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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

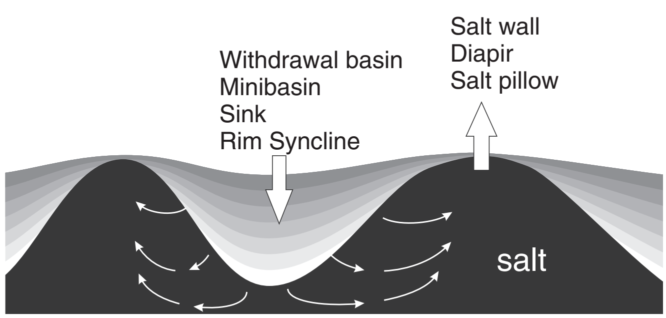

Fig. 1. The basic elements of a salt-withdrawal basin, showing alternative names for the region of salt depletion (minibasin) and the region of salt accumulation.

(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.