Sedsim Stratigraphic Forward Modelling

A Brief Introduction

What is Sedsim Stratigraphic Forward Modelling?

The Sedsim three-dimensional stratigraphic forward modelling software enables a variety of inter-dependent surface and basin-forming processes to be studied at both geological and engineering time scales. The results reflect possible changes in sediment distribution over time as a function of the depositional environment. Past studies that have demonstrated the value of this approach include those by Griffiths et al. (2001), Griffiths and Dyt (2001), Griffiths and Paraschivoiu (1998), Koltermann and Gorelick (1992), Martinez and Harbaugh (1993) and Tetzlaff and Harbaugh(1989). Any computer modelling is only as good as the validity of the input data and the algorithms used in the program. The Sedsim program has been shown to predict sediment distribution in a range of depositional environments and at scales from metres to several kilometres. The derivation of input data for such computer models should be no more onerous than that required for a conceptual geological model of an area. However, the need for quantitative data forces the geologist to a greater degree of commitment than may otherwise be the case.

Sedsim is a three-dimensional stratigraphic forward modelling program developed originally at Stanford University in the 1980's and extensively modified and extended in Australia since 1994. Sedsim consists of a series of computer programs that can be linked together or run separately. The core Sedsim flow and sedimentation programs are linked to modules including subsidence, sea level change, wave transport, compaction, slope failure and carbonates. The program models sediment erosion, transport, and deposition, and predicts clastic and carbonate sediment distribution on a given bathymetric surface. Modules that are yet to be linked include pore-fluid movement, aeolian deposition, and organic facies distribution.

The basic principles, background to, and operation of, Sedsim is described in Tetzlaff and Harbaugh (1989). Tetzlaff developed the program, with subsequent enhancements by Ramshorn and Wendebourg at Stanford, and Chris Dyt at CSIRO. Sedsim is controlled by a parameter input file, and files describing relative sea-level/base level change, water temperature, initial topography/bathymetry, and tectonic movement for each grid cell over time.

Basic Principles of Sedsim Operation

Fluid Flow

Hydrodynamics make up the core of the Sedsim program and utilise an approximation to the Navier-Stokes equations. The full Navier-Stokes equations describing the fluid flow in three dimensions are currently impossible to solve due to limitations in computer speed (it would take longer to simulate a flow than the real event). Sedsim instead simplifies the flow by utilising isolated fluid elements to represent continuous flow (Tetzlaff and Harbaugh, 1989, Chapter 2). This Lagrangian approach to the hydrodynamics allows for a significant increase in the speed of computation and simplification of the fluid flow equations. The downside of this approach is that individual events such as a rapid variation in fluid flows cannot be modelled. Simulations over geological periods can at best hope to capture the mean conditions and create a general pattern of sediment distribution, rather than capture the exact timing of each individual pulse of material.

Modelling of the fluid flow is performed by allowing fluid elements to travel over the grid describing the topographical surface, reacting to the local topography and conditions such as the flow density and the density of the medium through which the element is passing (eg. air, sea water, or fresh water). The fluid elements are treated as discrete points with a fixed volume, an approach known as "marker-in-cell". Several simplifications are made to the Navier-Stokes equations, comprehensively described in Tetzlaff and Harbaugh 1989. The most important of these is that the flow is expected to be uniform in the vertical direction (i.e. the whole of the fluid element has the same velocity), and that the friction experienced by the fluid element is controlled by Manning coefficients. The net result of these simplifications is that the Navier-Stokes equations are modified into non-linear Ordinary Differential Equations (ODEs). These equations are now solved using a modified Cash-Karp Runge Kutta scheme (Press et al., 1992) that ensures stable and accurate 4th order in time solutions.

The resolution of the simulation has an influence on the results. There are two discretisations that must be examined in Sedsim: the temporal and spatial. The spatial resolution is perhaps the most obvious. Because the fluid elements use the grid topography to determine their flow characteristics features smaller than the grid resolution have no influence upon the flow. The temporal aliasing comes in several forms, which can be controlled by the user:

- The choice of "display interval" in years simulated time (this is equivalent to the temporal resolution in cross-sectional models). This controls how often the data is output from the model. All sediment deposited during a time interval is included together. Thus, multiple events occurring within a display interval are seen as one.

- The choice of "flow sampling interval". This represents the interval between releases of new fluid elements. For example setting this to 100 years would mean that a new fluid element would be released every one hundred years. That fluid element would then contain the volume of water and sediment as if the original source had flowed for 100 years. As it is moved about the topography it is assumed to flow at each point over 100 years.
- Time step. The time step controls how far the simulation advances in time at each iteration. This variable is automatically calculated by Sedsim, and is chosen to be as large as possible whilst ensuring that the simulation remains numerically stable and accurate. It is also chosen so that no topographical features are by-passed by the fluid elements. It is indirectly controlled by the accuracy factor, which specifies to what precision any change in the flow must be calculated.

- The choice of "extrapolation factor" (ratio of computing time to simulated time). Because of the large geological time scales over which Sedsim is often run, a simplification is introduced where the conditions for one time step are thought of as being representative of the flow over that area for a multiple of that time given by the extrapolation factor.

- The choice of "parametric sampling interval". This variable affects how often in simulated time other effects such as sea level change, tectonic movements, wave/wind effects and slope instabilities are calculated. The value is generally chosen to be much shorter than the rate at which these items typically occur in nature. For example, change in sea level is typically referenced once every 100 years.

Sediment Transport
Sediment is transported across a bathymetry (bypassed), or deposited on its surface, according to the principle of conservation of mass. In other words, for each time interval:

sediment in + sediment eroded = sediment in the fluid + sediment deposited + sediment out

In Sedsim the sediment moves at exactly the same rate as a fluid element, because there is neither a velocity gradient in the fluid, nor any distinction between the rate of transport by the fluid element of the suspended and bed load in the default mode. Sedsim v6.2 allows for bed load to be modelled separately if required. Because of the use of the flow-sampling interval (described above), this crude approximation actually has little effect on the results, as the fluid flow represents a time-averaged response anyway. The boundary between erosion and transportation is determined by the critical shear stress, calculated as a function of particle diameter (threshold shear stress increases linearly with particle diameter above 0.1 mm). The rate of sediment deposition or erosion is proportional to the excess "effective sediment concentration". This is the difference between the actual sediment load within the fluid element and its capacity to hold sediment. This capacity is a function of the water density, the velocity, and average fall rate of the contained sediment and the buoyancy of the flow. Sediment sinks within a fluid element as a function of its excess density over the fluid, its diameter, and the viscosity of water at 15°C. For more detailed consideration of the algorithms used by Sedsim the reader is referred to Tetzlaff and Harbaugh (1989). Sedsim is typically run using four different siliciclastic grain sizes specified by the user. In addition to this are the options to include two types of carbonate reefs and resultant clastic grains and, in the near future, a similar treatment of organics.

After deposition from the fluid elements, the sediment can still be transferred due to slope angles within a fluid element's local environment. The sediment can be diffused through many grid cells until it is deposited on a stable slope angle.

Wave and Storm Effects
There are significant changes to the modelling of waves and storm events in the latest version of Sedsim. The changes have been brought about by largely be the application of Sedsim to engineering problems such as passive beach replenishment and erosion. Sedsim has been used to model successfully the movement of sand on a 5 km stretch of beach over a 5 year period from 1992 to 1997 at 18 day intervals at a resolution of 50 m in order to design artificial tyre reefs to passively retain sand and allow sea grass survival. The wave routine is designed to simulate longshore transport of sediment deposited by a fluid element in a shore-face setting. The program now allows the input of a wave height and direction file which contains information at as high a resolution as required (eg. minutes or hours) of wave incident angle and significant wave height. The net effect of the wave module is to transfer sediment exposed to the prevailing wind and wave directions and above wave base alongshore. Depending on the simulation, this can be a dominant process. Infrequent storms are modelled using a 'mean return period' or a file containing historical storm event data if available. Wave and storm refraction are handled independenty.

Temporal Aliasing/Time Sampling Sensitivity
There are two types of temporal aliasing to consider. The first concerns the relationship between flow time step and the maximum slope over which sediment will flow. For steep slopes, and irregular bathymetry, the flow needs to be calculated more frequently to ensure realistic sediment geometries. This problem is automatically handled by the code as discussed in the section on fluid flow. A reduction of the flow time step makes the simulation more stable, and potentially provides marginally higher resolution in the output geometries. A consequence however, is a significant increase in computing time. The second factor influencing temporal aliasing is the display interval. Temporal aliasing is the ability to model a given time event. If it is believed that a fan developed in ten years, its geometry and composition could not be simulated with a time step greater than five years. The consequence of choosing a display interval of 5 ka, therefore, is that the minimum temporal depositional event that can be modelled is one with a duration of 10 ka. If the aim is to model the effect of orbital forcing on high-frequency sedimentation cycles, then a display interval of at most 10 ka would be needed to capture the effects of the 19-21 ka cycle. The "parametric sampling intervals" are the time intervals at which the sea-level curve are sampled, wave influences calculated, slope's stability checked, compaction calculated etc. The smaller the parametric sampling intervals, the higher the resolution of the events that can be modelled, but the longer the computing time.

Tectonic Subsidence
Sedsim can incorporate vertical tectonic movement in a simulation. A subsidence/uplift value is defined for each individual grid node in the initial topography, and these arrays of values can be changed at any time in the simulation, independently of either the display or parametric sampling intervals.

Compaction
Compaction during the simulation is calculated using a "look-up table" containing porosity values as a function of effective stress and grain size. For each display interval, the lithostatic pressure is calculated from the overburden. This pressure controls compaction and the actual grainsize deposited. No post-depositional burial can be applied to the sediment column at present. Burial compaction has to be applied after the simulation by an additional program [Compcor].

Loading / Isostasy
Loading effects on stratal geometries can be included in a simulation, as a function of mantle density and flexural rigidity. The effects of the basement undergoing elastic deformation are typically small for most simulated areas.

Slope Failure and Turbidites/Gravity Flows
Slope failure is triggered by over-steepening of sediment due to tectonic movement, or the exposure of sediment due to sea level fall. The composition of the underlying sediment also plays a strong role in the failure prediction. The failed sediment is transferred into a new fluid element (or series of fluid elements), and then treated as a regular fluid element. Due to the high sediment

concentration, these flows can often lead to large turbidite flows.

Carbonates and Organics

A recent module introduced into Sedsim models the accumulation/growth of carbonates. Sedsim is capable of handling two types of carbonate formation (for example coral/rudist reefs and marine/lacustrine pelagic carbonates). The major problem with attempting to represent the growth of carbonate reefs mathematically is the wide range of situations and environments in which reefs may or may not develop. Prediction of reef development therefore tends to be descriptive, for example "reefs grow at a rapid rate in warm climates, with little sediment input". In order to deal with the inexactness of descriptive language, we turn to Fuzzy logic, inspired by the stratigraphic modelling package 'Fuzzim' (Nordlund 1996). Fuzzim utilises fuzzy logic to determine the entire system behaviour including the siliciclastic transport as well as organic and carbonate growth and erosion. We only model the growth of reef structures through fuzzy logic, leaving all the other processes to the existing hydrodynamic code. An advantage in the use of a fuzzy system is that the code executes very rapidly and so adds little in computational time to the already heavy load imposed by the fluid dynamics. The challenge in this modelling lies in developing the correct set of rules to model the simulation. These are currently under development. Organic material will be dealt with in the same way.

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