Closure of open wellbores in creeping salt sheets

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SUMMARY
Safe exploration and production of pre-salt (or subsalt) hydrocarbons require that drilling operations be optimized. We introduce analytical models of wellbore closure, accounting for variations in both the wellbore net pressure and far-field flow rate of an autochthonous or allochthonous salt sheet penetrated by the wellbore. We demonstrate how closure rates of such a wellbore evolve for increasingly stronger Rankine flow. For high viscosity salt (∼1015 Pa s) the wellbore closes by a pure sink flow without any Rankine shift from its vertical trajectory path. For low viscosity salt (∼1016 Pa s) Rankine flow dominates. Wellbore closure in salt sheets may vary within the same wellbore due to differential tectonic creep rates at different depths. Mitigation of wellbore closure by, for example, reaming, jarring, brine solution and thermal control, is most effective if spatial variation in closure rates is understood and quantified. Evaluation of wellbore closure rates due to salt creep should be customarily included in wellbore stability analyses before drilling and during well monitoring.

Key words: Geomechanics; Creep and deformation; Fracture and flow.

1 INTRODUCTION
Pre-salt or subsalt plays are important in hydrocarbon exploration and development in major salt basins around the world (e.g. Gulf of Mexico, Angola, Brazil, Zechstein, Levant and Precaspian basins). To reach these prospects, boreholes must penetrate and cross overlying bodies of autochthonous or allochthonous salt. An autochthonous salt layer rests on older pre-salt strata or basement. Conversely allochthonous salt overlies stratigraphically younger strata (Hudec & Jackson 2007). Allochthonous salt occurs at stratigraphic levels above the autochthonous source layer and is emplaced as subhorizontal or moderately dipping, sheetlike salt diapirs. Due to the mobility and specific physical properties of salt bodies, in-salt drilling operations can be more challenging than non-salt drilling for the following reasons.

(1) Seismic depth estimates to target zones are inaccurate owing to velocity shifts near salt bodies. Predicting the accurate depth of salt entry for wellbores remains difficult as long as seismic drift is not calibrated and verified by prior drilling in the same area (Shumaker et al. 2007; Hoetz et al. 2011).

(2) Balancing the mud pressure for wellbores in salt sections is difficult because the pore pressure is close to zero in impervious salt sections. Wellbores are typically balanced by estimating the vertical pore-pressure gradient as a simple linear interpolation between pressures directly above and below the salt (Zhang et al. 2008). As a result, boreholes in salt layers tend to be overbalanced, creating the risk of losing wellbore fluid in the salt section.

(3) Sedimentary stringers trapped inside salt bodies and at salt canopy sutures (Dooley et al. 2012) may contain either over- 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. Rock salt has negligible porosity and is impermeable, except under unusual conditions, such as very shallow burial or high fluid pressures (Urai & Spiers 2007). Therefore, sediments trapped in salt will not adjust to pore-fluid pressure if not connected to surrounding porous rocks. Stringers may trigger kicks (when overpressured) or lost circulation (when underpressured, creating so-called ‘thief zones’); both of these risks make fast drilling through salt hazardous.

(4) Drill holes having an open annulus between the casing and the wellbore or uncased wells in salt tend to close rapidly by ductile creep (Dusseault et al. 2004). If salt viscosity is lowered by moisture and heat conduction along the wellbore, salt creep accelerates and provides a dynamic pressure on the wellbore fluid. This pressure needs to be accounted for in wellbore-stability analysis.

(5) Additional forces on the wellbore arise from rapid horizontal flow inside mobile salt layers, an effect common in salt-sheet spreading at continental margins. Localized shear stresses in faster low-viscosity layers may cause shear deformation of wellbores (Weijermars & Jackson 2013).
When wells are cased, drag forces on the vertical wellbore casing will move the casing horizontally out of its original trajectory. The displacement, although insignificant for production wells with life cycles shorter than a decade, needs to be accounted for to ensure well integrity for longer production time (Weijermars et al. 2013).

Our study analyses the closure rates of open wellbores in moving salt sheets. Because drilling and completion costs account for nearly two-thirds of the costs of field development, routine geomechanical analyses before drilling should be cost effective. The importance of drilling optimization by continuous feedback has been highlighted in numerous studies (e.g. Hougaz et al. 2012; McManus et al. 2012). Sensitivity analysis is required over the full uncertainty range of critical variables that may affect wellbore stability and integrity.

2 VISCOELASTIC RELAXATION TIMES FOR SALT

Salt behaves as an elastoplastic solid on short timescales and responds elastically to a drill bit (10^6–10^9 hr). On tectonic timescales (10^8–10^9 yr), salt behaves viscoelastically and deforms by crystalline solid-state creep. The elastic stresses \( \tau_0 \) imposed on the rim of a wellbore in rock penetrated by a drill bit immediately begin to dissipate by viscous creep. The rate of elastic relaxation and the relative importance of elastic and viscous distortion can be evaluated by a linear Maxwell model. In viscoelastic salt, initial elastic stresses on the wellbore will decay at a rate approximated by the relaxation rate of elastic stresses, \( \sigma_0 \), given by

\[
\sigma(t)/\sigma_0 = \exp(-Et/\eta)
\]

with time \( t \), Young’s modulus \( E \) and effective viscosity \( \eta \).

Young’s modulus for common halite salt has been relatively well constrained in recent laboratory studies; we use a typical reference value of \( E \approx 3 \) GPa (Liang et al. 2007), which is within the range of 2.2–3.5 GPa for relatively pure Mogilno salt (Poland; Gryzybowski et al. 2008). Young’s modulus of rock salt reaches peak values of \( \approx 11 \) GPa at confining pressure of 40 MPa and elevated temperature of 85 °C (Du et al. 2012). We also note two review summaries on physical properties of salt quote rock salt Young moduli in the range 28–35 GPa (Roberton et al. 1958) and 31 GPa (Fossum & Fredrich 2002). These values we cannot verify as the primary data sources are not accessible.

The effective viscosity of halite salt is dependent on temperature, moisture content, grain size and strain rate (Urai & Spiers 2007). The effective viscosity of rock salt ranges between 10^{16} and 10^{19} Pa s (Van Keken et al. 1993) for tectonic strain rates reviewed in Weijermars & Jackson (2013). The relatively fast closure rate of 10^{-8} s^{-1} of low viscosity salt (10^{15} Pa s) outlined in Section 4.3 (this study) is within the range of effective viscosities for our ‘high’ strain rate (Van Keken et al. 1993). Using a conservative range of effective viscosities (10^{16},10^{18} Pa s) and a fixed Young’s modulus for halite of 3 GPa the normalized elastic wellbore stress dissipates to just 7 per cent of its initial value after 100 days for salt of effective viscosity 10^{16} Pa s and 1000 days for viscosity of 10^{17} Pa s (Fig. 1). For salts of 10^{18} Pa s and higher, elastic stress relaxation requires at least 10 000 days (∼27 yr). For 10^{19} Pa s it would take centuries for elastic wellbore stresses to dissipate by crystalline creep. Using a Young modulus of a factor 10 higher than our reference value of 3 GPa would shorten the above relaxation times by a factor 10.

The important conclusion is that before elastic stresses relax by viscous creep of salt into the borehole, salt wellbores are subjected to both elastic stresses (e.g. Kirsch 1898; Zoback 2008; Weijermars 2013) and viscous creep stresses imposed by surrounding salt.

![Figure 1](http://gji.oxfordjournals.org/)

**Figure 1.** (a) Sensitivity plot of elastic-stress relaxation time versus viscosity. (b) Elastic stress relaxation time for wellbore stresses using three different salt viscosities. (b1) 10^{16} Pa s; (b2) 10^{17} Pa s; (b3) 10^{18} Pa s. The cut-off (dots) is taken at 7 per cent of residual elastic stress \([\sigma(t)/\sigma_0 = 0.07]\).
3 WELBORE STABILITY IN SALT FORMATIONS

The geomechanical behaviour of salt and adjacent layers is complex: the closure rate of wellbores in salt is affected by the depth and ambient temperature of the salt, tectonic flow rates and by fluid-pressure gradients in the well. This section summarizes current knowledge of wellbore creep and ways of retarding wellbore closure. Closure of caverns and uncased wellbores by viscous creep in salt bodies on timescales of weeks to months is a well-known problem (Fig. 2a). Wellbore closure rates have been calculated using a standard wellbore stress expression and a range of rheological parameters for salt creep (Leyendecker & Murray 1975; Infante & Chenevert 1989; Bogobowicz et al. 1991; Barker et al. 1994; Fossum & Fredrich 2002; Willson et al. 2003; Carcione et al. 2006; Zhang et al. 2008). These rates range from days and weeks to months and years, depending on the wellbore fluid net pressure, ambient temperature, and creep law adopted. The full range of creep rates may affect any single wellbore because salt viscosity varies with its grain size, mineralogy, water content, temperature, depth and strain rate.

Even cased wells are vulnerable to salt creep. Production-induced heating of salt may accelerate inward creep of salt and enhance both the radial and tangential (hoop) stresses on the casing string. The annulus between the steel casing and the salt may remain difficult to cement effectively in deep-set casings near the base of salt, where rubble zones form superpermeable thief zones that do not support heavy loads of cement. Salt can directly impinge on the steel casing by creep (Fig. 2b). Because of the unusually high thermal conductivity of salt, salt creep may accelerate if conductive heat is absorbed along the wellbore steel casing from deeper production zones (Durham et al. 1980). But even under geothermal conditions typical of drilling depths, salt can creep inward and make ready contact with a steel casing string within a few days after drilling.

One strategy to mitigate premature wellbore closure is to drill rapidly through the salt. This strategy can be assisted by cooling the wellbore fluid to retard creep, which is highly temperature dependent (Dusseauet al. 2004). Alternatively, reaming, washing and jarring may be needed to keep the wellbore open (Chatar et al. 2010). The drilling-fluid density chosen to counter wellbore closure is critically dependent on anticipated conditions in the salt body. Oil-based mud (OBM) suppresses wellbore dissolution, and this retards wellbore washout but is ineffective for slowing wellbore closure. Additional cooling of the OBM should slow wellbore closure (Dusseau et al. 2004). Drilling with saturated brine in water-based mud (WBM) is cheaper than with OBM, and prevents washout by dissolution. Preheating of the WBM can supersaturate the brine so that it will still effectively retard salt dissolution when injected into deeper, hotter wellbore sections (Dusseau et al. 2004). Adding bentonite flocculate to the brine can further slow any wellbore dissolution. The flocculate can be engineered to seal salt wellbores with a mud cake; bentonite does not swell in saturated brine.

In thinner salt intervals, the rate of salt dissolution with undersaturated WBM can enlarge the wellbore fast enough to counter creep closure. For thicker salt intervals, the rate of creep increases with depth, so precisely balancing closure with dissolution is impractical. Drilling with more costly OBM may be more practical where seams of highly soluble potash and magnesian salts (sylvite, bischofite and carnallite) are intercalated in predominantly halite bodies. Because each evaporite mineral has different solubilities, it cannot be simultaneously saturated using NaCl-saturated WBM fluid.

Alternatively overbalanced drilling using mud loads higher than the pressure imposed by creeping salt can slow wellbore closure. However, the window for overbalanced drilling is narrow. A rule of thumb in the Gulf of Mexico assumes that critical fracture pressure is reached at 1.05 times the minimum horizontal stress (Willson & Fredrich 2005). Stress effects on wellbores near salt bodies have been highlighted recently (Sanz & Dasari 2010; Nikolinakou et al. 2011, 2012; Luo et al. 2012a,b; Schutjens et al. 2012). Salt causes significant perturbations of stress magnitude and may rotate the direction of principal stresses within the wallrock sediment, which complicates well stability in near salt drilling. Rheological anisotropy in the mylonitized boundary layers of salt bodies (Weijermars & Jackson 2013) and brecciation and tarry bitumen at the salt-sediment boundary (Marinez et al. 2008) may contribute to enhance stress and pressure anomalies that increase the risk of near and in-salt drilling operations. To reduce the risk of well failure, wellbore stresses must be continually assessed during drilling in salt bodies. Calliper measurements in conjunction with incremental

Figure 2. (a) Perspective view of open wellbore encased by salt creeping inward. (b) Depth-section normal to a cased wellbore having eccentric annulus between steel casing and salt. Wellbore closes by inward creep of salt and displacement of wellbore fluids.
adaptation in boremud density may help to prevent borehole closure (Kim 1988).

4 ANALYSIS OF WELLBORE CLOSURE

4.1 Rationale for model

Our study analyses wellbore closure patterns caused by superposed effects of gravity-driven flow in spreading salt sheets and of drilling-induced sink flow of salt into the wellbore. We use sink flow as the fluid mechanical term commonly used to describe the radial flow of fluid into a sink (negative source) which may be presented by a point source or hole with a finite radius (Krause 2005). Previous studies have elucidated wellbore closure rates in salt sections (Leyendecker & Murray 1975; Infante & Chenevert 1989; Bogobowicz et al. 1991; Barker et al. 1994; Fossum & Fredrich 2002; Willson et al. 2003; Carcione et al. 2006; Zhang et al. 2008). However, these studies do not take into account the effect of far-field salt creep on wellbore closure. Horizontal creep of salt may be neglected for wellbore closures in salt bodies under isotropic stress; these are stable before drilling. However, few salt bodies cease moving internally, especially on continental margins, where salt is destabilized by seaward flow and differential sedimentary loading (Hudec et al. 2009; Ings & Beaumont 2010; Brun & Fort 2011; Van Gent et al. 2011; Wagner & Jackson 2011; Albertz & Ings 2012; Burchardt et al. 2012; Dooley et al. 2012; Fiduk & Rowan 2012; Gradmann & Beaumont 2012; Gradmann et al. 2012; Rowan et al. 2012; Strozyk et al. 2012). For example, in the northern Gulf of Mexico, the leading edge of the thinly covered Sigsbee salt canopy is overriding Holocene sediments and forming the kilometre-high Sigsbee Escarpment (Hudec & Jackson 2009).

4.2 Rankine flow analysis

Closure of a wellbore in the absence of a far-field flow in the salt sheet is a pure sink flow. Its strength \( m \) (Fig. 3b) can be represented by the following stream function \( \psi \) in polar coordinates \((r, \theta)\):

\[
\psi(r, \theta) = m \theta.\tag{2}
\]

A far-field uniform flow \( U_{\infty} \) (Fig. 3a) superposed on the sink flow (Fig. 3b) can be accounted for in the expanded stream function:

\[
\psi(r, \theta) = U_{\infty} r \sin \theta + m \theta.\tag{3}
\]

Eq. (3) describes a Rankine flow pattern (Fig. 3c). The specific streamline \( \Psi = \pi m \) delineating the Rankine surface through the stagnation point \((x, y) = (b, 0)\) follows from \( b = m/U_{\infty} \) and is described by (e.g. White 2011):

\[
\psi_{\text{Rankine}} = \frac{[m(\pi - \theta)]}{(U_{\infty} \sin \theta)}.	ag{4}
\]

The Cartesian velocity components for the Rankine flow described are given by

\[
v_r = \frac{\partial \psi}{\partial y!} = U_{\infty} + (m/r) \cos \theta \tag{5a}
\]

\[
v_\theta = -\frac{\partial \psi}{\partial x!} = (m/r) \sin \theta. \tag{5b}
\]

We can now evaluate wellbore closure patterns and rates caused by a combination of (1) sink flow having strength \( m \), driven by the effective overburden load and (2) tectonic far-field salt creep rate \( U_{\infty} \). When \( |m/U_{\infty}| \rightarrow 0 \), the strength of the sink flow is much less than the tectonic salt flow rate; when \( |m/U_{\infty}| \sim 1 \), the Rankine flow pattern will affect wellbore closure; when \( |m/U_{\infty}| \gg 1 \), sink flow dominates, and the stagnation point of the Rankine flow field is too far away to affect wellbore closure.

4.3 Particle paths near open wellbores in salt

A vertical, open wellbore drilled into a salt layer sets up a Rankine flow pattern in horizontal flow planes (Figs 4a and b). The streamlines in the flow plane are uniquely defined by just one parameter, \( b \), determined by the far-field flow rate and the strength of the sink flow into the wellbore. Physically length \( b \) is equal to the (non-dimensional) distance between the sink point in the centre of the wellbore and the stagnation point of the Rankine flow pattern. The stagnation point will be located at \((-b, 0)\), provided the coordinate axes are centred on the sink point. Any tectonic flow in a salt sheet prior to drilling will affect the Rankine flow pattern of a closing wellbore.

The specific Rankine flow pattern varies at each depth in the salt layer because \( U_{\infty} \) varies highly with depth (Fig. 4b) and \( m \) generally increases in deeper boreholes as the overburden load increases. The theoretical range of flow patterns around a wellbore for progressively larger \( b \) values are mapped in Figs 5(a)–(f). Next we demonstrate how these salt particle paths control how drillholes will close. Note that particle paths for constant \( |b| \) values are steady and not transient or time dependent. However, uncased wellbores will close according to time-dependent particle paths. This is because the \( |b| \) values for any particular wellbore generally diminish over time as the strength \( m \) of the sink flow in the wellbore slows with wellbore radius \( a \) according to:

\[
a(t)/a_0 = (1 - t \dot{a}_z). \tag{6}
\]
Figure 4. (a) Superposition of far-field flow and sink flow results in Rankine half-body separating (1) zone where particle paths all move toward sink (brown region) from (2) far-field flow lines that move past sink (pink region). (b) Perspective view of salt layer creeping by Poiseuille flow between upper and lower no-slip boundaries. In the well, far-field flow rates vary with depth. Right-hand part of view shows mid-depth flow plane for uncased wellbore closing by Rankine flow.

Figure 5. (a–f) Visualizations of flow lines of uniform far-field flow to the right superposed on sink flow. (a) \( b = 0 \), (b) \( b = -0.5 \), (c) \( b = -1 \), (d) \( b = -5 \), (e) \( b = -10 \) and (f) \( b = -20 \) (with \( b \) divided by dimensional unit [m]). Fluid particle paths from far-field flow and sink flow do not cross and are separated by Rankine curve (thick line) through stagnation point. Non-dimensional field of view (40 × 40) is scaled relative to wellbore radius of unit length. Matlab models generated from our analytical flow equations.
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Figure 6. (a–f) Progressive closure of uncased wellbore in salt for non-dimensional time steps. (a) 0.1, (b) 0.3, (c) 0.5, (d) 0.7, (e) 0.9, and (f) 1. Particle paths of wellbore margin are outlined by yellow curves. Closed part of wellbore (filled by creeping salt) is pale blue, and remaining hole is dark blue. Far-field salt is pink, and flow lines within it start at \( y = -2.5 \) at time 0. Original hole radius provides unit-length scale and units along the margins of the salt box are scaled relative to the normalized initial wellbore radius. Speed of closure is controlled by initial \( b \) value of \(-2.25\), which diminishes at rate of \(-0.99\) each time step. Matlab models generated from our analytical flow equations.

with \( a_0 \) being the initial wellbore radius at \( t = 0 \) and \( a(t) \) the changing radius at subsequent times. Contraction rate \( \dot{e}_{xx} \) can be approximated by (Nye 1953):

\[
\dot{e}_{xx} = -(U_\infty)d/a_0 = \left[ (\rho_{\text{MEAN}} \times g \times d) - P_{\text{NET}} \right]/2\eta. \tag{7}
\]

It follows from eqs (6) and (7) that the wellbore closure at depth \( d \) is driven entirely by the overburden load \( \rho_{\text{MEAN}} \times g \times d \), with \( \rho_{\text{MEAN}} \) a representative density for the entire overburden complex; for an empty wellbore the net pressure \( P_{\text{NET}} = 0 \). Adopting a wellbore section in a salt sheet at \( d = 4 \) km, \( \rho_{\text{MEAN}} = 2500 \) kg m\(^{-3}\) and dynamic salt viscosity \( \eta = 10^{15} \) Pa s, yields a contraction rate of \( \dot{e}_{xx} = 5 \times 10^{-8} \) s\(^{-1}\) (eq. 7), which closes the wellbore in about 7 months (eq. 6). For a higher effective viscosity of \( \eta = 10^{19} \) Pa s, the wellbore is stable longer and would take over 600 yr to close by salt creep. The time-dependent strength \( m(t) \) of a salt sink flow is given by

\[
m(t) = -(2\pi a(t)^2)[(\rho_{\text{MEAN}} \times g \times d) - P_{\text{NET}}]/2\eta. \tag{8}
\]

The dimension of eq. (8) is m\(^2\) s\(^{-1}\). For an empty hole, \( P_{\text{NET}} = 0 \), arbitrary depth of \( d = 4 \) km, \( \rho_{\text{MEAN}} = 2500 \) kg m\(^{-3}\), viscosity \( \eta = 10^{16} \) Pa s and wellbore radius of 0.2 m (a 16-inch drill bit) yields an initial sink-flow strength \( m_0 = -2.5 \times 10^{-9} \) m\(^2\) s\(^{-1}\); a higher effective viscosity for salt (\( \eta = 10^{19} \) Pa s) implies a sink-flow strength of \( m_0 = -2.5 \times 10^{-11} \) m\(^2\) s\(^{-1}\). For low-viscosity salt, \( b \) will generally be higher than for high-viscosity salt. Assuming a typical \( U_\infty \) of 1 km Myr\(^{-1}\) (3.17 \( \times \) \( 10^{-11} \) m s\(^{-1}\)) and taking
Figure 7. (a–g) Wellbore closure paths for six types of time-dependent flow into open wellbore. Case (a) is our time-independent reference model for a cased wellbore, which is displaced but does not close ($b = 0$). Cases (b)–(g) are for uncased wellbores closing by successively faster initial sink strengths (deeper salt sections), as shown by the time-dependent $b$-values plotted in the lower-right graph. Model (b) is for shallow salt layers having weak sink flow rates ($m_0 = -U_\infty$). Model (g) is for deeper wellbore sections having larger $b$ values and stronger weak sink flow rate ($m_0 = -5U_\infty$). Progressive closure of wellbore for model (e) is shown for intermediate time steps in Figs 6(a)–(f). Matlab models generated from our analytical flow equations.
\(m_0 = -2.5 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}\) yields \(b_0 = -130 \text{ m}\). Thus in low-viscosity salt (faster wellbore closure), Rankine flow dominates. For high-viscosity salt, the value of \(b\) becomes less significant: \(b_0 = m_0/U_\infty = -2.5 \times 10^{-11}/3.17 \times 10^{-11} [\text{m}] = -78 \text{ cm}\), and the Rankine displacement effect is negligible. For each specific case of salt penetration, wellbores will close according to the principles outlined next.

5 SIMULATION OF WELLBORE CLOSURE

Closure and distortion of open-hole wellbores by Rankine creep in salt bodies were modelled using a simple Matlab code that was based on our equations in Section 4. The streamlines from the wellbore rim are traced as discrete particle paths. The \(b\) values are time dependent, so streamlines are transient. For each point on the initial wellbore margin, we specify in matrices the \(x\)- and \(y\)-velocity components of the particle paths. We calculate for each subsequent time step the position, speed, angle, and radius of the wellbore particles. Non-dimensional time \(t^*\) is defined by

\[t^* = (t U_\infty)/b_0, \quad (9)\]

with dimensional time \(t\) and initial \(b\)-value \(b_0 = m(t)/U_\infty\) for \(t = 0\).

The progressive closure of a wellbore with time-dependent particle paths has been modelled and contours for the shrinking wellbore are tracked as equally spaced non-dimensional time steps (red curves in Figs 6a–f). Far-field particle paths are also tracked (black lines) using a separate plotting routine for each particle starting at some distance from the wellbore as it begins to close. These particle paths are time dependent and converge because \(b\) diminishes as the sink flow weakens, thus reducing the width of the Rankine flow body. Comparison of six distinct cases of wellbore-closure profiles for time-dependent particle paths (Figs 7b–g) and a time-independent reference case (Fig. 7a) show that for higher initial \(|b|\) values, the funnel shape of the particle paths is more pronounced. For example, for \(b_0 = -5\) (Fig. 7g), the wellbore closes almost as a pure radial sink flow, and the effect of the far-field flow becomes negligible as the wellbore closes. Over a similar duration, the wellbore is displaced passively for \(b = 0\) (Fig. 7a) and closes little.

6 PRACTICAL APPLICATION

Our results allow visualization of the range of closure patterns that could arise at various depths within a single wellbore. Wellbore closure patterns may change downward along the drillhole (Fig. 8d), because \(b\) values will vary with depth within the same salt body as \(U_\infty\) and \(m\) vary (Figs 8a–c). The wellbore at level 4 remains open longer and shifts farther from the wellbore trajectory than at level 1.

A more complex set of wellbore closure profiles (Figs 9 and 10) arises near a drill hole firmly anchored in underlying sediments (location 5 in Fig. 8a). This situation may occur near the base of a salt layer, where salt disappears out of the flow plane into the drill hole below as the closing wellbore moves over the principal sink point. The progressive closure of the wellbore near such ‘anchored’ sink points is characterized by the development of deformed outlines for the shrinking wellbore (Fig. 9). The shrinking wellbore continues to move to the right with the far-field salt flow while salt also sinks into the underlying drill hole until it is completely filled. The remaining wellbore void in the salt section above may be kept open by wellbore fluid but will continue to deform. Comparison of six cases with different initial sink strengths (Figs 10a–g) show that wellbore deformation is negligible when the translation rate is fast relative to the flux of salt into the wellbore sink.

Figure 8. Explanatory diagram showing how (a) tectonic flow rate and (b) sink-flow strength both vary with depth and result in (c) different initial \(b\) values at each depth. (d) Closure profiles in a single wellbore may vary according to depths labelled 1–4. Higher \(|b|\)-values mean that the wellbore closes faster. A special situation may arise at depth level 5; see Figs 9 and 10.
Our results also show that all cases where wellbore closure occurs, closure rates decelerate as the wellbore shrinks. Radial closure velocities follow from our Rankine flow analysis (Section 4.2), which is arguably more accurate than approximations by Barker’s solution (Barker et al. 1994) and several proposed revisions (see Liu et al. 2011).

7 CONCLUSIONS

Wellbores in salt are subjected to both elastic stresses and superposed creep stresses until elastic stresses relax. Time-dependent closure of uncased wellbores by laterally creeping salt can be effectively modelled by Rankine flow equations. The wellbore section in the overlying and underlying sediments is stable (if properly pressure balanced) and remains anchored in space. However, inside creeping salt sheets, wellbores may be shifted from their initial vertical trajectory by horizontal far-field creep as they close. As the wellbore shrinks, the risk of stuck pipes increases. Our models may help to establish the application rate of wellbore widening measures. For example, chemical dissolution, thermal cooling, and reaming or jarring all need to be applied at rates commensurate with actual wellbore closure rates at each depth.

Our non-dimensional results map the full range of geometrical wellbore outlines that evolve during closure. The dimensional closure rates are controlled by the pressure differential between the
Figure 10. (a–g) Wellbore closure above fixed sinkhole for range of sink strengths, as shown by time-dependent $b$ values plotted in lower-right graph. Model (a) is for cased wellbore ($b = 0$). Models (b)–(g) are for successively faster initial sinking (progressively deeper salt sections) in uncased wellbores. Model (b) is for shallow salt layers having slow sink flow ($m_0 = -U_\infty$). Model (g) is for deeper wellbore sections having larger initial $b$ values and faster sink flow ($m_0 = -5U_\infty$). Matlab models generated from our analytical flow equations.
wellbore fluid and the confining salt pressure owing to its overburden load. Dimensional analysis could help predict stability before drilling and help choose the best ways of mitigating closure of any particular wellbore. This analysis could follow the principles outlined in our study (Section 4) using estimates for the physical parameters (far-field flow rate and effective viscosity) controlling the flow for a specific wellbore depth. Our closure-rate analysis for wellbores is equally valid for cylindrical salt caverns used for gas storage, although a moving salt sheet would be a hazardous setting for a large cavern.

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**SUPPORTING INFORMATION**

Additional Supporting Information may be found in the online version of this article:

**Movie W1.** Animation of in-salt wellbore closure under conditions specified in Fig. 6 of this article.

**Movie W2.** Animation of in-salt wellbore closure under conditions specified in Fig. 9 of this article (http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggt346/-/DC1).

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