Salt sheet coalescence in the Walker Ridge region (Gulf of Mexico): Insights from analytical models

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A B S T R A C T

This study visualizes in analytical models the development of salt sheets from nested feeder stocks as they coalesce into a canopy. Algorithms based on complex potentials can trace multiple source flows as they compete for space when spreading into a 2D fluid continuum (a canopy). The method can visualize detailed flow patterns of coalescing source fluids, and may improve our understanding of how salt sheets coalesce to form an expanding canopy. Any new insight of canopy formation is extremely valuable, because such canopies – like the Sigsbee salt canopy in the Walker Ridge region – are the scene of major hydrocarbon drilling projects. The suture zones between the colliding salt sheets are potential drilling hazards due to anomalous pressure behavior of entrapped sediments. A case study of the Walker Ridge region applies the analytical method to reconstruct the coalescence of the salt sheets issued from at least 22 feeder stocks. Using as inputs the location of the feeder stocks, ramps and flats reflected in the base of salt map, the analytical method can constrain the flow parameters (source strengths, timing of feeder onset) for each feeder stock. The model can be used to render synthetic allo sutures maps, which are valuable for practical application in the pre-drilling planning of well trajectories that should avoid drilling into sutures zones.

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1. Introduction

The Walker Ridge region in the Gulf of Mexico is the scene of frontier, deepwater E&P projects. While technologically challenging, the federal taxation and royalty rates for US offshore hydrocarbon fields are stable, which is why these fields rank as attractive, low tax burden assets (Weijermars et al., 2014a). Deepwater oil and gas fields in the Gulf have now become core assets in the upstream portfolios of the oil majors (i.e., Shell, Exxon, Chevron, BP). Nonetheless, operational risks remain real and include threats by hurricanes (EIA, 2013) as well as anomalous well-pressures (Israel et al., 2008; Weijermars et al., 2013). This study is part of an ongoing effort to quantify the dynamics and kinematics of salt bodies and reduce risks related to in-salt drilling and borehole integrity.

Sub-salt hydrocarbon targets in the Gulf of Mexico are overlain by a vast salt canopy formed from salt that migrated up the stratigraphic section (Hudec and Jackson, 2009). Salt is fed into the canopy by multiple feeder stocks which reach the canopy level as diapiric structures. In the central Gulf of Mexico, salt sheets sourced from more than 100 feeder stocks have coalesced to form the Sigsbee canopy covering about 137,000 km² (Hudec and Jackson, 2009). The salt canopy is today mostly buried by an overburden ranging in thickness from less than 100 m to many kilometers. The buried salt canopy continues its seaward advance. The Walker Ridge region, occupying the leading edge of the Sigsbee salt canopy (Fig. 1a), is an area of extensive ultra-deepwater drilling (>5000 ft) which targets hydrocarbon reservoirs located in Paleogene sands (Wilcox formation) up to 7 km deep below the Sigsbee salt canopy (e.g., Meyer et al., 2005). Hydrocarbon exploration and production require drilling through the allochthonous salt body ranging in thickness from several hundred up to several kmns (Fig. 1b). The numerous feeder stocks from which salt sheets emerge and coalesce in the canopy are not seen in the vertical seismic section (Fig. 1b). However, their locations can be identified from depth contours on base of salt maps which outline the subcircular salt stocks (Fig. 1c). The base of the salt canopy shows a typical flats and ramps structure, which is formed by successive cut-off of sedimentary strata as the canopy advances seaward (Fig. 1b).

The surface of the seafloor above the Sigsbee canopy exhibits numerous surface depressions (Fig. 1a). These depressions commonly mark the locations were newly deposited sediments actively sink in so-called mini-basins that seek static equilibrium with the underlying salt canopy. Earlier studies have detailed the structures and mechanisms involved in mini-basin formation and salt tectonics at passive
continental margins. Such structures commonly occur at the passive margins of the Atlantic Ocean, particularly where major river systems have facilitated the rapid burial of evaporite sequences. Examples are salt tectonic provinces in the Gulf of Mexico (Fort and Brun, 2012; Hudec and Jackson, 2006; Liro et al., 2001, 2004; Worrall and Snelson, 1989; Wu et al., 1990), and offshore Brazil (Cobbold et al., 1995; Quirk et al., 2012), West Africa (Cramez and Jackson, 2000; Duval et al., 1992; Fort et al., 2004; Spathopoulos, 1996) and east Canada (Albertz and Beaumont, 2010; Albertz and Ings, 2012; Gemmer et al., 2004, 2005; Gradmann and Beaumont, 2012; Gradmann et al., 2012; Keen and Potter, 1995).

Major advances in our understanding of salt canopy formation and suture terminology have been comprehensively reviewed and expanded in a recent study by Dooley et al. (2012). Various types of sutures form at the junctions between coalesced salt sheets (Fig. 2). One type of suture forms by internal folding and disruption of the original contact surface between the salt sheet and its overlying sediment veneer; these are termed autosutures. Larger and more prominent sutures form when different salt sheets coalesce: the junctions between different coalesced salt sheets are called allosutures. Salt sutures are potentially hazardous for drillers, because the entrapped sedimentary stringers (commonly clastic and carbonate sediments) may contain either overpressured or underpressured pore fluids (Schoenherr et al. 2007; Israel et al., 2008), depending on the depth at which the stringers were originally trapped and their subsequent rise or fall within the salt body. Sediments trapped in salt will not adjust to pore-fluid pressure if not connected to surrounding porous rocks; rock salt has negligible porosity and is impermeable (except under unusual conditions, such as very shallow burial or high fluid pressures; Urai and Spiers, 2007). Consequently, sediments trapped in sutures inside salt bodies may trigger kicks (when overpressured) or cause lost circulation (when underpressured, creating so-called “thief zones”); both of these risks make drilling through salt hazardous (Dusseault et al., 2004; Weijermars et al., 2013).

Although the tectonic development of the Walker Ridge region is increasingly better understood (Dooley et al., 2012; Fort and Brun, 2012; Hudec et al., 2009; Jackson et al., 2010), previous studies focused mostly on the development of structures floating and sinking into the salt. This study takes a different, complementary approach and highlights the principal flow patterns in the salt canopy that can be inferred from base of salt maps. Continuing deposition superposes local flows due to sinking mini-basins onto the basic flow pattern, but this study demonstrates that the principal flow directions are recorded in the base of salt by the flats and ramps. To better understand salt sheet interactions and the formation of sutures when numerous feeder stocks are involved, we studied the interaction of multiple source flows in analytical models.

This study visualizes the results of our analytical flow simulations. First, the basic model setup is briefly outlined (Section 2). The principal input parameters that control suture formation can be systematically...
varied over a broad range to investigate the sensitivity of source flow coalescence patterns to minor variations in key parameters. The initial models are kept simple for a systematic approach and assume simultaneous onset of all sources with steady source strengths, with and without a far-field flow (i.e., regional slope; Sections 3.1 and 3.2).

Next, the effect of transient flow due to time-dependent source strength is investigated and visualized (Sections 4.1 and 4.2). The analytical model tool is subsequently applied to a natural example using field data from the base of the Sigsbee salt canopy near its leading edge (Section 5). The results are discussed (Section 6) followed by conclusions (Section 7).

**2. Modeling method**

Analytical models can provide valuable insight, because these allow variations in the fluxes of sources over an unlimited range and each source can be activated at a pre-specified time. The basic algorithms of the model are derived from the Navier–Stokes equation using complex potentials as detailed in earlier work (Weijermars, 2014a; Weijermars et al., 2014b). The algorithms are valid for an incompressible fluid continuum (vanishing divergence) and irrotational flow (vanishing curl), which means free-slip is assumed at any physical boundaries. Our complex potential models are valid for viscous fluid flow, especially when the rotational flow effects of boundary layers effects are assumed negligible. For a detailed analytical description of boundary-layer effects, see a review by Wang (1991). An independent mathematical proof of potential flow as a scalable description of irrotational flow in viscous (incompressible) fluids is given in Weijermars et al. (2014b). The simplifying model assumptions may limit the extrapolation to coalescing salt sheets in nature, because such sheets may include heterogeneities and anisotropic properties that can create fast flow lanes, internal folding and ductile shear zones (Burchardt et al., 2012a,b; Chemia et al., 2008; Koyi et al., 2013; Strozyk et al., 2012; Van Gent et al., 2011). Such possible differences with our limiting assumptions are briefly reviewed later (Section 6.2) in order to place the translation of model results to natural salt flows in proper perspective.

The shape of advancing salt sheets issued as source flows from feeder stocks is determined by the relative position of their feeder stocks, their respective flux magnitude, any superposed far-field flow rate, and the relative onset times of flux from the individual salt feeders. In this study we visualize the results of flow simulations when nested sources are switched on simultaneously or at different times while they compete for space in a developing canopy. When the Newtonian creeping salt leaves the feeder location of n sources their velocity field is fully described by (see Weijermars, 2014a):

\[
\begin{align*}
\mathbf{u}_x &= \sum_{i=1}^{n} \frac{m_i (x-x_i)}{(x-x_i)^2 + (y-y_i)^2} \\
\mathbf{u}_y &= \sum_{i=1}^{n} \frac{m_i (y-y_i)}{(x-x_i)^2 + (y-y_i)^2}
\end{align*}
\]

These are the two velocity vectors (\(u_x\) and \(u_y\)) in x and y direction throughout the flow space, which may be time dependent when any of the sources (\(m_i\)) is defined as a time-dependent variable, \(m_{i(t)}\). We next introduce a superposed far-field flow, which is applicable when the evolution of the source migration is affected by a flow component directed downslope (Weijermars, 2014a). The source-flow-field description can then be amplified with a superposed constant uniform far-field-flow, \(U_{\infty}\), or time-dependent \(U_{\infty(t)}\), corresponding to gravity driven source flows onto respectively a stable slope or a tilting slope (Weijermars et al., 2014b). All analytical models in this study are produced with Matlab code.

### 3. Simultaneous nested source flows

#### 3.1. Simultaneous nested source flows without far-field flow (negligible regional slope)

The time series of Fig. 3 show the simultaneous spreading of nested sources for a particular constellation of feeder stocks where all sources have identical strengths. The competition for 2D flow space in the horizontal plane of view results in a large composite source flow that is directed radially outward. This becomes particularly obvious in an advanced stage of the flow evolution (Fig. 3f). The flow is steady and flow lines do not shift, so all stages of flow plume advancement are in fact included and preserved in the final flow snapshot of Fig. 3f.

The effect of weaker source strengths is modeled in Fig. 4. All parameters in Fig. 4a & b are identical to those used in the model of Fig. 3, but the source strength is weaker (\(m^* = 0.5\) instead of 1). The model of Fig. 4 is relevant because it confirms that minor differences in source strength do not significantly alter the overall infill pattern; it just evolves slower. Source strengths need to be steady and identical for multi-source flows to evolve similarly but their magnitudes may differ in each respective model run. Steady sources with identical spatial distributions of feeder stocks will develop identical flow patterns, irrespective of the scaling of their absolute source strengths.

Notice that the infill pattern of Fig. 4a for \(t^* = 3\) (at \(m^* = 0.5\)) is identical to that shown in Fig. 3c for \(t^* = 1.5\) (at \(m^* = 1\)). This confirms that varying the source strength has no effect on the suture development of the final flow patterns. The flows of Figs. 4b and 3f are identical, the plumes of Fig. 4b have developed a bit further due to the longer runtime. A typical ‘starfish’ suture pattern develops around the source located nearest to the center of the nested sources.

The flow simulations of nested sources resemble the suture patterns seen in boiling mud pots (Fig. 5a & b). Such mud pots occur in numerous volcanic areas [e.g., US: Yellowstone Park and the Davis–Schrimpf seep field in California (Lynch and Hudnut, 2008); Azerbaijan: near Baku; New Zealand: Rutuoa National Park (Howland et al., 1997)]. The mud slurries are water-saturated and gaseous bubbles rise to the surface and episodically shed fresh rings of mud carried up from below (Dimitrov, 2002). The nested mud sources may overprint each other when younger sources pierce mud plumes from previous sources that are no longer active (Fig. 5a). Most mud pots have a surface bulge indicative of a waxing source strength (\(\alpha > 1\), see discussion in Weijermars et al., 2014b). The example of Fig. 5a shows mud pot source flows with superposed downslope flow toward the left of the image and source flows develop into narrow plumes downstream. Fig. 5b shows another example of a central high with a slope gradient toward the left and right. Note the typical ‘starfish’ or ‘hydra’-shaped suture pattern that develops around sources located in the center of nested sources in the model (Figs. 3 & 4) is also seen in the mud pot flow patterns (Fig. 5b).

#### 3.2. Simultaneous nested source flows with superposed far-field flow (due to a regional slope)

In the Gulf of Mexico the allochthonous salt canopy, in which the salt feeder stocks emplace their salt sheets, is commonly assumed to creep seaward due to the shelf slope. This traditional view needs to be revised from the leading edge of the salt canopy as we can conclude from our case study of the Walker Ridge region (Section 5.2). First we studied the effect of a superposed flow on the canopy infill pattern of salt sheets spreading from their salt source feeder stocks (Fig. 6a–d). The positions of the salt feeder stocks are identical to those in Figs. 3 and 4, but the nested source flows are subjected to a superposed creep flowing from left to right. The displacement of a passive marker line (black contours) and far-field flow lines (green lines) shows that the fluid from sources near the western margin of the feeder stock cluster is actually moving opposite to the regional flow, due to the combined flow strength of...
the sources. However, there is a stagnation point to the left of the field of view where the far-field flow direction reverses, and fluid further downstream moves from left to right before being deflected around the nested sources. A typical ‘starfish’ suture pattern develops again for the plume issued from the source that is located near the center of the nested sources. When the far-field flow becomes stronger relative to the source strengths, starfish-shaped sutures develop into hydra-shaped sutures (see next paragraph).

The flow simulation of Fig. 7 is nearly identical to that of Fig. 6, but the flow strength of all sources is halved. Although the regional flow velocity $u^* = 1$ is identical to that used in Fig. 6, the flow patterns develop differently because $m^* = 0.5$ (and not $m^* = 1$ as in Fig. 6). The final suture patterns of Fig. 7b cannot be matched to those seen in Fig. 6d due to the different ratios of the far-field flow rate and the source flux strengths. Fig. 7b clearly exhibits the shape of a Rankine body as outlined by the densely spaced time-step contours (perpendicular to the green far-field streamlines). The stagnation point is located at $(x,y) = (-7.5,0)$, and the far-field flow is now stronger than the combined sources due to which the far-field flow-net no longer reverses its flow direction near the nested sources (opposite to what occurred in Fig. 6d). Further note that no less than three sources formed hydra-shaped sutures (labeled 1–3 in Fig. 7b), which originated from sources closer to the upstream side of the nested sources. Apart from the hydra-shaped sutures, plumes tapering in downstream direction are common.

Again we look at natural prototypes found in mud pots. Fig. 8a & b shows mud flows with numerous tapering plumes. The source flows are clearly affected by a far-field flow due to the sloping bulge in the mud mounts. The tapering plumes are commonly indicative of the

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**Fig. 3.** a–f: Mathematical model showing progressive infill of salt canopy (pink space) by salt sheets (grey shade) issued from feeder stocks in fixed (arbitrary) locations. Particle paths (yellow curves) of fluid issued at $t^* = 0$ from the fourteen injection sources (yellow dots) propagate as outlined by the non-dimensional time contours (red curves) for progressive time-steps $\Delta t^* = 0.5$. The speed of fluid particles is determined by the initial strength of each (all sources with non-dimensional strength $m^* = 1$ over the total runtime $t^* = 3$) and the relative position of the sources. Time steps shown are: (a) $t^* = 0.5$, (b) $t^* = 1$, (c) $t^* = 1.5$, (d) $t^* = 2$, (e) $t^* = 2.5$ and (f) $t^* = 3$. 

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weaker sources that lost space to stronger sources. Plumes issued from weaker sources cannot fan out and are pinched by the stronger sources. Nested sources with different starting times are modeled in the next section (Section 4). These observation are relevant for understanding the kinematics of salt sheets. Diagnostic rules are formulated later (Section 4.3), and are subsequently applied in our case study of the Walker Ridge region (Section 5.2).

4. Nested source flows with variable onset times

4.1. Sources without far-field flow (negligible regional slope)

The next set of models explores the effect of delayed feeder onset in nested source flows. Fig. 9 has the same final constellation of feeder stocks as used in the previous models, but the infill of the fluid canopy by the source flows arrives in four waves. There is no far-field flow superposed, so the nested sources spread radially outward until obstructed by neighboring sources. The final suture patterns developing by the coalescence of individual plumes (Fig. 9f) do not differ much from the final patterns seen in the coalesced plumes of Figs. 3f and 4b (which developed for the same constellation of nested sources but without delayed onset of the sources). The conclusion is that suture patterns for nested sources without a far-field flow (no regional slope) develop nearly identical, irrespective of the absolute strength of their sources. They display almost no variation in final suture pattern.

The most central source typically develops a starfish-shaped suture, adjoining sources develop hydra-shaped sutures and outermost sources develop unperturbed fans. The overall suture pattern mainly is determined from the outset by the geometrical constellation of the feeder sources. This may vary from run to run depending on the length of time older sources were active prior to switching on new sources, and also on the constellation of the feeders.

4.2. Sources with a far-field flow (due to a regional slope)

Fig. 10 shows a constellation of feeder stocks with the same positions as used in Figs. 3, 4, 6, 7 and 9, but the sources have delayed starting times and are subjected to a far-field flow. The delayed onset of the sources in the presence of a far-field flow leads to unique flow patterns. The source that started flowing early in the canopy development history is later pierced by no fewer than four of the later sources (Fig. 11). Plumes or salt sheets pierced by other individual sources are diagnostic for feeder stock development with different starting times. Also note that the far-field flow net is pushed backward in a later stage of the flow simulation (Figs. 10 and 11). This may occur when the number of sources increases and gives the nested sources enough flow strength to reverse the direction of the far-field flow in the vicinity of its upstream cluster of sources.

Fig. 11 highlights a final stage of the model in Fig. 10 for a slightly longer run time. The position of all sources is identical to those seen in

Fig. 4. a & b: Progressive infill of salt canopy (pink space) by salt sheets (grey shade) issued from feeder stocks in same locations as in Fig. 3, but the strength of the sources was halved ($m^* = 0.5$ instead of 1). Time steps shown are: (a) $t^* = 3$ and (b) $t^* = 10$. Particle paths (yellow curves) of fluid issued at $t^* = 0$ from the fourteen injection sources (yellow dots). Non-dimensional time contours (red curves) are outlined for progressive time-steps $\Delta t^* = 0.5$.

a
b

Fig. 5. a: Boiling mud pot with slope to the left. b: Mudpot with central ‘hydra’-shaped suture, which is a deformed ‘starfish’ due to flow downslope (see Section 3); [source (a): http:// lenorecrawford.blogspot.nl/; source (b) lost].
Figs. 6da and 7b. The strength of the far-field flow is also identical in all models. However, the delayed onset of some of the feeder stocks in Figs. 10 and 11 results in a distinct suture pattern, different from Figs. 6da and 7b. We can conclude that suture patterns for nested sources with a superposed far-field flow (due to a regional slope) display a large variety of final suture shapes depending on the relative magnitudes of their source strengths and far-field flow rates.

4.3. Diagnostic observations on suture development

The simulations of nested source flows in sections 2 to 4 revealed the following diagnostic properties for allo-suture development.

(1) Nested source flows starting simultaneously develop radially spreading plumes with the central sources generally traveling...
less far than the peripheral sources. The innermost source develops a starfish-suture. Adjacent sources develop hydra-shaped arms squeezed in between the outermost sources. The outermost sources develop into fans.

(2) Suture patterns for nested sources with a far-field superposed (due to a regional slope) display a large variety of final suture shapes depending on the relative magnitudes of their source strengths and far-field flow rates. The starfish-shaped central source is replaced by a hydra-shaped source when the far-field flow becomes stronger and deforms the source flows.

(3) Upstream sources may flow in a direction opposite to that of the far-field flow (i.e., they move up the regional slope). This effect is due to the combined strength of nested source flows, which may outperform the far-field flow (Figs. 6 and 11; sources furthest upstream).

(4) Nested sources that start flowing simultaneously cannot develop any plumes that are pierced by adjacent source, only later sources could pierce an earlier plume. This seems a trivial conclusion, but is of great practical importance because salt canopy regions that show no piercings (in the base of salt map, see Section 5.2) may be assumed to have been fed by feeder stocks that reached the canopy more or less simultaneously.

(5) Reversely, sheets pierced by plumes of individual sources (such as seen in Fig. 11) are diagnostic for feeder stock development with different starting times. If nested sources are started at variable times, plume shapes and sutures develop in unique ways depending on the timing of the onset of the individual sources.

The above diagnostic feature of suture development may be useful for the interpretation of natural salt sheets. An application to the Sigsbee salt canopy in the Walker Ridge region is elaborated in the next section.
Fig. 10. a–l: Progressive infill of salt canopy (pink space) by salt sheets (grey shade) issued from feeder stocks in same locations and a superposed far-field flow from left to right with non-dimensional velocity \((u^*, v^*) = (1, 0)\) as in Fig. 6. Time step between images is \(\Delta t^* = 0.5\). A new feeder stock is switched on at \(\Delta t^* = 0.5\). Yellow particle paths show fluid issued at \(t^* = 0\) from the injection source. Far-field flow lines (green curves) are tracked for an arbitrary marker line (black) starting \(x = -8\) and displacing as shown for progressive time-steps \(\Delta t^* = 0.5\). Total run time shown is \(t^* = 6\). Non-dimensional time contours (red curves) are outlined for progressive time-steps \(\Delta t^* = 0.5\).
5. Application to Walker Ridge region

5.1. Geological outline of the Walker Ridge region

The autochthonous Louann salt source layer in the Gulf of Mexico is of Jurassic age. The salt has subsequently migrated laterally down the shelf slope and up the stratigraphic section in response to (1) progressive loading by aggradation of sediments originating from the Mississippian and Rio Grande delta systems, and (2) passive margin tectonics that continue to modify the internal structure of the sedimentary wedge. The deltas that supplied the sediments to the Gulf have shifted their locations along the shore which is reflected in some 25 principal depositional systems distinguished by Galloway et al. (2000). The shelf break has migrated outward as its sediment load expanded by aggradation.

In the Walker Ridge region, the leading edge of the Sigsbee salt canopy shows up as fluid-like lobate contours on the regional bathymetry map (Fig. 12). The outline of the frontal edge consists of a steep escarpment following a continuous series of interconnected great circle segments. In fact, these circular lobes can be explained from their origin as salt source flows (see model in Section 5.2). An ephemeral veneer of sediments covers the leading edge of the canopy, which advances over the sea-floor as salt thrusts its sedimentary roof over the Quaternary sediments in front (Jackson et al., 2010). As the canopy creeps forward assisted by the peripheral roof-edge thrust it forms flats and ramps in the base of salt (c.f., Fig. 1b and c). The salt flats occur where the basal contact of salt is largely concordant with the underlying strata (Jackson et al., 2010). These salt flats may be attributed to a hiatus or slow sedimentation in front of the salt, so that basinward spreading of salt is not buttressed. In contrast, ramps in the base of salt mark epochs of relatively fast sedimentation which forces salt to climb up section as it advances outward in accordance with the model of diapiric downbuilding (Jackson et al., 1988; Fuchs et al., 2011).

In this study, we adopt the view that most of the flats and ramps in the base of salt are due to sedimentary downbuilding of the expanding salt canopy. Some caution is required in places where thicker sediments cover the canopy. Thrusting can create ramps independent of the aggradation rate, because a stepped thrust can form a salt ramp (Jackson et al., 2010). However, the continuity and curved nature of the base of salt ramps, with constant spacing, in the Walker Ridge region (Fig. 13) supports their interpretation as timelines. The ramps form during epochs of faster aggradation while salt advancement is more steady resulting in a steeper sloping salt-sediment contact. Bryant Canyon is a submarine flow channel where salt continues to push the canyon walls inward (Lee et al., 1996).

The southward slope of the seafloor in the region is very gentle, generally less than 1°, which means the salt sheets experience more spreading due to their active flux from sources than from any superposed far-field flow due to the slope. In gravity flow terms, the Rankine number is relatively large \((R_k > 100\), for details see Weijermars et al., 2014b). The seaward spreading of the salt canopy is principally due to the salt flux from the sources and competition for space pushes the salt outward. Behind the leading edge of the canopy the base of salt actually slopes landward (Fig. 1b and c), precluding the occurrence of a superposed far-field flow. The kinematic implications are further highlighted in more detail later in this study (Section 5.2).

The salt sheets in the Walker Ridge region began to arrive at the canopy level through their feeder stocks (imaged in Fig. 1c) in the Pliocene.
Folds and faults in the underlying Upper Jurassic–Eocene layers are commonly cored by autochthonous Louann salt (Worrall and Snelson, 1989; Diegel et al., 1995; Peel et al., 1995; Fort and Brun, 2012). The salt migrated upward along faults and feeder stocks formed by rapid downbuilding until the salt coalesced in the allochthonous salt canopy above Cretaceous and Early Miocene sediments (Schuster, 1995; Rowan et al., 1999; Hudec and Jackson, 2006).

Numerous regional studies of the geological evolution of the Gulf of Mexico have been published (e.g., for a review and sources see Hudec and Jackson, 2006). Detailed studies are also completed for many E&P license blocks, but remain largely unpublished due to company policies that prevent the sharing of proprietary data. This study focuses on the Pliocene–Quaternary advance of the salt canopy as can be reconstructed in below case study with our new analytical method using seismic features (locations of feeders, ridges and ramps) reflected in the base of salt map (Section 5.2).

5.2. Base of salt model for Walker Ridge region

The analytical model of the nested source flows with variable source strengths outlined in sections 2–4 can now be applied to a natural example. The effects of sources switching on at different times and with different strengths are modeled in below case study of the Walker Ridge region. The aim is to find a best fit for the pattern of flats and ramps concentrically arranged around feeder stocks as reflected in the base of the Sigsbee salt canopy (Fig. 13). All 22 feeders identifiable on the base of salt map (marked in Fig. 13) are used in our analytical model simulation of the canopy formation.

A basic assumption is that feeder stocks in the Walker Ridge region are so closely spaced that a continuous salt canopy forms by early coalescence of the issued salt sheets. The continuous contours of the ramps in the base of salt seem to confirm salt advancement in a continuous front. By tediously modulating the source strengths of the 22 feeder stocks and 6 phantom feeders, we managed after 24 runs of about 1 h each, to generate a reasonably close match with the Walker Ridge prototype (Fig. 14). We had only access to seismic images of base of salt for a limited region, which is why we used the series of phantom sources to supply source flow pressure from the canopy’s interior region. Feeder stocks are known to exist there and provide salt to the canopy in the area adjacent to our base of salt map.

Feeder stocks nearer to the edge of the canopy started their plumes later than interior ones, which allowed them to develop into fan-shaped salt sheets. Table 1 lists the relevant source parameters (source strength and onset times) used in our best model run, which for the given constellation of feeder stocks are the critical parameters to affect the final suture pattern of the Walker Ridge region.

We suggest that a best fit between our model and the natural salt canopy means that the selected source strengths and switch on times in the model provide fairly reliable estimates for the natural prototype. Otherwise, the close fit of the salt plumes (or sheets) in the model and the natural prototype could not occur. The seismic maps for the base of salt depth with the feeder stock locations marked enables a unique
reconstruction of the nested source flow dynamics in the Walker Ridge region. The resulting salt sheets coalesced and their junctions mark the allosutures. There are numerous sutures, and some zones are densely packed with allosutures. Although allosutures can be imaged in 3D seismic surveys, not all sutures may show up. Because of the danger posed by the allosutures for drilling, as explained in the Introduction of this paper, the map of Fig. 14 provides valuable additional insight for pre-drilling plans.

Table 1 specifies the source strengths used in our best fit model uniquely required to fill in the pattern of Fig. 14 in 10 Ma. Precise cutoff ages for sedimentary horizons against the base of salt were not available during the time of our analysis. If such data become available, these can be used to adjust the absolute time scale for the flow simulation. The relative strengths of the sources will not alter, but their absolute strengths can be adjusted simply by multiplying with the fractional difference between 10 Ma assumed in our study and any dated ramps in the base of salts. The strengths of the sources in the Walker Ridge area range between 5 and 60 km²/Ma. These sources are relatively strong as compared to the calibrated source strength of 5.7 km²/Ma for shallowly burrowed salt sheets moving near the Mississippi Delta area (Hudec et al., 2009). The flow map of Fig. 14 suggests the rim region of the canopy moves faster outward and in a different direction than its interior region, which may explain the distinct differences observed between the two mini-basins styles. In our present study we aim for a demonstration of principle rather than an industry study that should merge the base of salt flow with the superposed effects of sinking mini-basins.

Most of the deep-water hydrocarbon fields in the area have planned life cycles between 30 to 40 years, which means salt shifting at 60 to 70 cm per decade may affect vertical wells that are anchored in the stable exit points at the base of salt. A separate, follow-up study quantifies the regional distribution of strain rates and stresses (Weijermars and van Haren, 2014). Knowing the locations where the salt speeds, strain rates and stresses are lowest aids well planners in identifying the most stable locations for well trajectories when planning drillholes through a salt canopy that overlies pre-salt hydrocarbon targets.

### 6. Discussion

#### 6.1. Model implications

This study introduces a fundamentally new view where lateral salt movement in the Sigsbee canopy is considered driven by a salt flux maintained by feeder stocks (bringing up salt from a lower source layer pressured by regional loading). The salt moves radially outward from the sources by gravitational collapse but any flow contribution due to the regional slope is negligible. In the Walker Ridge region, the basic salt flow is entirely dominated by the fast flux of the salt feeders (i.e., $Rk > 100$; Weijermars et al., 2014). Higher up in the canopy (i.e., closer to shore) superposed flow contributions may locally occur by subsiding mini-basins, but these flow perturbations are considered minor and do not appear to affect the principal regional flow pattern as inferred from the base of salt image.

The analytical flow map of the salt canopy (Fig. 14) includes estimates for the average horizontal speed of salt in each potential drilling location. In regions close to some of the larger feeder stocks in the Walker Ridge area, the horizontal flow rate attains ultrafast speeds of 60 to 70 km/Ma, which corresponds to 6 to 7 cm/y. The rapid spreading of the salt sheets near the advancing frontal edge of the Sigsbee canopy at Walker Ridge occurs in a region characterized as the Outer-Canopy Contractual Province where mini-basins evolve complex structures (Hudec et al., 2009). Mini-basins in the adjacent Midslope Province of the Garden Banks region (Fig. 12) are interpreted to evolve in a simpler fashion (Hudec et al., 2009). The flow map of Fig. 14 suggests the rim region of the canopy moves faster outward and in a different direction than its interior region, which may explain the distinct differences observed between the two mini-basins styles. In our present study we aim for a demonstration of principle rather than an industry study that should merge the base of salt flow with the superposed effects of sinking mini-basins.

#### 6.2. Model strengths and limitations

The new analytical method developed is used to model the formation of allosutures patterns as implied in flow solutions for sources fed by feeder stocks in a specific constellation. The analytical description by complex potentials requires a minimum of input parameters. The values of the analytical code can be computed at any desired scale of resolution, which means that grid resolution issues which frequently limit the accuracy and practical application of numerical methods do not arise in our method. The scale of resolution is infinite and allows visualization of high resolution flow lines and the velocity field can be computed at the scale of individual well sites for any subarea of the Walker Ridge region. This makes our method a valuable tool for studying salt sheet interaction, especially when feeder sources are closely spaced so that a fluid continuum is formed early in the formation of the canopy.

Interaction with sediments at the boundaries in front, below and above the salt is assumed as a friction free flow contact. Differential flow inside salt sheets due to any internal heterogeneities inside the salt sheet are not considered (see Section 2). A further limitation is that our analytical model for multiple sources is 2D, and therefore

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Table 1: Walker Ridge Base of Salt–Nested Sources Input Data (Red highlights are for phantom sources)
cannot account for overriding of neighboring salt sheets as is frequently observed in physical models of nested source flows (Dooley et al., 2012). Downbuilding of individual salt sheets is separately modeled in a 3D expansion of the model code (Weijermars et al., in review). The 3D expansion using multiple sources allowing overriding is modeled in a companion paper (Weijermars, 2015). Our analytical models do not implement the sedimentary stringers or any sedimentary roofs as salt is being intruded into salt. Ramping of the salt above sediments deposited in front is considered to occur at a scale that justifies neglecting its effect on the overall horizontal displacement pattern. Analytical models therefore do not replace physical models, but are complementary because the exclusion of complicating boundary conditions can provide additional insight as highlighted in this study. The sources in our analytical model expand into a viscous continuum (with a viscosity identical to that of the source fluid), which causes a difference in flow patterns seen in the early stage of physical models where individual source commonly move down a subaerial slope (see fig. 20 in Weijermars, 2015).

7. Conclusions

The analytical method outlined here can be used to generate nested source flow maps based on seismic imagery of the base of salt as inputs and then quantifies the flow parameters (source strengths, timing of feeder onset) for each salt feeder stock. The method can visualize flow patterns and the allosutures formed between the coalesced salt sheets. Such synthetic allosuture maps are of considerable value for pre-drilling planning of borehole trajectories. These should avoid drilling in allosutures, because such zones may contain sedimentary stringers swept into suture zones when the sheets coalesced. The models do not include stringer blocks, but indicate the location of the suture zones where they might be expected, highlighting where drilling risk is increased (but not necessarily an actual risk). Our case study of the Walker Ridge region demonstrates the method using feeder stock locations and their source strengths to match the model flow with flats and ramps visible on 3D seismic maps for the base of salt.

A comprehensive analytical model is presented for the formation of the coalescing salt sheets issued by the nested feeder stocks in the Walker Ridge region in the frontal part of the Sigsbee salt canopy (Fig. 14). These salt sheets form complex patterns of apical sutures at their junctions. The model accounts for different strengths and different onset times of the various feeder stocks. Once feeder stocks were activated, their individual strengths were kept constant in the model. The modeling code can account for time-dependent source strengths, but this functionality was not utilized in the model of the Walker Ridge region (Fig. 14). The analytical method has no resolution limitation, as the solutions given are mathematically exact for any scale considered. Applications in high resolution studies are now possible.

Analytical models can help predict the likely position of suture outlines, based on the base of salt maps with feeder stock locations, ramps and flats, and basal suture ridges as input constraints. Even when suture zones do not show up on seismic images, our analytical and physical models provide clues to their most likely location, which helps seismic
interpreters who must delineate hazardous suture zones in the salt can-opy prior to drilling. The analytical model uses the constellation of nested sources to render the most plausible allostratigraphic patterns resulting from a certain salt creep field. A wide range of suture patterns can occur and the models developed provide clues to better delineate hazardous suture zones prior to drilling. Our model enables the generation of synthetic maps detailing allostratigraphic patterns based on input data from 3D seismic images of the base of salt.

Diagnostic recommendations for practical application have been summarized in Sections 4.3. These detail the link between observable geometrical features and the dynamic conditions responsible for their formation. We suggest the production of detailed salt flow maps should become an essential part of pre-drilling studies, both for exploration and production drillholes planned to safely reach sub-salt and pre-salt hydrocarbon targets. Pre-salt refers to reservoir rocks that are stratigraphically older than the autochthonous salt, whereas sub-salt reservoir rocks are stratigraphically younger than the allochthonous salt above them. The distinction is important because for pre-salt targets (as in Santos Basin, Brazil), the overlying salt tectonics is geologically irrelevant (being a later feature), though very important for correct seismic imaging of the pre-salt target, and very important for drilling. In contrast, for sub-salt targets (e.g. Gulf of Mexico) the overlying salt is important for all three aspects: geology, imaging, and drilling (Pers. comm. Martin Jackson, 6 November 2014).

Acknowledgments

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Appendix A. Alternative model runs

We produced 24 runs of about 1 h each to generate a reasonably close match with the Walker Ridge prototype (Fig. 14). This result was obtained after iteratively modulating the source strengths of the 22 feeder stocks and 6 phantom feeders. Figs. 11–15 show results of some earlier runs. Convergence between the prototype pattern and the model was relatively rapidly obtained for the Amery sheet but more difficult for the Cortés sheet. The reason is that the single, principal source that feeds the Cortés sheet (source 13) develops a broad fan, and needs to be buttressed to prevent excessive northerly expansion. Fixed locations for the feeder source in the interior part of the Sigsbee canopy were not available for this study. Shifts in the locations and strengths of phantom sources affect the final flow patterns. The dense cluster of sources that feeds the Amery sheet is less affected by changes in the phantom sources. A major conclusion of our runs is that inclusion of a far-field flow (due to a regional slope) makes it impossible to produce the broad, diverging salt fans that characterize both the Amery and Cortés sheets. Inclusion of a far-field flow from the north quickly stretches the fans to the south, without any possibility to match the observed timelines inferred from flats and ramps in the base of salt map. This is why we conclude with confidence that salt in the Walker Ridge area moves radially outward from the sources toward the free, leading edge of the canopy. Any far-field flow contribution must be negligible.

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2014.11.018.

References


Bryant, W.R., Liu, J.Y., 2000. Bathymetry of the Gulf of Mexico: College Station, Texas, Texas Sea Grant, TAMUGS-00-506, CD-ROM.

Burchardt, S., Koyi, H., Schmeling, H., 2012a. The in-fl ow from the north quickly stretches the fans and ramps in the base of salt map. A wide range of suture patterns relevant (being a later feature), though very important for correct seis-mic imaging of the pre-salt target, and very important for drilling. In contrast, for sub-salt targets (e.g. Gulf of Mexico) the overlying salt is important for all three aspects: geology, imaging, and drilling (Pers. comm. Martin Jackson, 6 November 2014).

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