Response

Reviewer 1

Comment

The reviewer wants further explanation of how geological processes used in GPM™ transport/deposit sediments, and the mathematical equations that guide these processes. For example, on sediment accumulation process, the reviewer asked the following questions:

1. How does the accumulation process account for different sediment types?
2. Does the accumulation process use mass balance for each sediment type entering and leaving a cell?
3. What are the actual processes and equations used in GPM for the accumulation process?

Author Response: To begin, GPM™ is commercial software developed by Schlumberger to simulate clastic and carbonate sedimentation in a deep or shallow marine environment. It is made up of geological processes such as steady and unsteady flow, sediment diffusion, wave action, tectonics, and sediment accumulation that rely on physical equations and assumptions to replicate the process of sedimentation in a geological basin. A realistic realization of a stratigraphic pattern as observed in seismic or well data will provide a 3-dimensional framework to constrain subsurface property representation that conforms with the real-world trend. In clastic sedimentation, the movement of sediments relies on equations from the original SEDSIM developed in Stanford University. Sediment transportation, erosion and deposition is governed by a simplified Navier Stokes equation. It is termed “simplified” because the Navier-Stokes equation in its original form define sediment movement in a 3-

dimensional differential form, while the flow equation used in GPM^{TM} is 2-dimensional with an arbitrary input of flow depth.

Following a review of the original Stanford SEDSIM (Harbaugh, 1993) from which the steady and unsteady flow process in the GPM software are derived, and also through personal communication with Daniel Tetzlaff (GPM software), further details of the GPM processes involved in this work is given to answer the questions asked by the reviewer. Lastly, due to software copyright constrains I do not have access to the code/ algorithms that control each step of simulation in the software. However, the general guiding equations and assumptions used in computing the movement of sediments are provided in the manuscript.

Author Changes: The changes made in the manuscript includes further details of how sediment movement and deposition occur under the steady, unsteady, diffusion, and especially the accumulation processes in the GPM^{TM} software.

Steady and Unsteady Flow Process

Fluid/sediment movement in the steady and unsteady flow process in GPM relies distantly on the Navier-Stokes flow equation. As indicated earlier, the Navier Stokes equation deals with flow in a 3-Dimensional framework, but the simplified flow equation used in GPM defines a 2-Dimensional system with an arbitrary dimension that accounts for flow depth (Tetzlaff, D. personal communication, February 2021).

Although the steady and unsteady flow governing equations distantly rely on the Navier-Stokes equations, the steady flow is quite distinct, as it uses a finite difference numerical method for faster computation and to also depict the frequency of flow that is characteristic of flow in channel such as rivers. The finite difference method use an assumption that flow velocity is constant from channel bottom to surface. On the other hand, the unsteady flow uses the particle method from SEDSIM3 to solve the sediment concentration in flow and sediment transport capacity (Tetzlaff & Harbaugh 1989). The simplified flow equation in the GPM software attempts to solve the problem of "shallow-water free-surface flow" over an arbitrary topography surface (Tetzlaff, D. personal communication, February 2021). "Shallow water" in this context indicates the instance where only the vertically-averaged flow velocity and flow depth are applied and kept track of as a function of two horizontal coordinates.

The flow equations in the steady and unsteady processes are expressed through:

$$\frac{\partial h}{\partial t} + \nabla.\mathrm{hQ} = 0 \qquad (1)$$

Where: h is flow depth, t is time, and Q the horizontal flow velocity vector.

$$(\frac{\partial Q}{\partial t} = -(g\nabla)H + \frac{c_2}{\rho}\nabla^2\mathrm{Q} - \frac{c_2 Q/Q/}{h} \qquad (2)$$

Where: $\frac{\partial Q}{\partial t}$ is the Lagrangian derivative of flow relative to time, g is gravity, H is the water surface elevation, c_2 is the fluid friction coefficient, ρ is the water density, c_1 is the water friction coefficient and h is the flow depth.

The Manning's equation is applied to relate flow, slope, flow depth and hydraulic radius channels with a constant cross-section for the steady flow process. Manning's formula states:

$$\mathrm{V} = \frac{k}{n} {R_h}^{2/3}\, \mathrm{S}^{1/2} \qquad (3)$$

Where: V is the flow velocity, k is the unit conversion factor, n is the Manning's coefficient which depends on channel rugosity, R_h is the hydraulic radius and S is the slope.

As mentioned earlier, the unsteady flow process uses the particle method equation, which relies on the assumption that erosion and deposition depend on the balance between the flow's transport capacity and the "effective sediment concentration". The equation for multiple-sediment transport in flow is given as follows:

$$A_{em} = \sum_{k_s} \frac{l_{Ks}}{f_{1k_s}} \qquad (4)$$

Where: A_{em} is the effective sediment concentration of mixture, l_{ks} is the sediment concentration of each type, and f_1,k_s is the transportability of each sediment type.

The transport capacity of a sediment type is expressed by equations (5) and (6). Let consider

$$R = (A - A_{em})f_{2,}k_s \qquad (5)$$

Where $f_{2,}k_s$ is the erosion-deposition rate coefficient for sediment type k_s. For every sediment type $,k_{s,}$ the formula for transporting sediment of different grain sizes is given as:

$$(H - Z)\frac{Dl_{Ks}}{Dt} = \begin{cases} R & if\ R > 0\ and\ \tau_0\ \geq f_{3,k_s}\ and\ k(x,y,z) =\ K_s \\ & or\ R < 0\ and\ K_s = 1\ or\ l_{k_s-1} = 0 \\ 0 & otherwise \end{cases} \qquad (6)$$

Where;

H is the free surface elevation to sea level, Z is the topographic elevation for sea level, $K_s$is the sediment type, $l_{ks,}$ is the volumetric sediment concentration of a specific type (k).

Diffusion Process

The diffusion process simulate sediment movement from a higher slope (source location) and deposition into a lower elevation of the model through gravity. Sediment diffusion runs on the assumption that sediments are transported downslope at a proportional rate to the topographic gradient, making fine-grained sediments easily transportable than coarse-grained sediments. Sediment diffusion depends on three parameters: (i) sediment grain size and turbulence in the flow, (ii) diffusion curve, which is a unitless multiplier in the algorithm and,

(iii) diffusion coefficient. The diffusion coefficient, among other variables depend on the type of sediment and “energy” of the depositional environment. In this contribution, the highest depth-dependent diffusion coefficient occurs near sea level, where the “energy” is highest over a geological time (Dashtgard et al. 2007).

In GPM, sediment diffusion is computed using:

$$\frac{\partial z}{\partial t} = D_i \nabla^2 \mathrm{z} + \mathrm{S_n} \qquad (7)$$

where **z** is topographic elevation, D_i is the diffusion coefficient, **t** for time, and ∇^2z is the laplacian of z, and S_n is the sediment source term.

In other studies such as From Dade & Friend (1998); and Zhong (2011), sediment diffusion is defined through a considering that the grain size for each sediment component (coarse sand, fine sand, silt, and clay) are known. Also an assumption that these particles have a uniform diameter (D) in the flow mix. In that case, external fore (F_e), which consist of drag, lift, virtual mass, and Basset history force is given as:

$$F_e = \alpha_e M_e + \alpha_e \Phi_D . \frac{U_{fi} - U_{ei}}{T_p} \qquad (8)$$

M_e is the resultant force of other forces with the exception of drag force, T_p stokes relation time, expressed as: $T_p = \rho_\rho D^2/(18\rho_f V_f)$, with ρ_f and V_f as density and viscosity of fluid respectively. Φ_D is a coefficient that accounts for the non-linear dependence of drag force on grain slip Reynolds number (R_p).

$$\Phi_D = \frac{\mathrm{Rp}}{24} C_D \qquad (9)$$, with C_D sediment grain coefficient.

With the flow component in place, the diffusion coefficient (D_i) is deduced from the Einstein equation. Using an assumption that the diffusion coefficient decreases with increasing grain size and rise in temperature, and that the coefficient f is known, the expression for D_i is:

$$D_i = \frac{K_B.T}{f} \qquad (10)$$

Meanwhile, f is a function of the dimension of the spherical particle involved at a particular time (t). In accounting for f, the equation for D_i changes into:

$$D_i = \frac{K_B.T}{6.\pi.\eta_o.r} \qquad (11)$$

Sediment Accumulation

The sediment accumulation process in GPM is designed to produce an arbitrary amount of sediment representing the artificial vertical thickness of a uniform lithology as interpreted in a well or outcrop data (Tetzlaff, D., personal communication, February 2021).

The areal input rates for each sediment type (coarse-grained, fine-grained sediments) use the value of the map (topographic surface) at each cell in the model and multiply it by a value from a unitless curve at each time step in the simulation to estimate the thickness of sediments accumulated or eroded from a cell to another. In doing so, the accumulation process accounts for the different sediments involved in the simulation.

Sediment accumulation in the GPM software requires other processes such as steady flow and diffusion to account for sediment transport (sediment entering or leaving a cell). In line with the principle of mass balance the accumulation process uses a deposition/year (mm/yr) function to artificially produce the height of sediment deposited per cell.

The equation that guide sediment accumulation in the GPM software is given as:

$$A_T = \sum_{S=1}^{n} [(M_{v1} * S_{c1}), \_\_ n] \qquad (12)$$

Where;

A_T is the total sediment accumulated in a cell over a period, S is the sediment type, M_v is the map value of sediment in each cell, and S_C is the sediment supply curve as a function of topographic elevation.

Summary Answers to Specific Questions on Accumulation Process.

1. How does the accumulation process account for different sediment types?

Answer: It account for different sediment types by using curves (sediment type as a function of time that is not less than zero) and sediment probability maps.

2. Does the accumulation process use mass balance for each sediment type entering and leaving a cell?

Answer: Yes it uses Mass balance. It applies deposition height/year (mm/yr) as input in each cell and requires other processes such as diffusion to account for sediment transport.

3. What are the actual processes and equations used in GPM for the accumulation process?

Answer: It is solely the sum of all sediments (map value in cell * sediment supply curve) to produce the height of the deposited layer per cell.