One-dimensional discrete computer model of the subduction erosion phenomenon (plate tectonics process)

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Abstract

In this proceeding, we present a discrete computer model of a tectonic process : the subduction erosion (without accretion) phenomenon. Up to now, models that have been studied were too inflexible. Here, we describe an original and simple approach, that has not been explored yet, based on overlapping cellular automata. Problems concerning implementation are exposed, as well as some results. At least we present a parallel code implementing the model.

1. Introduction

This work is the result of a cooperation with the *Laboratoire de Géodynamique Tectonique et Environnement* (Paris). It refers to the modeling of a geotectonics phenomenon : that of the subduction erosion on the contact between two convergent margins (or tectonic plates). We start initially by presenting the context geotectonics, then we approach our discrete model and finally we expose the results of our simulation. We show, in particular, that we have to develop a software adapted to our own simulation.

2. Subduction of oceanic crust beneath continent

In the theory of plate tectonics, the lithosphere is divided into a network of blocks (plates), floating upon viscous asthenosphere. Plates are mechanically decoupled from each other, although plate margins are in intimate contact. There are relative plates motions of approximately 10 cm a year due to the convection process in the mantle. The boundaries of plates can take three forms : mid-oceanic ridge (where plates are diverging ; accretive or constructive plate margins), trenches (where plates are converging ; destructive plate margins) and transform faults (relative motions of adjacent plates are tangential ; conservative plate margins). Plates are considered to be internally rigid, that is to say : when a stress is applied to a margin of a plate, it is transmitted to its opposite margin with no deformation of the plate interior[6]. The deformation, then, only takes place at plate margins.
At convergent margins, the oceanic plate (the lower plate) is subducted beneath a continental crust (the upper plate). The subduction zone is characterized by an oceanic trench, an overpressure of fluids along the subduction interface, a landward dipping zone of earthquakes (Figure 1)...
In this kind of kinematics, two types of major processes can occur[1] : a compression (type 1 margins, accreting process) and an extension (type 2 margins, subduction erosion process). At type 1 margins, accreting ones, sedimentary material that has been laid down the outer slope, is progressively accumulated to the front of the inner slope. At type 2 margins (21,000 km in global length, all over the world), all incoming sediment is subducted beneath the upper plate and sunk to the viscous asthenosphere.
Up to now, some experimental Sandbox modeling and some global numerical models (Finite Elements methods) have already been made[7]. The goal of such studies is to estimate the amount of solid mass of sediment subducted at convergent ocean margins, that is not frontally accreted.

3. Cellular Automata as an alternative to differential equations in modeling physics

Introduction
In the last two decades, a wide variety of cellular automata applications has been proposed, including modeling of reaction-diffusion systems, hydrodynamics, biological modeling... Sandbox modeling approaches of this geophysical phenomenon and simplicity, efficiency, but also easiness to implement, of models of physics of the granular state[5], have finally convinced us to develop an original model based on fully discrete dynamical systems. Space, time and even dynamical variables are defined to be discrete. Moreover, the simplicity of the computational model means that it is very easy to incorporate different physical effects. We really think that "discrete dynamical systems, in this view, attempt not to simulate specific physical phenomena but rather embody general physical ideas"[9].
As it is simpler to simulate avalanches and self-organized criticality in a sandpile with a one-dimensional cellular automaton rather than with a two-dimensional one, we have first decided to study a one-dimensional model of the *subduction-erosion phenomenon*.

Modeling

Topology : in our model, "space" is a discrete universe, a regular array of sites (cells), as shown in figure 2. Each cell is a vertical portion of "space" the value of which belongs to a finite set. Therefore, we consider a finite set, in one-dimensional

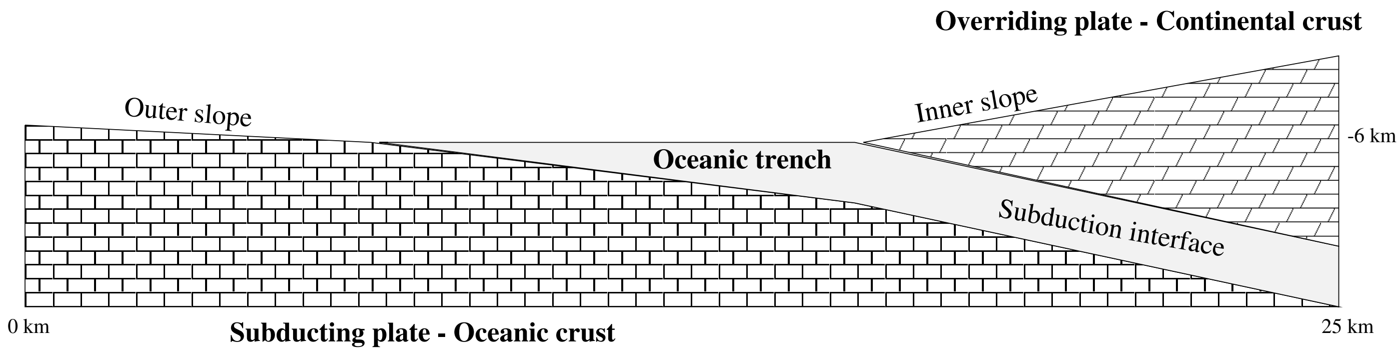

Figure 1: Subduction of oceanic crust beneath continent (8 cm/year, 8^0 dip).

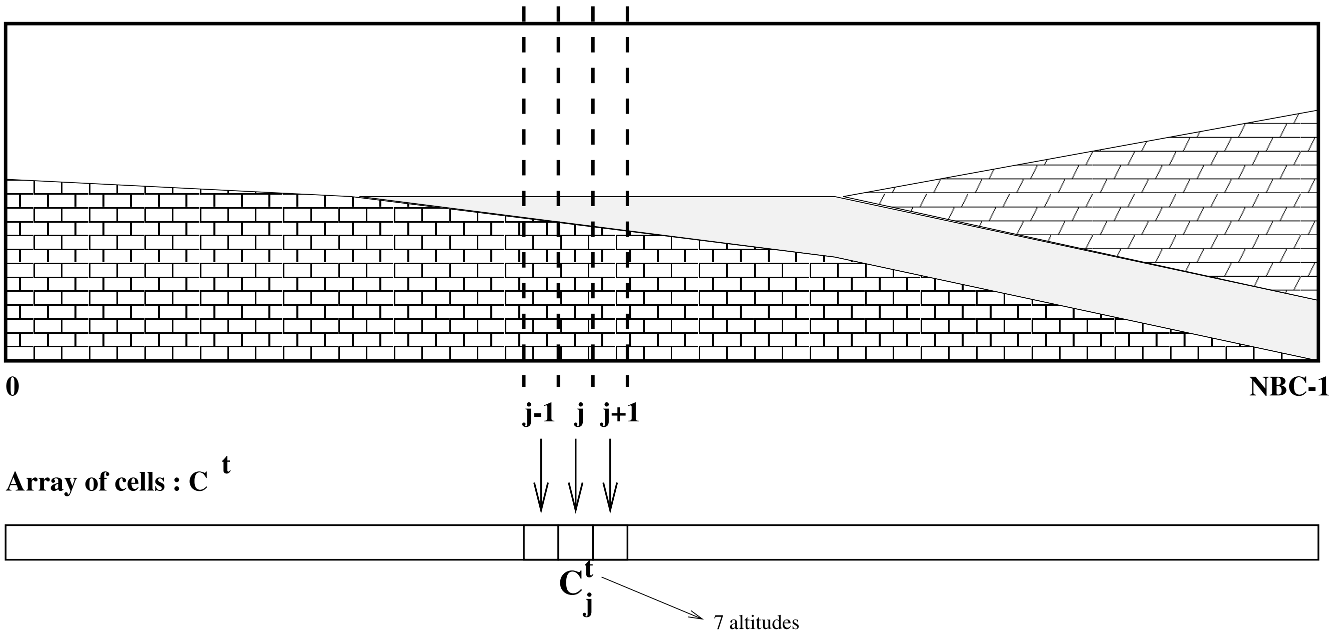

Figure 2: "Space" is a regular array of cells.

space, of finite automata. The state of a cell is determined by a set of seven cross-section thicknesses. Each of those thicknesses is an integer less than the global height.

Dynamics of the discrete system : starting from an initial configuration, the set of cells evolves at each discrete time step according to a local transition (updating) rule. The sampling of the motion is periodic and the update is local, parallel and synchronous. The rule of transition can be seen as a function whose arguments are the states of the cell itself and its neighboring cells, at the previous time step. The evolution of a cell depends only on a local neighborhood of three cells (running cell included).

About our automaton : The subducted lithosphere is mechanically smooth and passes from an almost horizontal level in front of the pit to a constant dip under the volcanic arc (beyond 50-100 km). It is generally estimated that the subduction speed is a constant.

With regard to the boundaries problem, it is necessary to compute separately the cells located at the two limits of the unidimensional automaton (the first introduces material into the system, whereas the last makes possible to eliminate it).

The engine of "our" basal erosion is not the subduction of asperities (such as the underwater mounts, mid-oceanic ridge, grabens. . .) on the oceanic plate. It is rather necessary to take into account overpressures of fluid at the top of the subduction interface, which can induce a hydrofracturation.

Specificity of our global transition function : Our cellular automaton is, in fact, an overlap of three global functions of transition. These three functions of transition can be regarded as generalizations of the one-dimensional Sand Pile Model. They represent three different physical phenomena, themselves, on three quite distinct scales of time. In the circumstances : a dive of the oceanic plate (oblique downward translation under the constraint of the weighty effort exerted by the upper plate), a subcrustal erosion (by hydro-fracturing and overpressures on the outline level of subduction) as well as the subsidences which result from it on all the height from the overlapping plate, and, finally, surface avalanches at the top of the higher plate.

These last phenomena, true rockslide on the surface of the overlapping margin, occur when the local dip of this one is too important.
It is important to distinguish three different scales of time. That of the "instantaneous" phenomena (relative to the other phenomena at least) initially, which occur on a "fast" scale of time (it is the case of the surface avalanches). That of the phenomena "with great width", then, which occur on a "slow" time scale (it is the case of the subduction even of the oceanic margin with the "generation of steps" which is correlated to it, but it is also the case of "ageing" and the subcrustal erosion of the overlapping continental margin).
Lastly, we introduce an "average" scale of time to represent physical phenomena intercalating themselves between the two classes of above mentioned phenomena (it is the case of the general translation of the face of the oceanic margin, of the levelling of the oceanic trench and the subsidences within the overlapping margin).

Possibilities and limits of the model
Our local transition function[8], is able to represent phenomena on a wide time scale such as : a dip of the lower subducted plate (80 km / 1 million years), a landward migration of the front of the upper plate and the trench axis (20 km / 1 million years), a subcrustally erosion of the continental margin basement, an underthrust of sediment material and avalanches at the top of the overriding plate (almost instantaneous phenomena compared with the dip or the landward migration).
On the other hand, in a cellular automaton, physical reality is only approached by simplistic rules of evolution that have to be modified according to the experiment. The physical rules are replaced by rules of evolution. The interpretation of the results can thus be as well as possible only qualitative.

4. Simulation

Development of a new dedicated software
There already exists, in the public domain, software tools making possible to visualize[2] or handle cellular automata. However, it seems us necessary to develop our own platform. Indeed, although very effective and very useful for a two-dimensional simulation, *The Cellular Automata Simulation System*[3], developed around the Cellang language, cannot absolutely be appropriate to us here, since it does not allow us a two-dimensional visualization in the case of a uni-dimensional automaton.
We chose the tandem C and Parallel Virtual Machine[4] library for questions of portability. Thus our application functions as well, except for the performances, on a network of heterogeneous workstations as on a Massively Parallel Processors computer like the CRAY T3E (concerning the processing and the first graphic postprocessing at least).

A parallel implementation on the CRAY T3E computer
The parallel strategy we use is the following one : work and data are distributed among the processor elements. We use a simple and natural one-dimensional domain decomposition : the array of cells has been divided into a number of parts (subdomains of contiguous cells) equal to the number of PEs. After each iteration, solution values on the boundaries of a subdomain need to be exchanged with the adjacent subdomain. We can see that each processor will exchange messages with its left and right neighbors except the first and last ones which have respectively no predecessor and no successor. That's why there is an increase of communication time as the number of processors increases (figure 4).
There is a unified framework for parallel and sequential simulation (speedup measures are consequently more fair).

Parallel algorithm
We call "supervisor" the first of the processes to have been included in the group named "workers".
As we may notice in the program below, there is transmission of an aggregate variable called $Coeff_{Tr}$ between the "slow" global transition function and the "average" global transition function from the dynamic system.
This aggregate variable is recovered at output of the "slow" global transition function. It is then passed in parameter of the "average" global transition function. It makes possible the whole of the cells to take note, immediately and in a synchronous way, of a phenomenon of translation of the oceanic margin.

```
procedure F_global(c,cc,f_local,coeff)
  cc ← c
  Send the values of c_1 and c_length to the
  left and right neighboring processors
  Receive the updated values of c_0 and
  c_length+1 (the "ghost cells") from the
  corresponding processors
  Compute the global boundaries cells (on
  the two boundaries PEs)
  For i ← 1 to length, do
    c_i = f_locale(cc_i-1, cc_i, cc_i+1, coeff)
end
```

Notes :

- in order to optimize the performance of the previous procedure, we have overlapped time of communications by time of computations (non-blocking sending of boundaries values, computation of local data, receiving of updated values from the neighboring PEs, last computations of boundaries cells),
- the "saving condition" of the following program depends on three parameter : whole number of images, period between two images, number of the first image,
- the number of cells must be a multiple of the number of processor elements.

```
program
  PVM initialization
  Join the group "workers"
  If the current process is the supervisor
  then
    Read the files of parameters
    Broadcast the values of parameters to
    all the tasks of the group "workers"
  else
    Receive the values of parameters sent by
    the supervisor
  Let c and cc be two arrays of length + 2
  cells, where length = NBC/nbproc  (NBC ∈ ℕ)
  Initialize the local array c
  do
    F_global(c,cc,f_slow,Coeff_Tr)
```

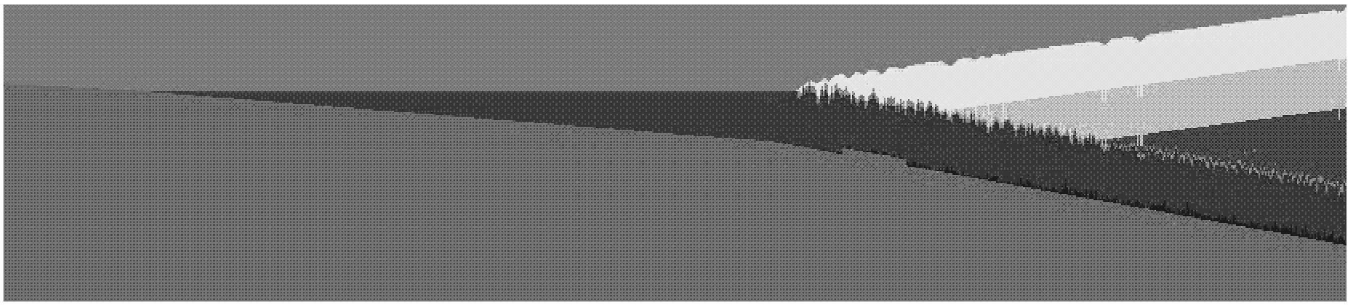

Figure 3: 1100^{th} time step of the motion picture (MPEG format).

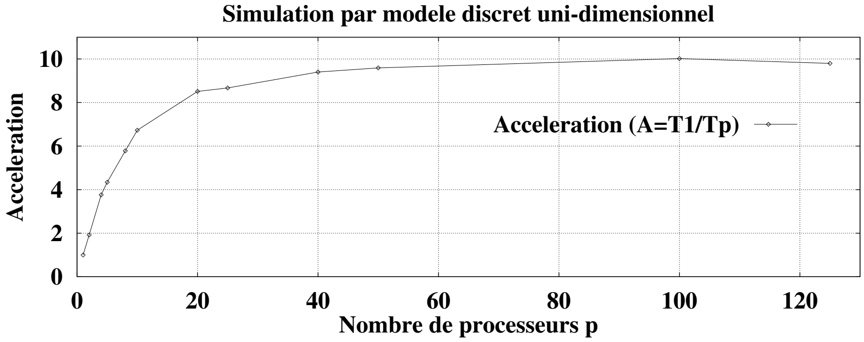

Figure 4: Speedup for a given size of 2-dimensional geometric animation ($1000 * 200$ pixels, 250 *clichés*, 7500 time steps, array of 1000 cells).

```
    The supervisor gather and add all the
    values of CoeffTr distributed on the
    workers
    If the current process is the supervisor
    then
      Broadcast the value of CoeffTr to all
      the tasks of the group "workers"
    else
      Receive the value of CoeffTr sent by
      the supervisor
    do
      Fglobal(c,cc,faverage,CoeffTr)
      do
        Fglobal(c,cc,ffast,0)
      until "fast condition" is achieved
    until "average condition" is achieved
    If "saving condition" is achieved then
      The supervisor gather all the locals
      arrays distributed on the workers
      If the current process is the
      supervisor then
        save the current image
  until "slow condition" is achieved
exit PVM
```

5. Results, visualization and future improvements

A two-dimensional motion picture is available at http://quartz.dgs.jussieu.fr:8080/ANIM/ using a MPEG-player software. It has been made using the *convert* tool of the ImageMagick software. These images were generated, for the processing, on a CRAY T3D with 256 processors DEC ALPHA EV5, and, for postprocessing, on a four-processors Silicon Graphics Power Challenge XL.

As shown in the figure 3, the dynamical behavior of our model is proper. We are expecting from a further improvement of the two dimensional cellular automaton we are developing, that it will also represent a frontal accretion, a subcrustally underplating and an internal fluid overpressure causing hydrofracturing effects in the upper plate.

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