COUPLING LANDSCAPE EVOLUTION MODELS WITH CARBONATE PRODUCTION MODELS: HOW SEDIMENT FLUX COULD INFLUENCE CARBONATE PLATFORMS*

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Terrigenous clastic sediment input is known to affect carbonate production and reef growth, which are primary elements of sedimentary studies. However, carbonate production models often use arbitrary sediment source inputs to capture such interactions. For sediment source information to be useful, it needs to include geometrical information about sediment transport pathways that are based on proximal erosion sources and incorporate flux and grain size data. For that, the coupling of a landscape evolution model with a rule-based carbonate model could provide a meaningful modeling workflow for clastic sediment flows and their interference in carbonate platforms. The LEM used is based on modeling erosion in mountain catchments and escarpments by fluvial, and hillslopes processes. Such a model is controlled by input parameters like uplift rate, lithology, and climate parameters, and it outputs channel network distribution along with discharge, and sediment flux information integrated from area accumulation and vertical erosion rate. Additional code is built to calculate grain size along the sediment pathways based on a simple degradation function of grain size with distance. In contrast, carbonate models are usually built with a turbidity threshold where the carbonate production distribution and rate are controlled by bathymetry and modulated by the incoming flux of sediments. Once LEM outputs are generated, they are put into the carbonate model at every time step. Also, while keeping the parameters constant, multiple sensitivity tests are performed on the influence of sediment input to the growth of carbonates based on different LEM parameters. The outputs from the LEM show that sediment flux is not simply an induced flow in the landscape but could be the result of drainage catchments expansion and competition. Once the incision of drainage basins reaches equilibrium with the uplift regime of the domain, the sediment flux stabilizes at a constant rate while grain sizes decrease as channels propagate, increasing their length farther into the mountain chain, or the retreating escarpment. The calculated velocity to steady-state drainage basins and constant sediment fluxes is shown to be dependent on the ratio of uplift to erodibility. This erodibility is also intrinsically dependent on how weakened the underlying rock is and the volume of annual precipitation rate. As a response, the carbonate production rate at the beginning is constant despite the penetration of coarse sediments into the system by early formed river channels. However, once the turbidity level is triggered, the production rate decreases exponentially at areas consistent with the sediment input pathways, while sediment transport spreads the influence of clastic input on carbonate production. These findings support the need for the application of this workflow to a case study where the incision of drainage basins near marine carbonate factories is tested for its effect on carbonate reservoirs.

Key words: stratigraphic model, landscape evolution model, carbonate platform.

INTRODUCTION

It is well documented in literature that siliciclastic sediment input, whether it is settled or suspended, into a carbonate system (*e.g.*, a coral reef) has inhibiting effects on carbonate production (sources within Browne *et al.*, 2013; Perez III *et al.*, 2014). These effects include blocking sun rays and limiting photosynthesis, bringing poisonous chemicals into the medium, and competing for space with the carbonate-producing communities (sources within Perez III *et al.*, 2014). Such effects could lower the production rate of carbonate-producing organisms or halt their growth. This in turn has indirect effect on carbonate deposition in marine environments exposed to continental runoff. Conversely, carbonate strata hold information

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For an attempt in quantifying such interaction, I construct a workflow to combine two types of forward geological models. First, a landscape evolution model (LEM) is used to simulate mountain denudation, continental sediment generation and flow transport by surface erosion processes. Because the surface erosion processes modulate the spatial and temporal response of topography to the climatic and tectonic forces and bed properties, LEMs could be applied to studying both the efficiency of surface processes and the geological history of landscapes. In this study, it is assumed that fluvial channels and mountainous mass movements are the only active players in producing sediments and transporting them to boundaries. Second, a process-based stratigraphic carbonate model (SCM) is used to solve for carbonate buildups in marine setting. Such a model is based on the accumulated knowledge about the net response of carbonate production to sunlight, turbidity level, wave energy, and water depth. By coupling the two models, it's possible to quantify and analyse the dynamics of continental sediment generation/ transport and terrigenous-carbonate sedimentation. In this project, I build multiple simulations of the LEM, extract the output sediment information, and input such data to the carbonate production model. Based on this workflow, a sensitivity test is feasible to analyze both the indirect effect of the LEM parameters and the direct effect of the carbonate model on carbonate thickness and distribution.

METHODS

LEMs are simulations of surface processes shaping topography with progressing age. Conventionally, most LEMs are built on numerical approximations of diffusive and advective erosion and transport processes. As such, millennial-averaged erosion and transport by surface processes define mountain ridges and channel networks, at different scales. Consequently, these processes determine the continental pathways of clastic sediment into the coast at the boundary of the LEM. The volume of the eroded sediments is calculated as the vertical eroded sediment length integrated over the upstream drainage polygon area and time step (Fig. 1). In addition to the sediment coordinates and volume information extracted from the LEM, a simple logarithmic function is used to calculate the decay of sediment grain sizes as a function of the travel distance from their detachment point to the boundary of the model domain (Fig. 2). This assumes that sediments are largest at a reference point at the mountain ridge and decrease exponentially in size as they transported.

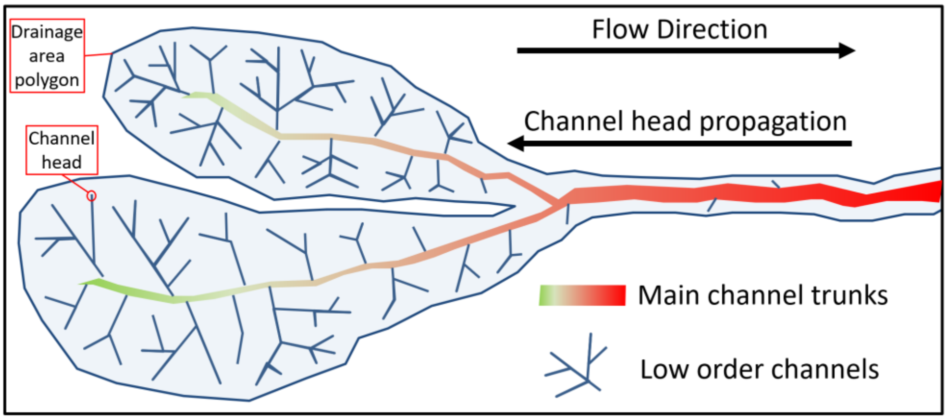

Fig. 1 – Channel networks at multiple scale levels with polygons which are delineated by mountain ridges and count for the upstream drainage areas of the channels. The main channel trunk is color-coded with discharge accumulation; the green color are channel nodes with low accumulation of upstream flow, while the red color represents channel nodes with high flow accumulation.

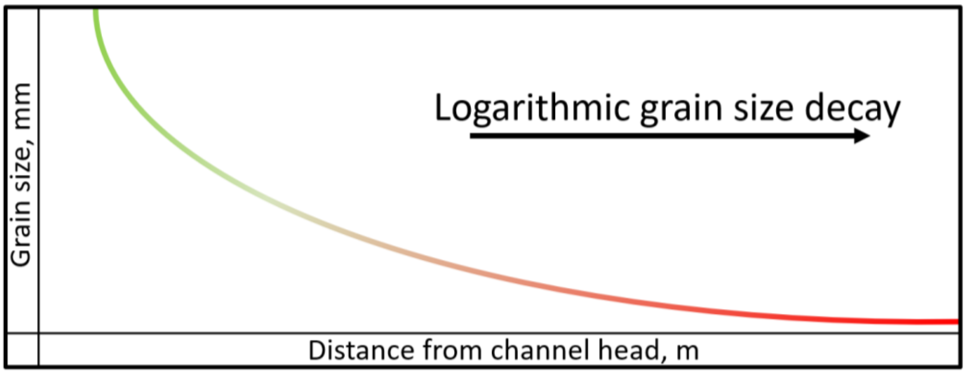

Fig. 2 – Logarithmic calculations of grain size decrease, in millimeters, as a function of distance, in meters, from the channel head where sediments are detached and transported to the base level at the boundary of the model domain.

However, for the information generated to be valid, LEMs have to include relevant surface processes with accurate numerical formulations and established by field evidence. First, hillslope processes control the crests around the mountain ridges. They include diffusive processes (soil creep and rain wash) and initiated by rock cohesion decay. Such a diffusive behavior of sediments is linear with increasing slope (Eq. 1) until slope failure causes the transport to behave non-linearly due to landslides (Roering *et al.*, 2001; Roering *et al.*, 2007; Tucker, Bras, 1998). In (Eq. 1), **z** is the vertical coordinate, **t** is time, **x** is the horizontal distance from the water divide of the mountain ridge, while the production rate by linear hillslope diffusion is equivalent to the vertical erosion rate, **E**. This erosion rate is equal to the hillslope curvature multiplied by a transport coefficient, or diffusivity, **D**.

$$\frac{\partial z}{\partial t} = E = D\frac{\partial^2 z}{\partial x^2} \qquad \text{(Eq. 1)}$$

Along the hillslopes, there is a distance, the hillslope length, where incision rate by debris flows and fluvial channels exceeds soil production rate (Stock, Dietrich, 2003; Heimsath *et al.*, 2005). Downstream from the hillslope length and in the majority of the landscape, the detachment-limited stream power incision model (SPIM) is widely used to account for the fluvial incision (Eq. 2; Whipple, Tucker, 1999; Tucker, Bras, 1998). SPIM is a first-order formulation of channel incision by shear stress and energy flux and it based on field observations. In such formulation (Eq. 1), the drainage area, **A**, is used to account for the runoff accumulated discharge, while **m** and **n** are components of SPIM and their ratio, m/n, is called the concavity index ranging between 0.35 and 0.8 (Whipple, Tucker, 1999). Starting from the water divide as a reference point, SPIM predicts that as the drainage area of a channel increases downstream, the channel profile flattens. Also, the scaling between increasing drainage area and decaying channel slope is described by an erodibility coefficient, **K**. This coefficient is a measure of how susceptible the bedrock is to erode, based on bed strength, precipitation, and channel geometry among other factors.

$$\frac{\partial z}{\partial t} = E = KA^m \frac{\partial z}{\partial x}^n \qquad \text{(Eq. 2)}$$

The LEM used here is, divide and capture (DAC), and it is unique for its optimized numerical solution of the fluvial stream power law at the node level, and analytical solutions of erosion processes between the nodes (Braun, Willett, 2013). The analytical solutions allow precise positioning of mountain ridges, between channel nodes, without the restriction of node resolution. In addition, while many LEMs use the method of “steepest descent” to reorganize channel networks, DAC has an explicit method of channel capture. In this method, the two channel nodes that are not connected have a mountain ridge, or a water divide, between them. As the position and elevation of the mountain ridge in this case is solved with analytical solutions from the two nodal sides, a match has to be reached. This assumes that a match in solution suggests an equal erosion rate from the two sides. If a match is not achieved, the mountain ridge is destroyed and the node with the higher elevation is captured as part of the channel of the lower node. This capture method enables the formulations and parameters of the different active processes to control channel capture and network rearrangements (Goren *et al.*, 2014).

It is assumed that at of the boundaries of the LEM is the coastal marine platform where carbonate-producing communities prosper and carbonate sediments are deposited. To model carbonate production, DionisosFlow, a 3D process-based stratigraphic model, is used. In this model, several aspects of sediment generation, transport and deposition are simulated. First, generation of sediments is carried out through direct volume flux at the boundaries, which is used here to input the sediment volume generated in the LEM. Another way of sediment generation is with constant *in situ* production rates specified by intervals of geological time and water depth. Moreover, certain restrictions are additionally configured in the stratigraphic carbonate model. These include intervals of turbidity levels, salinity, and temperature where generation of carbonate sediments is inhibited. Second, transport discharge of sediments, $\mathbf{Q_{sediments}}$, is carried out based on linear diffusion law, (Eq. 3), with constant diffusion coefficients. Such coefficients, $\mathbf{K_{gravity}}$ and $\mathbf{K_{water}}$, are weights that account for the fractal transfer of volume between cells due to gravitational potential energy, water discharge, and waves. Third, once sediments are transferred, different constant volumetric rates can be adjusted to account for uniform dissolution, and erosion. The specifications of the different methods are varied for different sediment classes/types which in turn are defined based on grain size and density. In addition, the water depth of the model domain is calculated based on the eustatic sea level changes and the initial bathymetry map.

$$Q_{sediments} = \frac{\partial z}{\partial x} K_{gravity} + \frac{\partial z}{\partial x} Q_{water}\, K_{water} \quad \text{(Eq. 3)}$$

RESULTS

The simulation of both models is in the span of 30 million years with a time step of half a million year, a domain of 100 km length and 50 km width, and a cell size of 1000 m^2. A breakdown of the parameters of the main simulations of the LEM and the SCM are in Tables 1 and 2, respectively. Both the sediment volume flux and the landward channel propagation are highly sensitive to the ratio of uplift rate to erodibility coefficient. However, the outputs from the LEM show that sediment flux is not simply a uniform induced flow in the landscape but could vary at a smaller scale due to drainage catchments expansion and competition. Once the incision of drainage basins reaches equilibrium with the uplift regime of the domain, the sediment flux stabilizes at a constant rate while grain sizes decrease as channels propagate, increasing their length farther into the mountain chain, or the retreating escarpment (Fig. 3). Also, the increase in the length of hillslopes slightly increases sediment flux.

Table 1

Parameters of the landscape evolution model: DAC

Uplift rate	0.1 mm/year
Erodibility	10^{-7}
Hillslope length	300 m

Several tests suggest that grain size variations of clastic sediment input have no observable effect on carbonate deposition in the SCM. Based on this observation, five litho-facies are defined in the SCM, based on the proportions of only four sediment classes. Sediments inputted from the LEM are termed “Clastic sand” and “Clastic mud” and they represent average coarse and fine grain sizes, respectively (Table 2). On the other hand, carbonate sediments produced locally represent coarse grains which include fossils and reworked carbonate fragments, and mud which include clay size and very fine grains (Table 2). The litho-facies of carbonate sediments include facies that are made up of certain ranges of carbonate sediment proportions based on a modified version of the Dunham (1962) carbonate classification (Table 2). In addition, the SCM simulations assume a marine platform with open connection to the ocean and good circulation between the surface and bottom inhibiting the formation of organic matter, whether *in situ* or by an input of nutrients from the continental clastic runoffs.

Table 2

Parameters of the stratigraphic carbonate model: DionisosFlow

Eustatic sea level change		+5m/Ma			
Sediment class/type		Clastic Sand	Clastic Mud	Carbonate grains	Carbonate mud
Grain Size, mm		2	0.04	4	0.04
Litho-Facies sediment proportions	Sand	0–50%	50–100%	0–50%	0–50%
	Mud	0–50%	50–100%	0–50%	0–50%
	Grainstone	0–10%	0–10%	90–100%	0–10%
	Packstone	0–10%	0–10%	10–90%	0–10%
	Mudstone	0–20%	0–20%	0–20%	80–100%
Diffusion coefficients	by gravity, m^2/Ma	30	20	5	5
	by water, m^2/Ma	50	100	50	100
	by waves, m^2/Ma	200	500	200	500
Carbonate production rate, m/Ma		0	0	0.01	0.1
Dissolution rate, m/Ma		0	0	0.5	0
Allowed turbidity level, m/Ma		0	0	0–0.2	0–0.5
Allowed discharge energy, kW/m		0	0	0–10	0–15

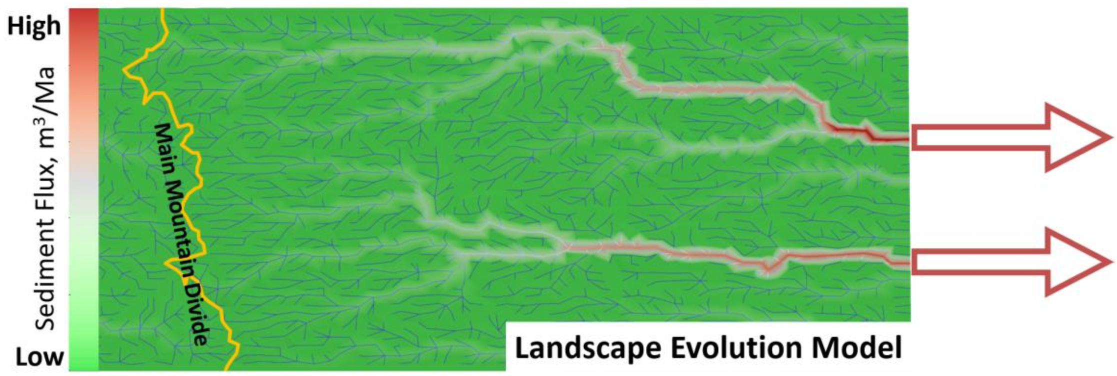

Fig. 3 – The landscape evolution model, which shows grid distribution of sediment volume flux, color-coded, and channel network, thin blue lines. The output from the LEM at the right boundary is assumed to be at coastal areas and is used as an input for the carbonate model.

The distribution and growth rate of carbonate production in the SCM is mainly controlled by water depth which in turn determined by the topography of the sea bottom and eustatic sea level changes. This carbonate production rate is constant at the beginning despite the introduction of coarse sediments into the system by early formed river channels. The consequences of the introduction of clastic sediment inputs is apparent once the concentration of clastic sediments increases. The more clastic sediments introduced to the system the less space exists for carbonate deposition, and the lower the net carbonate production in areas consistent with the sediment input pathways (Fig. 4). Also, once the turbidity threshold is triggered at clastic deltaic fronts, there is an exponential decrease in the production rate of carbonate sediments. As the deposition of both clastic and carbonate sediments progresses, the slope of the carbonate platform lowers leading to limited transport of the clastic deltaic input. Such transport limitation is only relevant to diffusion caused by gravity, while transport by waves and water discharge is still active above the wave base and near the surface.

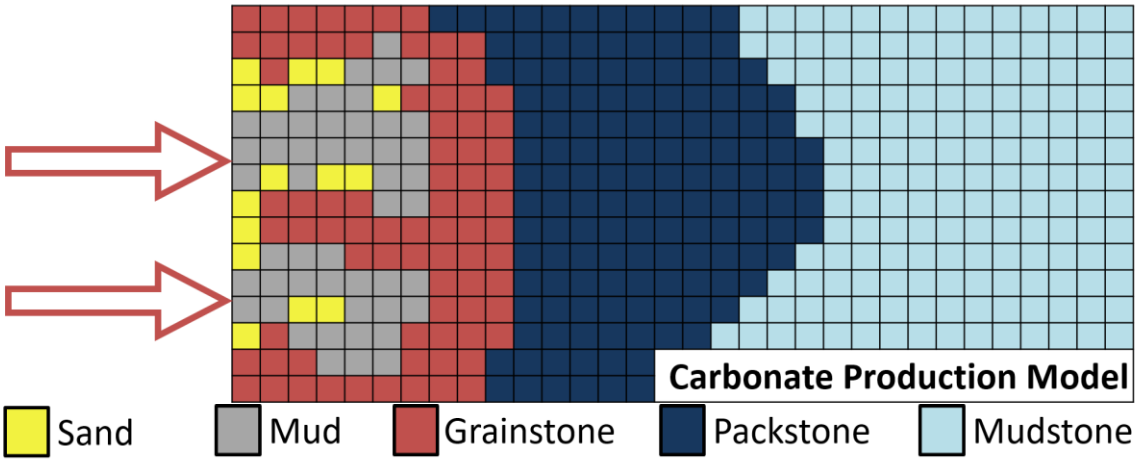

Fig. 4 – The stratigraphic carbonate production model, which shows grid distribution of clastic and carbonate litho-facies. The output from the LEM (Fig. 3) is used as an input at the left boundary of the carbonate model.

DISCUSSION

Process-based geological models are important for a quantitative analysis of sedimentary processes. Once coupled, these models, landscape evolution, stratigraphic, and geodynamic, can further unfold the complexity of the interactions between different natural processes (Ueda *et al.*, 2015). Based on the formulation of surface processes, the output sediment flux from the LEM is sensitive to uplift rate, lithology, climate parameters, and other specific parameters of the active processes (*e.g.*, fluvial erodibility, and landslide-triggering threshold at hillslopes). This sediment output can often be traced in marine deposits mixed with carbonates layers. However, due to the random drainage network rearrangements and the complex interactions between the clastic runoff and the carbonate-producing communities, patterns in sedimentary layers caused by cyclical forces, like climate can be masked (Goren *et al*., 2014).

In the carbonate model, the volume of clastic sediment input determines the magnitude of their effect on carbonate deposition, while the location of such sediment sources controls the distribution of such effect. In addition, the bathymetry, or water depth, and annual production rates are most important in determining carbonate production in the absence of clastic input. Furthermore, diffusion coefficients that determine sediment transport has a second-order effect on clastic-carbonate deposits as they extenuate the effect of clastic sediments on areas at deeper depths and change the bathymetry of the environment of deposition. Despite such observations, limitations are observed in this workflow. Although care has been taken overall to use reasonable parameter values, a case study in a similar setting as is proposed in this study would be highly beneficial. Specifically, constraining certain parts of the workflow based on measurable parameters, like the uplift rate, would lower the complexity of the two models and help isolate the effect of other variable processes. Moreover, the processes in the workflow are approximated at first order. This limits the application of such workflow to stratigraphic studies at large scale rather than respecting random variations with short timescales.

CONCLUSION

I model terrigenous clastic sediment pathways penetrating a carbonate platform and analyze the effect of such interaction on carbonate reservoir thickness and distribution. These pathways are generated by a landscape evolution model (LEM) where fluvial incision creates channel networks and erodes sediments.

In addition to a better modeling workflow, I built a code to incorporate grain size information with the sediment inflow as a function of distance from the channel heads. However, grain size information has proven not to have critical influence on carbonate production. On the other hand, by modeling a siliciclastic sediment input with information about its volume and runoff pathways, I show a method to test their inhibiting effect and the importance of the different parameters in both models. These findings support the need for the application of this workflow to a case study where the incision of drainage basins near marine carbonate factories is tested for its effect on carbonate deposits. In addition, the tested workflow could help in studying mixed clastic-carbonate deposits in marine environment, or deciphering information about landscape surface processes based on such deposits.

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