Modeling Sedimentation and Load Deformation in the Marine Environment
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Abstract

Sedimentary process models help determine the depositional history of a basin and the details of its stratigraphic configuration. Their output, consisting of the history of sedimentary accumulation as a function of space and time, provides the framework on which other subsequent processes such as diagenesis, structural deformation, heat flow, and hydrocarbon maturation and migration can be modeled. Of these subsequent processes, sedimentary deposit deformation due to loading (which includes compaction, salt flow, and growth faulting) has a significant feedback effect on sedimentation. Load deformation creates accommodation space and may modify the overlying topographic surface, which in turn affects the amount, type, and distribution of sediment that is deposited later. Therefore it is important to model sedimentation and load deformation as interdependent processes.

Model runs that incorporate this interdependency may show a completely different behavior than runs that ignore it. More importantly, the interdependent models better explain depositional patterns and structural deformation features in several examples.

In conclusion, sedimentary processes should not be treated as “a priori” knowledge for studying compaction and other load-deformation processes. A better understanding and predictive ability are achieved if sedimentation and load deformation are studied as interdependent processes.

Introduction

To the exploration and hydrocarbon-reservoir geologists, the past behavior of a sedimentary system is a fundamental key to predicting the present distribution of rock properties. After sediment deposition, however, many other processes occur that affect those properties. Therefore, a clear understanding postdepositional processes is fundamental for predicting present-day properties. In some instances, however, postdepositional processes have a feedback effect on concurrent depositional processes. In these cases, we cannot fully understand the depositional processes without understanding their interdependency with postdepositional processes.

In this paper, I have focused on the interaction between sediment deformation due to loading and sedimentation. It is clear that the distribution and properties of deposited sediment affect its future compaction history. Sediment compaction may in turn alter subsequent sedimentary events by altering the topography of the sediment surface and

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changing the accommodation space. This effect may not be as strong or obvious in the sedimentary record as the effect of sea-level change, climate variations and tectonics, but it acts together with these effects in determining future sedimentation events.

Sediment deformation may occur due to many different causes. Here we focus on deformation that is caused by loading, rather than by external tectonic forces. These deformation processes include compaction (in which sediment bulk volume is reduced with accompanying fluid expulsion), plastic deformation (in which sediment deforms without major change in volume), and growth faulting. Salt and shale flow and diapirism are particular cases of plastic deformation. Growth faulting is not treated in this paper due to the need for additional theoretical considerations and modeling requirements, that go beyond the scope of the model used here.

**Theoretical considerations**

The model used for this work is a new experimental computer model (called GPM, for Geologic Process Modeling). It combines the simulation of three geologic processes:

1. Clastic sedimentation, which includes free-surface flow, and erosion, transport, and deposition of sediment.
2. Single-phase fluid flow in porous media, (which is closely coupled with point 3, below)
3. Sediment compaction and plastic deformation, including diapirism.

Even when modeling only the compaction history of a sedimentary basin it is important to have detailed and plausible information on the type and amount of sediment that is being deposited at each step of simulated time. Many basin-analysis packages treat sedimentation as input: the user works out the sedimentation history from available data, and enters it into the program. In this work, we have attempted to understand and model the depositional processes and their interaction with sediment deformation. Therefore, we used a fairly elaborate sedimentation model rather than treating sedimentation as input.

Clastic sedimentation in this model is based on the same equations and principles as the SEDSIM model (Tetzlaff and Harbaugh, 1989). The principles are not repeated here in detail. In essence, the model simulates free-surface flow (such as river flow, turbidity currents, waves, and marine longshore currents) using a two-dimensional (in plan) approach but taking into account water depth. Erosion, transport, and deposition of clastic sediment is assumed to be governed by the shear stress at the bottom of the flow (which determines whether a certain type of sediment may be picked up from the bottom under given hydraulic conditions), and transport capacity (which determines how much sediment of each type can be carried as bed or suspended load). The governing equations are implemented by means of a particle-in-cell method. It is possible to add other sedimentary processes to this model (such as carbonate growth and evaporite deposition), but for the work described in this paper, only clastic sedimentation was used.
Flow in porous media is important in this work because it is tightly related to water expulsion and compaction. Single-phase fluid flow in porous media is a thoroughly understood phenomenon, and has been extensively modeled numerically. Generally, it is assumed to be governed by Darcy’s law, which states the following:

\[
v = \frac{F}{A} = -\frac{K}{\mu_w} \nabla (P - Z \rho_w g)
\]

where:
- \(v\) = flow velocity vector
- \(F\) = flow (volume per unit time)
- \(A\) = cross-sectional area
- \(K\) = permeability (assumed isotropic in this version of the equation)
- \(\mu_w\) = fluid viscosity
- \(\nabla\) = gradient operator
- \(P\) = pore pressure
- \(Z\) = depth underneath reference
- \(\rho_w\) = fluid density
- \(g\) = gravitational acceleration

The weight of the sediment and water column present above any point is supported by both the pressure of the fluid in the pores (pore pressure) as well as by the stress in the solid part or grains of the sediment. This is known as Terzaghi’s law, which states the following:

\[
S = \sigma + P
\]

where:
- \(S\) = lithostatic load or geostatic stress, which, in the absence of other external stresses, is equal to the load of sediment and fluid above the point being considered = \(\int_{\infty}^{Z} \rho_b(z)dz\)
  where:
  - \(\rho_b\) = local bulk density of sediment and fluid
  - \(z\) = depth from top of sediment column or water surface downward
  - \(Z\) = depth at which geostatic stress is calculated
- \(\sigma\) = effective stress (assumed isotropic in this version of the equation)
- \(P\) = pore pressure

Sediments compact due to the effective stress acting upon them. As a first approximation, it can be assumed that all this compaction occurs due to porosity reduction, and that the relative porosity reduction is proportional to the increase in effective stress, as follows:

\[
\frac{\partial \sigma}{\partial \phi / \phi} = -k
\]
where:
\[ \partial = \text{partial derivative} \]
\[ \phi = \text{porosity} \]
\[ k = \text{compaction coefficient} \]

Equations (2) and (3) show that if pore pressure is reduced (for example by allowing it to “drain” into an adjacent lower-pressured porous medium) then effective stress will increase, and therefore porosity will decrease.

Assuming that the initial porosity at deposition is \( \phi_0 \) and the effective stress \( \sigma_0 \) at that time is 0, then it can be shown that the volume of a given sample is given by:

\[
V = V_0 (1 - \phi_0) \exp\left(-\frac{\sigma}{k}\right)
\]

where:
\[ V = \text{volume after applying effective stress } \sigma \]
\[ V_0 = \text{initial volume at effective stress } 0 \]
\[ \exp = \text{exponential function} \]

Compaction is not fully reversible, i.e. if effective stress is reduced after first having increased, the rock or sediment does not recover to its original volume or porosity. For most sediments a good approximation (used in this model) is to assume that porosity does not recover at all after a decrease in effective stress, and that the effective stress referred to in Equation (4) is the maximum effective stress to which the sample has been subject.

Shales may compact down to almost one third of their bulk volume at the time of deposition by dewatering and effective stress increase. Additional compaction is possible due to chemical changes in the clay molecules and water molecules bound to them. These chemical changes have not been modeled in this work.

Many commercial basin modeling packages utilize Darcy’s law and some variation of Terzaghi’s law to model compaction and fluid expulsion in one, two, or three dimensions. The experimental model used here also models plastic sediment flow. Sediment flow is the physical movement of sediment due to pressure distribution, not necessarily involving volume change. This deformation occurs readily in salt and to a certain extent in some shales. Sediment layers adjacent to highly deforming sediments (such as layers near a piercing diapir) also deform plastically. Furthermore, recently deposited soft sediments also may deform plastically in response to a load deposited on top of them, particularly when this load is sudden or unevenly distributed (as for example in turbidites).

The plastic deformation of sediment can be assumed to be similar to the flow of a fluid with extremely high viscosity, as follows:
\[ v_r = \frac{1}{\mu_r} (\nabla S - \nabla(z \rho_b g)) \]  \hspace{1cm} (5)

where:

\( v_r \) = plastic flow velocity vector \\
\( \mu_r \) = plastic “viscosity” \\
\( \rho_b \) = bulk density

The stress \( S \) is the same geostatic stress that appears in Equation (2). However, when modeling plastic deformation, it cannot be assumed to be always equal to the load of sediment and fluid above a given point, because it is also affected by additional forces that arise during deformation.

Equation (5) involves several approximations. Even though sediments may flow over long periods of time, they do not behave as Newtonian fluids. Their “viscosity” changes according to the state of stress. Additionally, and no flow occurs unless a certain threshold stress is exceeded. Despite these approximations, Equation (5) is used in this model because it does represent the primary behavior of rocks or sediment subject to stress.

A continuity equation is implicitly used in conjunction with Equations (3) and (5). The continuity equation states that sediment volume is conserved when sediment flows (except as determined by porosity changes in equation 3), and that all sediment properties (porosity, permeability, compaction coefficient, and plastic viscosity) are “carried” with the flow.

\[ \frac{\partial p_i}{\partial t} = (v_r \cdot \nabla) p_i \]  \hspace{1cm} (6)

where:

\( p_i \) = sediment property \\
\( t \) = time

**Numerical methods**

Numerical methods used in the sedimentation component of the model are similar to those described by Tetzlaff and Harbaugh (1989). Fluid flow coupled with compaction is solved in this model (as well as in many commercial basin modeling packages, by a finite volume method (Doligez et al., 1986, Duppenbecker and Illiffe, 1998).

The model used for this work utilizes a finite volume method to model single-phase flow in porous media and plastic deformation. It works on a grid that contains cells that are square and regular in plan, but whose vertical dimension varies from cell corner to cell corner, and also varies through time.

Plastic sediment deformation in the vertical direction is achieved by simply changing the height of each cells vertical edges. Since the grid cannot deform in the horizontal direction, horizontal sediment movement is achieved by transferring sediment properties and layer thicknesses horizontally.
This arrangement is simple and generally leads to stable solutions, despite the presence of some artificial numerical diffusion (which is minor provided that horizontal gradients of sediment properties are small). The scheme has limitations regarding sediment plastic flow, in that layers may not become overturned, salt domes may not have vertically concave edges and may not become detached (although they may become laterally “pinched out” from their source), and non-vertical faults cannot be modeled. It is important to notice, however, that these are limitations of this first implementation of the model, and are not inherent in its equations or basic assumptions.

Examples

In order to illustrate the behavior of this model, and show how it can help understand processes that relate sedimentation and sediment deformation, three example applications are presented:

1. Modeling the deformation and further sedimentation after sudden depositional events, in this case turbidite flows.
2. Modeling salt diapirism and collapse at the top of diapir.
3. Modeling shale compaction and further sedimentation on a shelf edge.

These examples were chosen because they represent three different scales and three very different phenomena.

Local deformation after depositional events

Even at the centimeter scale, sudden turbidite flows involving sands deposited on preexisting soft sediments produce a variety of deformation and dewatering structures. Seismic evidence suggests that some deformation may occur at the scale of turbidite channels (Fig. 1), in the form of a partial sinking of newly deposited sediments into the preexisting soft sediments.

![Figure 1: Seismic section across a filled submarine channel in the upper part of a turbidite fan. Layers of preexisting sediment bend upward near the channel (as shown by arrows), suggesting possible deformation of soft sediment due to the load imposed by the fill.](image-url)
Load deformation would presumably tend to deepen the channel, allow more flows to traverse the same channel, and extend the length in which the flow remains channelized (as opposed to spread out over a fan). In order to test these hypotheses, two model runs were made: one without allowing sediment deformation (Fig. 2), and another one identical in all aspects, except that both the preexisting substrate as well as the newly deposited sediments were allowed deform under the load of each new flow (Figure 3). Both runs involved simulating 40 consecutive turbidite flows. Although compaction by dewatering was allowed, most of the sediment deformation was due to plastic flow without significant volume change, because the burial depth was not great enough for significant compaction.

**Figure 2:** Computer simulation of submarine canyon erosion and fill assuming no deformation of sediments and no compaction after deposition. The fill spreads out at the base of the slope, with no well-defined channel.

**Figure 3:** Computer simulation of submarine canyon erosion and fill assuming deformation of underlying sediments as well as compaction of canyon fill. Although some of the fill "spills over" to the flanks of the canyon, most of the fill is confined to a well-defined channel.
Although the examples are somewhat coarse (the channel width is only about 3 cellsides), these experiments do suggest that load-deformation may affect subsequent sedimentation. As more flows occur, they tend to follow the channel more closely in the second case (with deformation) amplifying the effect even further.

**Salt tectonics**

The understanding of salt tectonics carries great economic importance due to the association between salt structures and hydrocarbon reservoirs. Salt diapirs often conducive to hydrocarbon traps, and their associated faults may constitute oil migration paths. A summary of the geometry of intrusive salt structures can be found in Jackson and Talbot (1994). Salt sheets transmit stresses that may be related to faults and other structural features of importance in oil exploration (Withjack and Callaway, 2000).

The example run presented here is significant because it appears to provide a plausible further explanation of salt dome collapse (the “deflation” of the upper part of a diapir often seen in the latest stages of its evolution). Diapir collapse or fall is evidenced by salt sinking and collapse structures such as normal faults in the sediments above the diapir (Figure 4). It is often attributed to either a change in the dynamics of salt flow due to an external change, or to basin extension, which “starves the diapir of its source of salt.

![Figure 4: Diapir similar to that modeled in Figure 5. Collapse structures can be seen near the top.](image)
The run presented in Figure 5 provides an example in which all major aspects of diapir formation are modeled. The novelty in the explanation provided by modeling resides in that there is a stage in which the diapir is “overpressured”. “Overpressure” in this sense is not the same as excess pore pressure in drilling terminology, in which the pore pressure exceeds hydrostatic. In this case we use the term to refer to the fact that geostatic pressure at any point within the diapir is greater than what would be expected from the weight of the column of salt, sediment, and water above the given point. This occurs due to rapid sediment loading, and due to the diapir having been “cut off” from its salt source. If it was still connected to the source of salt, pressure would dissipate into the rest of the salt (unless it too was overpressured).

In this overpressured condition, the diapir rises higher (and perhaps faster) than if buoyancy conditions existed. That this is possible, can be seen by diapirs occasionally rising to the surface despite being surrounded by sediments of lesser density than salts. Ultimately, also magmatic intrusions illustrate this point, as they have a density higher than the surrounding sediments, and yet rise in a dome-like fashion due to the internal pressure provided by a magmatic chamber.

In the later stages of the evolution of the modeled diapir, the surrounding sediments yield and buoyancy conditions return. The top of the salt then sinks slightly and collapse structures result in the overlying sediments.

This explanation is only conjectural. Although the model shows it to be possible from the point of view of sediment and salt dynamics, field and experimental confirmation would be required to verify it.
**Figure 5:** Sequence of sections showing the evolution of a modeled diapir every 100,000 years. Initially, a layer of salt is deposited and further sedimentation causes a differential load on it (a). The incision in the overlying sediments in (a) is a submarine canyon. Differential loading causes salt to begin flowing (b). More sedimentation occurs in the areas overlying the flanks of the diapir than over its center (b and c). This further “amplifies” the diapir’s evolution, until eventually (c) it is cut off by pinch out from its source of salt. Further rapid sedimentation along the flanks causes an excess pressure in the salt (above the pressure that would result from sediment and salt weight alone) (c). This causes the diapir to rise beyond the level it would if buoyancy were the only force (d). The yielding sediments around the diapir and further sedimentation on top, cause the pressure to drop to the level expected only by the vertical load, and buoyancy conditions return (d and e), causing partial collapse at the top of the diapir.
Compaction in shelf progradation

This example involves the deposition of clastic sediments on a continental shelf (Figure 6) and the process of compaction due to dewatering. The compacting sediments, however, increase the accommodation space, leading to sedimentary structures that might otherwise not occur, or that may be attributed to a rising sea level.

Figure 6: Seismic section showing a prograding continental shelf

Figure 7: Section through simulated deposits. Red and green colors represent sand, while blue and gray represent shale.

The simulated run lasted 1 million years with a steady sediment supply. It involved two major seal level cycles and several minor ones. In the lower part of the sequence, clays are deposited during a highstand. Later sand deposition causes these clays to compact. The high permeability of the sand facilitates dewatering. Clays that are further seaward do not compact, because they are overlain only by thin impermeable clays. This produces a distal “bulge” (white arrow in Figure 7) in the lesser compacted clays. Further sedimentation overcomes this bulge, but compaction of the lower sediments continues. When new sedimentation overcomes the bulge, some erosion occurs due to the steep slope (black arrow in Figure 7). In the seismic section, erosion is somewhat more prominent than in the model (underneath the steepest part of the reflector colored light orange). Another sequence is then deposited on top of this slight unconformity.

In this example, sea level variations are partly responsible for the depositional geometries, but the topographic and accommodation-space changes induced by compaction interact with these and imprint their own signature. It is difficult to say which
features were caused by sea-level changes and which by the compaction history, as both processes interact closely.

**Future work**

Use of this model has led to hypotheses that present some novel explanations for sedimentary and deformational features. These hypotheses should be tested by field measurements, as modeling just shows the plausibility of a mechanism, not its actual occurrence.

Laboratory modeling should also be used in conjunction with numerical modeling. Although laboratory modeling may be affected by scaling problems, its ability to represent physical reality can be vastly superior to that of the most powerful computer. In the case of deformation modeling, the scaling problems are minor, and comparison between laboratory and the corresponding numerical models would strongly validate proposed mechanisms. In the case of sedimentation modeling, the scaling problems in a laboratory can be more severe. Nevertheless, a numerical model could be set up to run at the scale of a laboratory experiment. Even though this might not represent geological reality, it would help validate the physical reality or plausibility of the numerical model.

Growth faulting was not modeled in this work due to additional theoretical assumptions needed and complexities in the computer model. Growth faults, however, are likely affected by the load of overlying sediments, and their movement no doubt affects the accommodation space on top. This indicates that further insights into the evolution of growth faults could be obtained by future modeling of growth faults concurrently with sedimentation.

**Conclusions**

From the modeling work done, the following conclusions can be drawn:

- The simultaneous modeling of sedimentation and deformation sheds light on the evolution of systems in which both processes are highly interdependent.
- Rapid sedimentation on and around diapirs may cause them to attain an excess pressure and grow more rapidly and higher than if they were driven by salt buoyancy alone. This hypothesis, however, requires field confirmation.
- Compaction in shelf sediments may be fundamental to the correct interpretation of sedimentary features and sequences.
- Field observations and laboratory experiments should be used to validate explanations suggested by modeling.
References


