RC23065 (W0401-083) January 16, 2004
Mathematics

IBM Research Report

On Integrating Salt Motion in Basin Modeling: An Hybrid Approach for Goal-Oriented Salt Flow

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Abstract

In this paper, we describe techniques to calculate the internal flow from kinematic salt motions derived from palinspatic reconstructions. The calculated internal salt flow is integrated into the dynamic basin models. The internal salt flow is constrained by the imposed velocity field on the deforming boundaries, mass conservation and the incompressibility condition during the salt deformation, yielding an optimal, physically valid, kinematic motion that achieves the goals specified by the geologist. Stokes flow physics is used to calculate the internal flow of a salt body induced by the deformation of its surface. In the numerical solution of basin models, an Arbitrarian Lagrangian-Eulerian (ALE) numerical scheme is used to couple the motion field and compaction. This approach has the advantage of reproducing exactly the geologist's reconstruction of the salt evolution and the very complex salt shapes observed in the field can be simulated without the difficulties normally associated with the solution of dynamic viscous flow formulations. Therefore, this approach is an alternative to both the pure kinematic geometric reconstruction and the traditional dynamic approach.

Introduction

The presence and motion of salt may affect significantly the temperature and fluid flow history of sedimentary basins (e.g., O'Brien and Lerche, 1984; Mello et al., 1994, Mello et al., 1995) due to the fact that salt rock has very low permeability and very high thermal conductivity relative to other sediments. Consequently, the incorporation of salt into the thermal and fluid flow modeling of a basin evolution is fundamental for the assessment of any geological process operative in sedimentary basins that is temperature- or pressure-dependent (e.g., rock deformation, organic matter maturation, fluid migration, diagenesis, etc.). The majority of studies published in the literature that investigate the effect of salt on the sediments thermal regime assume that the salt is motionless and that the heat flow is in steady state (e.g., Jensen, 1990). Because steady-state models do not calculate the temperature through time, no maturation estimates can be done. On a geological time scale, the steady-state and motionless salt assumptions are unrealistic and a transient thermal analysis is the most appropriate to calculate the temperature in moving sediments (salt and the hydrocarbon source rocks). The inclusion of the salt movement into the numerical modeling of basin evolution is a very difficult undertaking. Despite the relative simple physics involved in salt motion (essentially buoyancy and creep motion), its numerical modeling in the context of evolving sedimentary basins is still a numerical challenge (e.g., Poliakov and Podladchikov, 1992; Zaleski and Julien, 1992; Schult-Ela et al., 1993). At the present time, salt motion can be described either kinematically or dynamically for basin modeling purposes, and both descriptions present computational problems. The kinematic description is purely geometric, and thus, there is no physics to support the interpreted salt motion. Consequently, kinematic reconstructions can be physically unrealistic. The major advantage of the kinematic description, however, is that it represents the geologist's view of the evolution of sediment deformation. Conversely, dynamic simulations of salt motion are completely determined by a set of differential equations and their initial conditions. Without a full inversion, it is practically impossible for the geologist to perform a dynamic simulation of the salt motion that matches the geological interpretation. In this case, the salt motion is obtained through time by solving some variation of the Navier-Stokes equation with a given set of initial conditions. The major drawback of the dynamic approach is that the evolving shapes of salt structures never coincide precisely with observations, although they may be similar in shape. This similarity shows that the dynamic models do capture the physics of the moving salt, but important details related to the strength of surrounding sediments and to the uncounted forces acting on the salt have to be determined ad hoc. Consequently, geologists are faced with the dilemma that, while they wish to tailor motion to portray geological reconstructions at specific times, they wish to have their models be constrained by the laws governing the flow of viscous fluids (e.g., local mass conservation, incompressibility, etc). A practical solution is to specify only some snapshots of the geological sections in time, based on reconstructions, and then incorporate the physics into the time-lapses between these snapshots. Here, we propose a goal-oriented technique that in our opinion retains the best of both kinematic and dynamic descriptions of salt motion. This approach also allows the validation of kinematic geological restorations by constrained dynamic models. In our approach, a reconstruction is used for specifying constraints and objectives for the salt motion, and for "guiding" the numerical solution.

Kinematic Modeling of the Salt Motion

In practice, the reconstruction of the geological evolution of a given basin is estimated by palinspatic reconstruction techniques that attempt to restore the sediment paleothicknesses by both balancing and applying corrections to sediment deformation through time (e.g., Moretti et al., 1990). The common procedure in reconstruction in time is stripping the youngest sediment layer out of the section and calculating a new position of the underlying sediment layers. This is done by decompacting the sediments kinematically and restoring the deformations associated with fault motions whilst conserving the sediment mass. When salt is present, it is normally considered as a wild card that fills the empty spaces generated during the restoration. In general, the geometrical history of salt masses can be obtained with variable degree of accuracy when balanced restoration techniques and sequence stratigraphy principles are applied.

Although the definition of the history of the salt external shape is sufficient for many purposes in basin analysis, it is inadequate for the evaluation of the thermal and fluid history of sediments. The definition of the salt internal flow is also necessary to calculate both the heat and fluid advected with the motion associated with salt. This salt advection can be very important if the salt is also a potential hydrocarbon source rock as suggest by some authors (e.g., Evans and Kirkland, 1988).

Assuming that a salt evolution was obtained by reconstruction techniques based on mass conservation (at least for the salt bodies), it is possible to estimate the internal salt flow using its well know mechanical behavior. The physics involved in the salt flow during formation of diapirs has been extensively discussed in the literature. Salt is normally treated as a viscous incompressible fluid with constant density that becomes buoyant as the surrounding sediments compact and become denser. The salt upwelling as caused by this gravitational effect is known as the Rayleigh-Taylor instability. The dynamic salt motion under these circumstances is described by the Navier-Stokes equation. In this work, we are interested in calculating the salt motion only in terms of velocities, without considering the stresses (kinematic approach). This can be achieved, for instance, by using a geological reconstruction, and its sequence of salt external shapes. This sequence is used to estimate the deformation and velocity boundary conditions between time intervals. Thus, we can calculate a physically constrained internal salt flow for an imposed velocity field on the salt body boundary by assuming that the salt undergoes an incompressible, slow (creeping), viscous, steady-state fluid flow between two time steps. Under these conditions, the salt motion can be described by the Stokes flow. In the following section, we demonstrate this concept for a very simple model in which a salt layer is bounded by two sediment layers.

Stokes Pipe Salt Flow

When a salt layer is bounded by two sediment layers (Figure 1), assuming that its flow is a 2D incompressible, creeping, steady viscous flow, its flow can be described as a Stokes pipe salt-flow. This is probably a very good approximation for the salt flow during its early stages of diapirism. The pipe flow is simple enough that its solution can be calculated analytically because of its restrictive boundary conditions (no overhangs). Despite its simplicity, this method is very effective for calculating the flow lines associated with the formation of pillows and diapiric structures without overhangs.

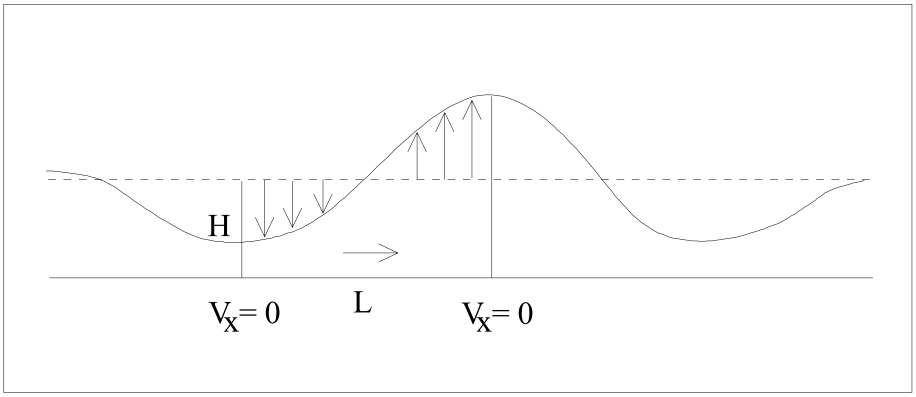


Figure 1 - Velocity field boundary conditions to the pipe flow model for the salt motion. Note that there is no horizontal motion on both the vertical and horizontal boundaries.

In Figure 1 the general characteristics and boundary condition used in this model are shown. Note that this figure is a cartoon without scale. In this figure the dashed line represents the initial upper boundary of a salt layer, whereas the solid line represents the position of this upper boundary after the deformation. Geometrically, there is no unique path between the undeformed salt body and its deformed configuration. However, using the pipe flow assumption, the solution is unique because of the mechanical behavior assumed, implying that the salt undergoes a two-dimensional channel flow, in which the salt motion has a parabolic distribution of the horizontal velocity. It is noteworthy that that the salt upper boundary can only move vertically whereas the lower boundary is stationary. Therefore, the horizontal upper and lower boundaries have non-slip horizontal boundary conditions. This is an extremely important condition, since it imposes no discontinuity between the salt and the overlying and underlying sediments during the salt motion. The horizontal velocity is zero on both the left and the right vertical boundaries. These boundaries are points of divergence and convergence of the salt flow, respectively. The solution of this problem can be calculated analytically using Fourier series to represent the upper boundary (Mello et al., in preparation).

For a special case in which the salt boundary deformation is linear (Figure 2), the solution is even simpler and does not require Fourier series, and the resulting velocity field for such a linear case is shown in Figure 3.

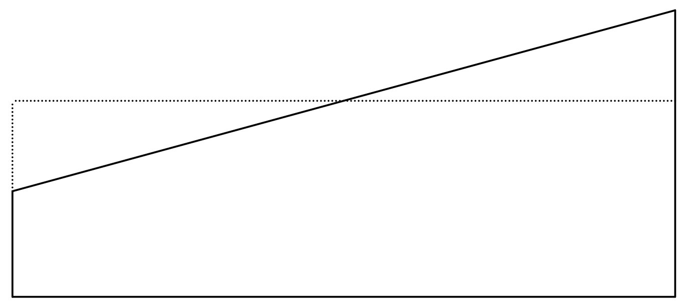


Figure 2 – Linear deformation. Salt body shape before (dashed line) and after deformation (solid line).

The internal salt flow solution is shown in It Figure 3. Note that the distribution of horizontal velocity is parabolic (Figure 3A). The total velocity field (Figure 3C) describes how the salt moves from the areas where the salt withdraws (left) to areas that it diapers up (right).

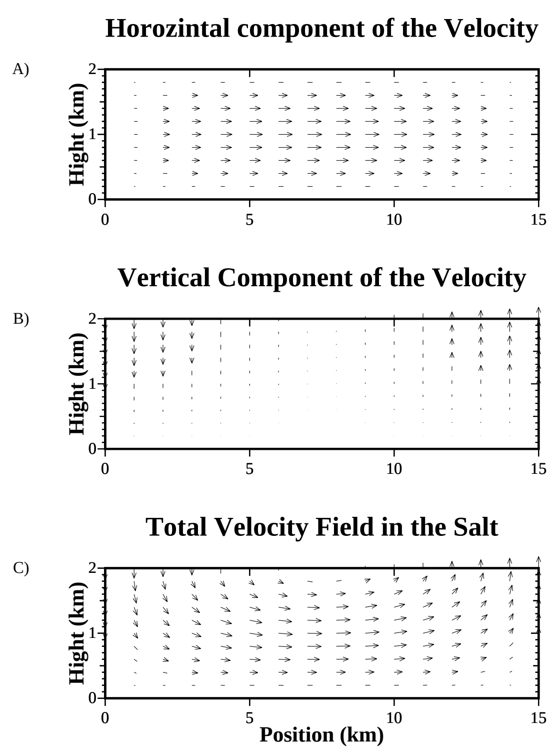


Figure 3 - Velocity field estimated using the pipe flow model for the salt motion assuming a linear velocity distribution on the upper horizontal boundary. A) Horizontal component of the velocity. B) Vertical component of the velocity. C) Total velocity field within the salt layer.

Stokes Salt Flow with Arbitrary Boundaries

In this section we discuss an approach that can be used to overcome the restrictive boundary conditions of Stokes Pipe flow discussed previously. In order to solve problems with arbitrary boundary conditions, the numerical solution of the Stokes flow equation is necessary (Mello et al., in preparation). Because of the incompressibility condition, the numerical solution of the Stoke flow equation is difficult, and there is extensive literature about possible discretizations using the finite element method. The most common techniques are the penalty methods with reduced integration (Malkus & Hughes, 1978) and mixed elements. Unfortunately, the mixed formulation allows only certain combinations of interpolation functions for pressure and velocity to be used without violating the celebrated Babuska-Brezzi condition (Hughes, 1987). The linear triangle, quadrilateral, tetrahedron and hexahedron do not conform to this condition. This is extremely restrictive because of the difficulty of generating numerical meshes for complex geological shapes without these elements. In order to circumvent this limitation, stabilized finite elements methods have been developed. The stabilized methods are generalized Galerkin methods where terms are added to the weighting function to enhance the stability. The well-known Streamline Upwind Petrov-Garlerkin (SUPG) approach is an example of these methods that stabilized convection-dominated problems. Hughes et al. (1986) developed a pressure stabilized Petrov-Garlerkin (PSPG) formulation that allows equal order interpolation of velocity and pressure and thus linear triangular and tetrahedral elements can be used. In this work we used the PSPG formulation. The general procedure to calculate the internal flow of salt body with arbitrary shape is discussed below.

General Procedure

For the sake of simplicity we use a 2D example for this discussion. The evolution of a given geological section is normally divided in various time intervals according to the stratigraphic data. For each time interval we follow the sequence: (1) define the external boundary; (2) define boundary control points; (3) estimate the velocity at the control points; (4) verify the correctness of the boundary conditions; (5) calculate the internal salt velocities; and (6) update the mesh. Each of these steps is discussed in more detail below.

1. Definition of the external boundaries. The initial "undeformed" salt shape and the "deformed salt shape at the end of the time interval is obtained by using palinspatic reconstruction techniques. The salt body must have the same volume (mass conservation) in the undeformed and deformed state. If the mass is not conserved during the restoration, one should use only the part of the salt body that is assumed to be conserved in the time interval. Alternatively, mass lost on the boundaries can be treated with flux boundary conditions. Figure 4 displays two possible shapes for a salt body. The dashed line represents the initial "undeformed" state and the solid line the state at the end of the time interval after the salt motion.

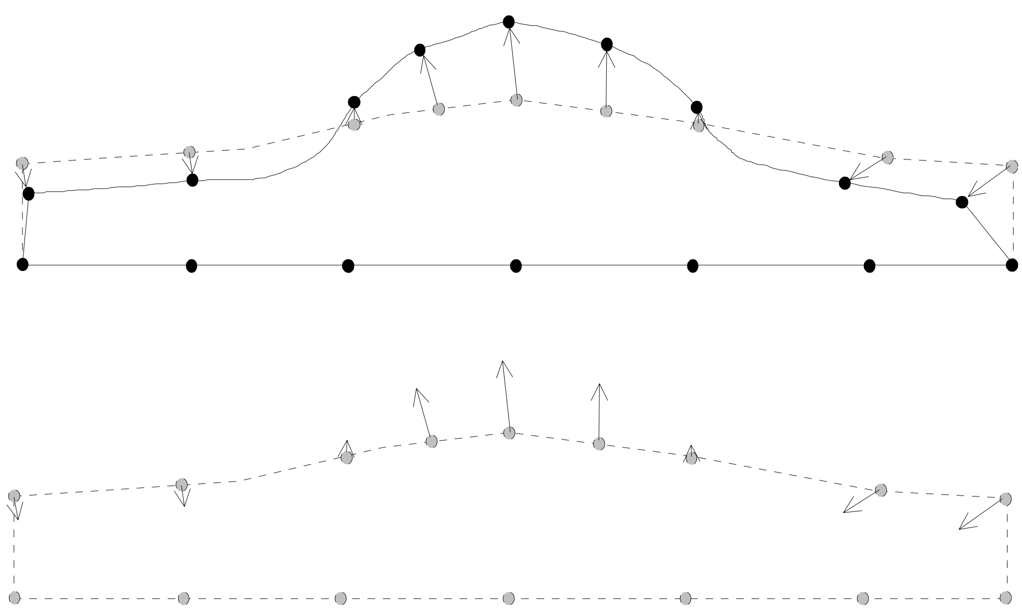


Figure 4 - Cartoon showing two configuration of a salt body. The dashed line represents the initial "undeformed" state and the solid line the state at the end of the time interval after the salt motion. The control points are represented by black and gray circles.

2. Definition of the control points on the boundaries. This is one of the most critical steps in the procedure because the distribution of the control points on the boundary controls the quality of the solution of the internal flow associated with the deformation. The control point definition is normally done as a part of the mesh generation process. The nodes belonging to the salt boundary become the control points. This step is similar to the one used in morphing techniques used in computer graphics. The control points are assumed to remain on the boundary during the deformation. In Figure 4, the control points are represented by black and gray circles. The black and gray circles represent the same point before and after the deformation. The mesh generation for the salt body in this step in normally executed using the operators described in Mello & Cavalcanti (2003).

3. Estimation of the velocity at control points. Using the initial and final position of the control points the average displacement vector is calculated. In Figure 4, the displacement vectors are shown. Note that this is the simplest approximation for the displacement since there are unlimited possibilities to define the deformation path of the boundaries. If the approximation is considered too coarse, the model can be refined by using a large number of time intervals. The average velocity vectors acting on the salt boundary is defined by the simple division of the displacement field by the time interval. This velocity field acting on the salt boundary is essentially the boundary conditions used to solve the Stokes flow equation.

4. Verification of the correctness of the boundary conditions. The velocity at the boundaries is interpolated using linear elements. Due to the linear discretization of the velocity on the boundary, the mass conservation can sometimes be slightly violated. The global volume has to be the same before and after the deformation; that is, no mass is entering or leaving the volume during the deformation. This condition is verified by integrating the velocity field along the salt body before and after the deformation. This assures the global mass conservation and the correctness of the solution of the incompressible viscous flow (Engelman et al., 1982). In case the volume the mass is not conserved, a better discretization or some correction on the velocities at the boundaries must be applied.

5. Calculation of the salt flow. In this step we solve the Stokes flow problem for the velocity and pressure using the stabilized finite element PSPG approach described by Hughes et al. (1986)

6. Update of the mesh. With the velocity field calculated for the internal salt flow, the position of the mesh nodes can be updated. The mesh update depends on the mesh type used in the simulation. In our modeling, we normally use Lagrangian meshes for the sediments and Arbitrary Lagrangian-Eulerian (ALE) meshes for the salt bodies (Figure 5).

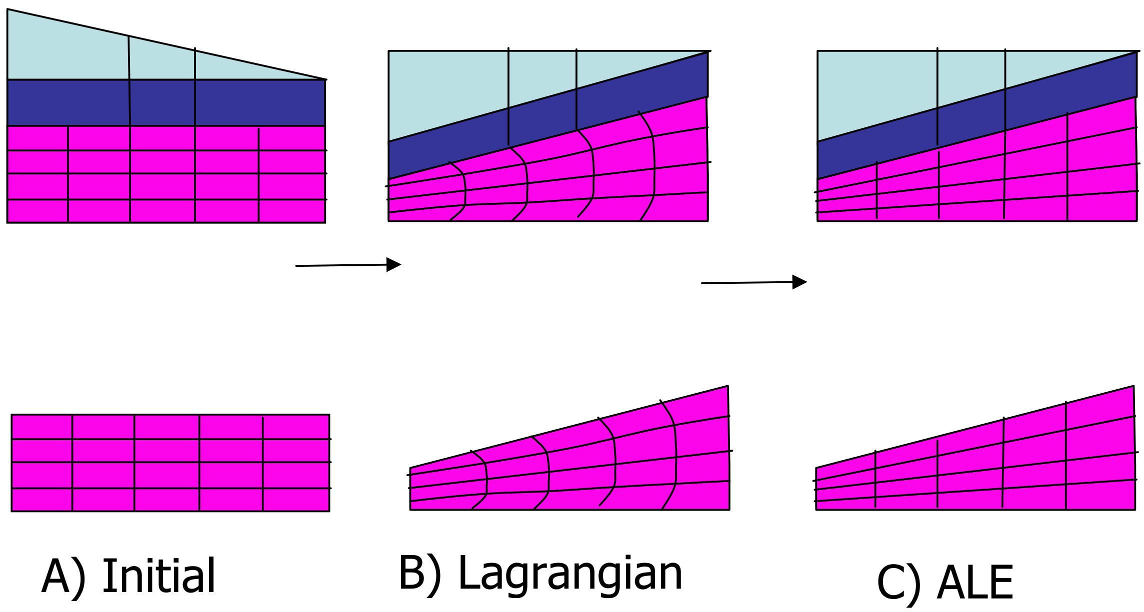


Figure 5. Cartoon demonstrating the mesh update process for a tabular salt body undergoing Stokes pipe flow. In A) a salt layer (magenta) is overlay by two sediment layers. The triangular layer on the top represents the sediment load deposit at the beginning of the time interval. After the salt flow is calculated the mesh for the salt body can be update using a full Lagrangian update (B) or and ALE update.

In Lagragian meshes, each mesh cell always contains the same sediment solid framework and, thus, the mesh moves with the velocity of the solid framework. Because the velocity of the mesh and the solid are the same in the Lagrangian meshes (Figure 5B), the solid advection terms are not required in the solution of heat or fluid transfer equations. On the other hand, Eulerian meshes, which are fixed in space, require advection terms because the solid moves through time and crosses cell boundaries carrying heat and fluid with them. In ALE meshes, the velocity of the mesh is arbitrarily set with values between zero (Eulerian) and the full motion (Lagrangian). Therefore, advection terms are required for the difference of the solid and mesh velocity. In Figure 5C, we show an ALE update, in which the mesh is updated with the full motion in the vertical direction but no update is done in the horizontal direction. This makes this update Lagrangian in the vertical direction and Eulerian in the horizontal direction. This procedure avoids excessive deformation of the elements within the salt layer.

Examples

We have applied the techniques discussed previously to two simple synthetic cases. The first case is a 3D tabular case, similar to the one shown in Figure 5 and the second case is a geological model with more complex diapiric salt geometry.

The geological model for the first case is shown in Figure 6 and this model is displayed in its final stage of deformation. The internal salt flow solution for the tabular body is shown in Figure 7. For this model, we used the ALE mesh update in the salt layer and Lagrangian mesh update in the other layers. The result for the temperature calculation is also shown in Figure 6. Although this is a simple model, it has been calculated without any artifact as lithology substitution. Futhermore, the transport of energy was calculated properly without neglecting the heat and mass conservation principles in the entire model including the salt model.

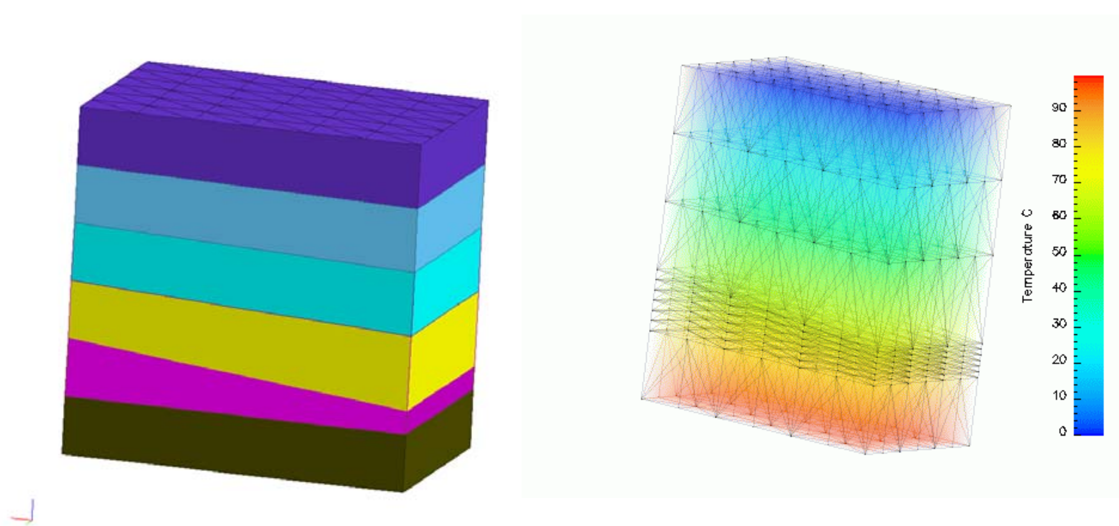


Figure 6. Geological model with a tabular 3D salt body (magenta) after deformation and its numerical mesh with the temperature solution on the right.

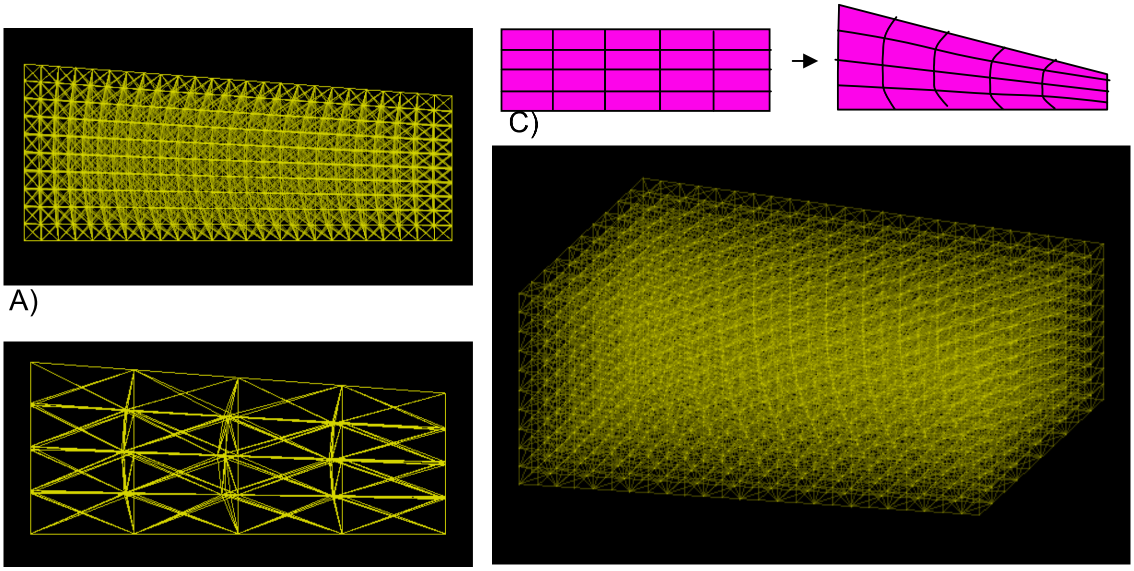
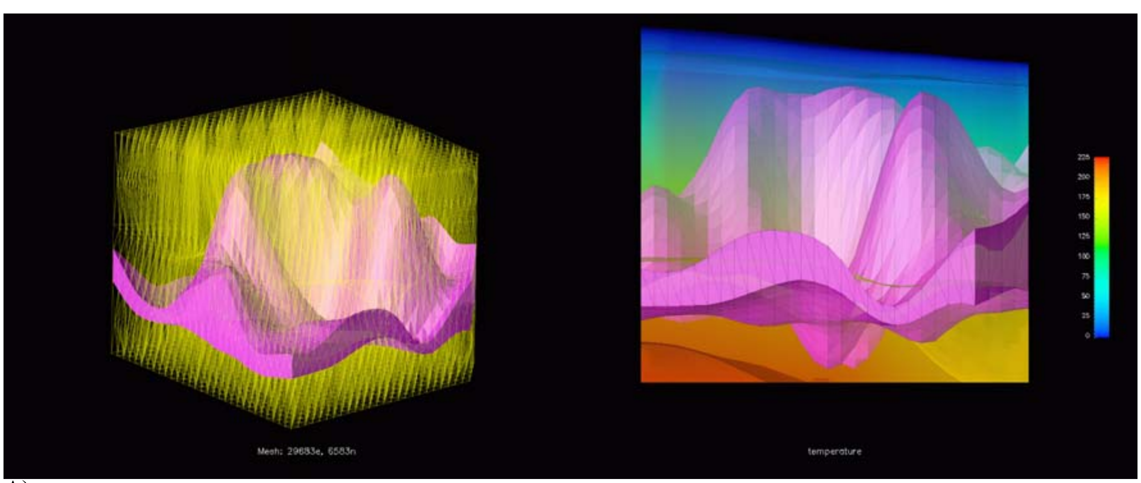
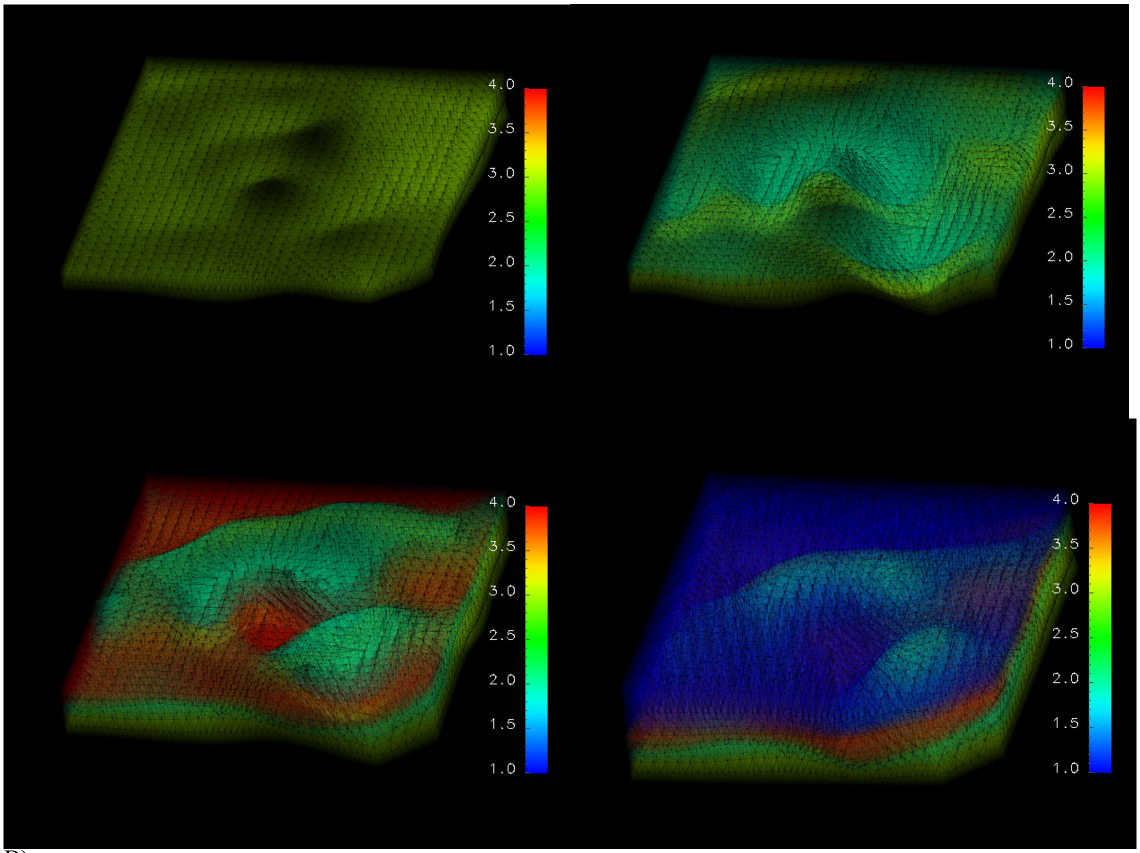


Figure 7. Stokes Flow solution applied to a tabular 3D salt body. A) and B) are solutions with different mesh resolution for a problem with characteristics displayed in C). The deformed mesh is shown in D with a view at angle.

We also applied these techniques to a more complex geological model (Figure 8A) with salt domes. The reconstruction of this model was done by changing the salt paleothickness through time. The change of salt thickness and the simulated evolution of this model are shown in Figure 8B. This application shows the power of this approach to estimate the salt evolution using this hybrid goal-oriented approach in basin modeling.



A)



B)

Figure 8. Stokes Flow solution applied to a salt dome (magenta). B) Evolution of the geological model through time.

Discussion and Conclusions

In this work we presented techniques that can be used to reconstruct the salt flow paths during salt motion using a physically-constrained kinematic approach. The internal salt flow is constrained by the imposed velocity field on the deforming boundaries, the mass conservation and the incompressibility condition during the deformation. This approach has the advantage of reproducing exactly the geologist's reconstruction of the salt evolution and the very complex salt shapes observed in the field can be simulated without the difficulties normally associated with the solution of dynamic viscous flow formulations. Therefore, this approach is an alternative to both the pure kinematic geometric reconstruction and the traditional dynamic approach. In our approach the salt is assumed to be an incompressible, slow (creeping), viscous fluid with constant viscosity that is in steady-state within a time interval. Under these conditions the internal salt flow is governed by the Stokes flow equation.

Currently there are still issues to be addressed to make this approach useable in a basin modeling production environment. The main challenge is how to integrate the reconstruction from commercial packages into the basin modeling workflows. In addition, 3D reconstruction packages are not mature enough to offer reconstructions based on models with 3D sealed regions. This makes it difficult to construct the mapping between the undeformed and deformed salt model since many times the mesh is not the same for those two stages. Other important issues are the strategies appropriate for models that change the topology significantly. This can happen for example when parts of the salt body become disconnected.

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