path of escape. In these models, the flanks can weld out, trapping a lens of salt under the middle of the minibasin that has no means of escape.

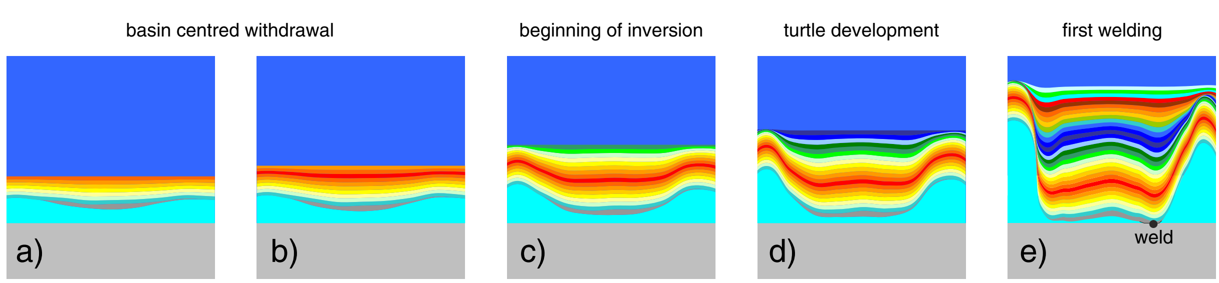

Fig. 15. Forward model of a turtle anticline created using DRAWL to investigate the timing of welding relative to the onset of inversion.

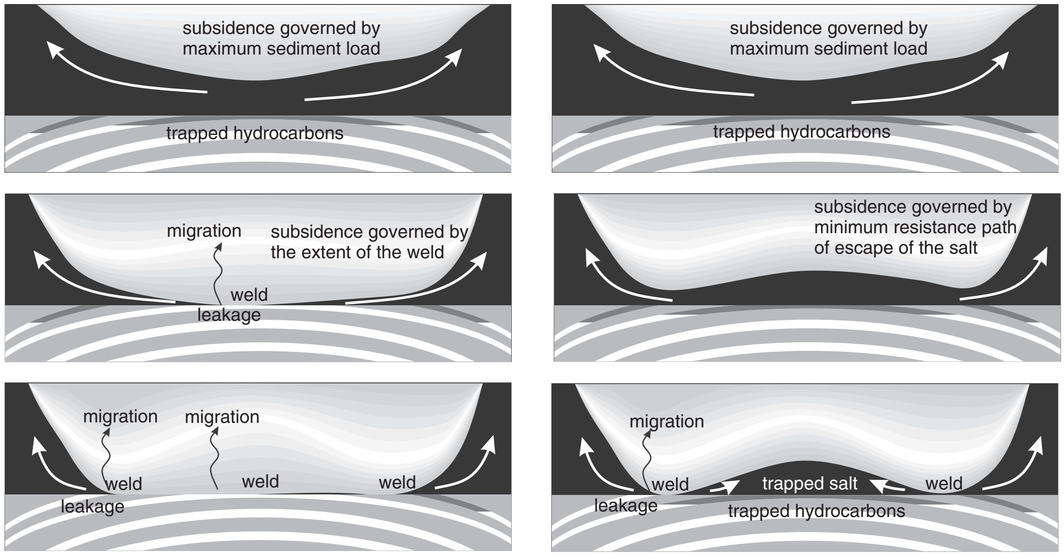

Fig. 17. Schematic section comparing the structure and evolution of conventional turtles (left) with that of salt-cored turtles (right).

The significance of this, as shown in Fig. 17, is that the trapped salt lens may prevent the passage of hydrocarbons into the suprasalt basin, harming the chances of success of a suprasalt prospect, but potentially improving the chance of a subsalt prospect sealing.

Similar structures have been shown in numerical forward models (Gemmer et al., 2004; Ings et al., 2004) and in physical models (Vendeville and Jackson, 1992b, in their Fig. 11). Additional examples are shown in the supplementary materials.

7. Discussion: What is the contribution of numerical simulation, compared to other methods?

Several different approaches have been used to deduce how natural salt withdrawal minibasins develop and the processes which control them. The first is the interpretation of natural examples on seismic and well data, coupled with palinspastic restoration (e.g. Brun and Fort, 2011; Diegel et al., 1995; Marton et al., 2000; Peel et al., 1995; Rowan et al., 2004; Schuster, 1995). This is a powerful tool with three major limitations. Firstly, it is only as good as the available imaging, depth migration or conversion, and interpretation. Secondly, natural processes are slow compared to human observation time so that the evolution cannot be observed and must be deduced. Thirdly, the process of palinspastic reconstruction over salt (Rowan, 1993) is imprecise; in order to deduce the thickness of even one salt layer we need to know the precise palaeo-geometry of the sea floor, the movement of the subsalt section and the basement, so that while this may provide a good representation of the general process, we cannot distinguish precisely when salt welding occurred. Additionally, the result of this study indicates that some of the assumptions used to infer the timing of initial welding in natural examples may not be universally applicable.

Physical modelling, commonly using sand/silicone models, is faster, so we can observe models evolving – but it is hard to look inside a model as it develops. Physical modelling also has some problems matching real-world behaviour when it comes to looking in detail at the process of welding; this happens on a small scale within the model, and the scalability breaks down as other physical factors start to dominate (Wagner, 2010).

Rigorous numerical modelling is repeatable, and the trajectory of every point in the model can be tracked through time – but rigorous finite element modelling is slow and complex. It has the advantage that the model can be prescribed to have material properties, rheologies, mechanisms and flow laws that match our current understanding of the natural world, but as a result the model is only valid if our definition of these laws and parameters is correct.

In general, if a physical or numerical model creates a final result that looks like geology, it has some value in understanding the process. The simple forward-modelling process used here can produce realistic geometries and therefore the insights it provides are considered to be valid.

8. Conclusions

A simple forward-modelling application, DRAWL, creates synthetic salt withdrawal minibasins with geologically realistic shapes and internal stratal architecture. This suggests that the model results should provide realistic insights into the origin and development of withdrawal minibasin systems.

A range of different processes may trigger the initiation of subsidence of salt withdrawal minibasins. Well-documented triggers include extension, contraction, lateral movement, and differential deposition by prograding slopes. While these processes are certainly sufficient, they are not necessary, and withdrawal minibasin initiation can also occur without them. These minibasins are effectively described by the original model of salt-withdrawal as proposed by Trusheim (1960) which remains valid.

Numerical and physical modelling indicates that in the absence of any other triggering processes, multiple generations of withdrawal minibasin can propagate across a region, with each successive minibasin forming in response to the effect of its older neighbour. The process of lateral propagation may explain the observations seen in natural examples such as the North German Basin of families of minibasins forming at different times on top of apparently prekinematic section.

The propagation effect may also provide an explanation of how natural withdrawal minibasins can appear to initiate in thin sedimentary sequences which are less dense than salt; the initial movement may be driven by the adjacent basin.

Forward modelling indicates that the change of behaviour seen as minibasins begin to invert to form turtle anticlines may not be diagnostic of weld formation; inversion may occur without development of a weld. For wider minibasins, even if a weld exists, inversion and turtle development may significantly predate the formation of the weld. The initial weld may not form under the core of the turtle anticline.

In wide withdrawal minibasins, stagnation of the salt under the minibasin centre may result in welding around the minibasin edges, leaving a trapped lens of salt under the basin. This creates a salt-cored turtle anticline. Recognition of salt-cored turtles can have major implications for hydrocarbon trapping and migration both above and below the salt, because the salt lens block hydrocarbon migration into the overlying basin, and may provide an effective seal for hydrocarbons below the salt.

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Appendix A. Sensitivity studies

Four sets of models were run as sensitivity studies, investigating the effect on the final model (dependent variable) of changing the value of one parameter (independent variable) while keeping the values of all others constant (control variables). Model results that resemble natural salt withdrawal minibasins seen in outcrop and seismic data are deemed “geologically realistic”. Models that give weird-looking geometries, or results not seen in natural examples, are deemed “geologically unreasonable”.

The parameters that were varied in the four experiments were (A.1) the flow law (dependence of salt flux on salt thickness), (A.2) the salt viscosity, (A.3) the relative density of the sediments relative to the salt, and (A.4) the relative rate of rise of sediment base level.

Sensitivity to variation in flow law

The first experiment (Fig. A.1) investigated the effect of varying the dependence of salt flux on salt thickness, using a range of different power laws $Q = (1/\eta)^*(dP/dx)^*H^k$. Models that run with a power greater than 1 give geologically unrealistic results. These unrealistic models include the standard plane Poiseuille flow model (which predicts flow be proportional to the cube of salt thickness). For power laws greater than 1, the minibasins do not weld; subsidence slows down progressively and they never hit the bottom of salt. Many natural examples of welded basins are known, indicating that this is not realistic. For power laws less than 1, the basins develop “weird” architecture not seen in nature.

The star marks the value (n = 1, flow directly proportional to thickness) that appears to giove the most geologically reasonable results, and which is used as the control variable level in all other model runs.

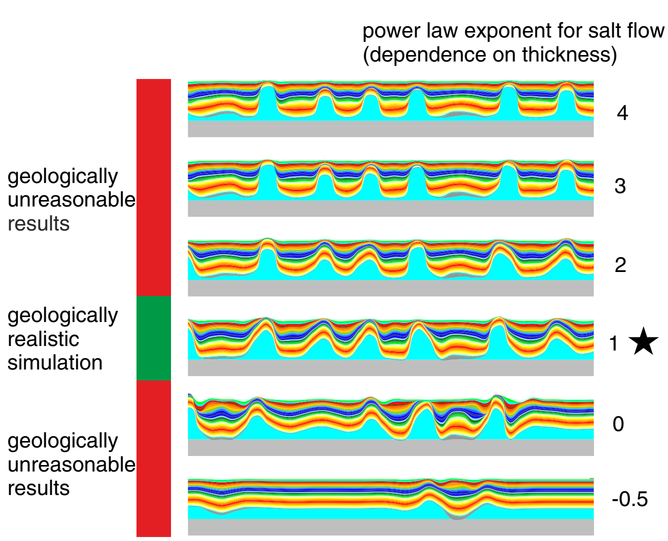

Fig. A.1. Experimental simulation of salt movement, investigating the effect of varying the flow law, using a range of power law functions for the dependence of salt flux on the thickness of the salt layer.

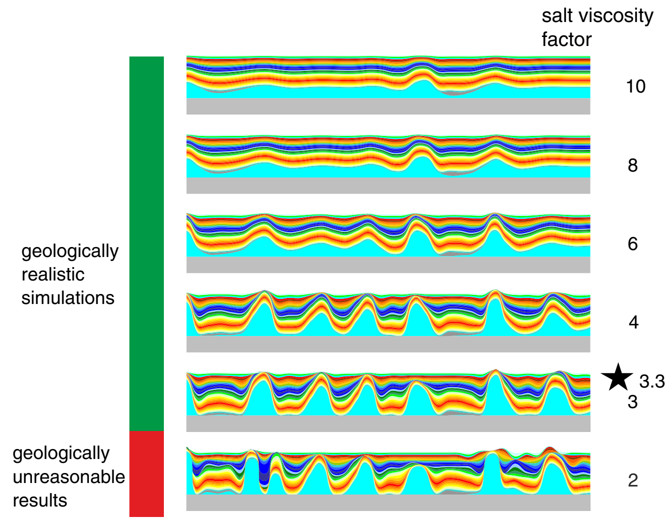

Fig. A.2. Experimental simulation of salt movement, investigating the effect of varying the salt viscosity.

Sensitivity to variation in salt viscosity factor

The second experiment (Fig. A.2) investigated the effect of varying the viscosity of the salt while keeping all other factors constant.

The number value quoted here is a dimensionless number n used in the DRAWL simulation as a proxy for salt viscosity (higher numbers representing higher viscosity).

In models run with n < 3, the simulations break down, giving geologically unrealistic results. This probably reflects the limitations of the forward model and is not interpreted as a limit on viscosities in nature. All the models run with higher viscosity give realistic results. The star represents the value n = 3.3 which is used as the control variable level in all other model runs.

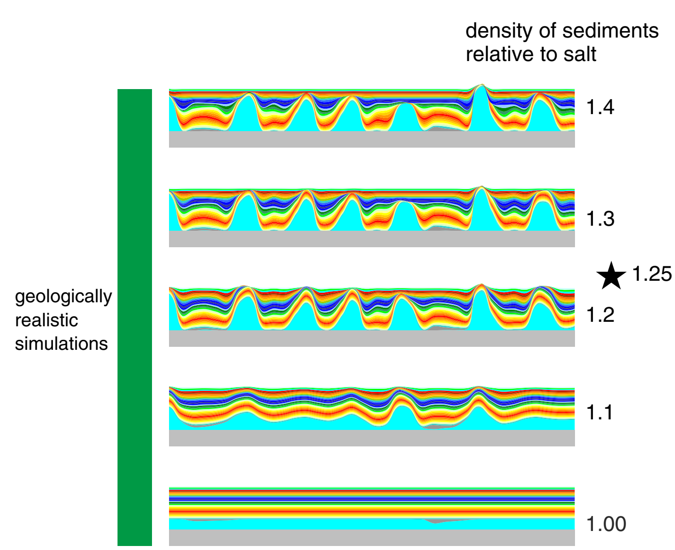

Fig. A.3. Experimental simulation of salt movement, investigating the effect of varying the relative density of the sediments relative to the salt.

Sensitivity to variation in relative density of the sediments

The third experiment (Fig. A.3) investigated the effect of varying the relative density of the suprasalt sediment while keeping all other factors constant.

For a value of 1.0, the sediments have the same density as salt, and no movement occurs (lower section); this behaviour is seen in parts of the US Gulf of Mexico such as southwest Keathley Canyon where anomalously low-density sediments are deposited directly on salt (pers. comm. Michael Hudec). As the density contrast is increased, the withdrawal minibasins develop progressively faster, but in all cases the results appear to be geologically reasonable.

The star represents the value n = 1.25 (sediment density = 125% salt density) which is used as the control variable level in all other model runs.

Sensitivity to variation in relative rate of rise of sediment base level

The fourth experiment (Fig. A.4) investigated the effect of varying the relative rate of rise of sediment base level while keeping all other factors constant.

The number value quoted here is a dimensionless number used in the DRAWL simulation as a proxy for vertical rise rate (higher numbers representing higher rate). For a discussion of scaling, see Appendix B. Increasing sediment accumulation rate causes the basins to change subtly in form; at low accumulation rates, the crests of the rising salt highs tend to be bald of sediments, while at higher rates the highs are blanketed with sediments throughout their growth. All models appear geologically realistic.

The star represents the value n = 2.8 which is used as the control variable level in all other model runs.

Appendix B. Scaling

All the DRAWL sections are shown without dimensions. The original intention was to use standard equations for Newtonian viscous fluid behaviour, combined with current estimates of halite viscosity at depth, which would have permitted direct scaling of the models – after noting that the error range on salt viscosity at depth ranges over three orders of magnitude (Wagner, 2010), implying an equivalent error on scaling! However, as discussed in Appendix A, the models that use the thickness exponent appropriate for a Newtonian fluid do not appear to give geologically reasonable results, and instead an exponent compatible with a shear-thinning fluid gives a more realistic model. While there is some evidence that natural salt can behave as a shear-thinning fluid at depth (Li et al., 2012a, b), this is no consensus and little calibration of such behaviour.

In consequence, we cannot scale these models deductively (starting with known properties and flow laws to deduce rates and scales) because the flow properties of salt at depth are inadequately constrained. However we can estimate an approximate scale inductively (comparing models with observed and calibrated real-world geology). For example, the individual minibasins in Fig. 10 are consistent with natural examples 10–20 km wide, 5–10 km deep, developing on halite substrate over a time period of 10–20 MA.

It is not the purpose of this research program to provide rigorously scaled models: given the vast uncertainty on halite viscosity and flow laws at depth over geological timescales, predictive scaling adds little value. Instead, the purpose is to create models that appear realistic in form and evolution; the more closely they resemble real structures, the more likely it is that their evolution is applicable to natural examples, and the more value we can derive from this approach.

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful... Essentially, all models are wrong, but some are useful" (Box and Draper, 1987).

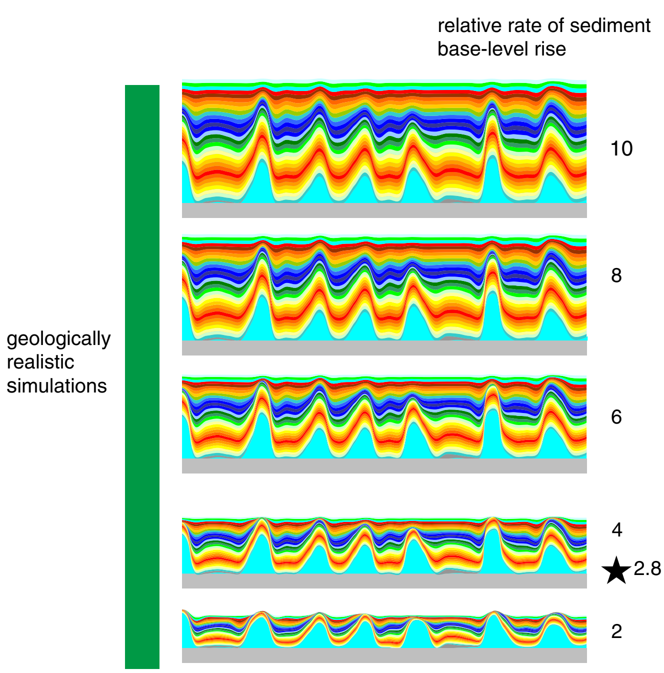

Fig. A.4. Experimental simulation of salt movement, investigating the effect of varying the relative rate of rise of sediment base level.

Appendix C. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2014.05.027.

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