Numerical Modelling of Carbonate Platforms and Reefs: Approaches and Opportunities

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ABSTRACT

This paper compares different computing procedures that have been utilized in simulating shallow-water carbonate platform development. Based on our geological knowledge we can usually give a rather accurate qualitative description of the mechanisms controlling geological phenomena. Further description requires the use of computer stratigraphic simulation models that allow quantitative evaluation and understanding of the complex interactions of sedimentary depositional carbonate systems. The roles of modelling include: (1) encouraging accuracy and precision in data collection and process interpretation (Watney et al., 1999); (2) providing a means to quantitatively test interpretations concerning the control of various mechanisms on producing sedimentary packages; (3) predicting or extrapolating results into areas of limited control; (4) gaining new insights regarding the interaction of parameters; (5) helping focus on future studies to resolve specific problems. This paper addresses two main questions, namely: (1) What are the advantages and disadvantages of various types of models? (2) How well do models perform? In this paper we compare and discuss the application of five numerical models: CARBONATE (Bosence and Waltham, 1990), FUZZIM (Nordlund, 1999), CARBPLAT (Bosscher, 1992), DYNACARB (Li et al., 1993), PHIL (Bowman, 1997) and SEDPAK (Kendall et al., 1991). The comparison, testing and evaluation of these models allow one to gain a better knowledge and understanding of controlling parameters of carbonate platform development, which are necessary for modelling. Evaluating numerical models, critically comparing results from models using different approaches, and pushing experimental tests to their limits, provide an effective vehicle to improve and develop new numerical models. A main feature of this paper is to closely compare the performance between two numerical models: a forward model (CARBONATE) and a fuzzy logic model (FUZZIM). These two models use common data sets, thereby permitting one to obtain similar results (Norlund, 1999). The geological model we use to test the validity of these two numerical models comes from a Holocene coral reef located at the island of Mauritius, Indian Ocean. A detailed description of the stratigraphy and general geological setting is given by Montaggioni and Faure (1997).
pattern and facies distribution obtained are similar to the Holocene reef section used as an example (Dalmasso, 2001). The results here include: (1) an enhanced understanding of similarities and differences between models and modelling philosophies; (2) critical evaluation of applications and assessment of how models have been utilized; and (3) improvements and refinements in techniques for generating and describing model inputs and outputs. The models have various drawbacks, most of which are due to the lack of knowledge about the systems we are trying to model, but also due to the incapability to make effective use of available knowledge. There is no perfect system for modelling carbonate platforms. Numerical modelling can help with both of these problems because it provides effective methods for making qualitative data available for numerical modelling and allows effective exploration of the behaviour of systems through experimentation thereby increasing our understanding.

INTRODUCTION

In the last two decades, numerical modelling has led to a bloom of quantitative models related to the filling of sedimentary basins (Cross and Harbaugh, 1989; Perlmutter et al., 1999; Watney et al., 1999). To address models and their evolution, a first question to pose is: What is a model? In simplest form, models are intellectual devices for making natural processes easier to understand (Lehr, 1990). Based on our geological knowledge, we can usually give a rather accurate qualitative description of the mechanisms controlling geological phenomena. Thus models are limited by our perceptions and understanding.

Making models requires that one derive the input for use in model runs. These data are independent of the model itself, but are used for predicting what should happen in a real situation on the basis of the numerical situation that we feed the model (Lehr, 1990). A second aspect of making models is the testing component, where model predictions are compared with observational data or with a geological model. This aspect leads directly to evaluation of the viability of models.

Models should be viewed with two levels of confidence (Watney et al., 1999): (1) models as learning tools for general understanding or hypothesis testing; and (2) models as status calculations for answering specific questions. Several sources of error may be present that may account for limited fidelity of predictions: (1) model error in the mathematical structure; (2) measurement error or uncertainty in model parameters; and (3) variability of complex natural systems. Bad data imply bad results. Without good data, an appreciation of how models work, or what geological conditions models use, their usefulness and reliability are all in question. Within the context of the search for a better understanding of geological phenomena, it is crucial to have good geological observations.

Many models have been constructed about geological systems. Carbonate sedimentation relates to partly self-controlling, homeostatic, evolutionary systems depending on multiple interactions and are hard to predict. That is why models are used more and more in simulating aspects of carbonate sedimentation (Aigner et al., 1990; Bosence and Waltham, 1990; Bice, 1988; Grauss and Macintyre, 1989). This paper compares different computing procedures that have been utilized in simulating the development of shallow-water carbonate platforms and reefs.
CLASSIFYING MODELS

Using available stratigraphic modelling packages, the first part of this paper is based on the performance evaluation of the various carbonate modelling models.

Numerical models may be classified in two categories: forward or inverse models. In forward stratigraphic models, stratigraphic data are simulated through time using a predefined set of input parameters that are usually chosen on the basis of geological knowledge to obtain a close fit between the numerical and the geological models. Calibration is done by repeatedly running models, comparing their output with geological data, and modifying the parameters to minimize the differences between the model and geological reality.

Inversion is a quantitative method of obtaining inferences from empirical observations (Lessenger and Lerche, 1999). From a stratigraphic data set, the inverse model extracts values of the processes that operated to produce an observed stratigraphy (Figure 1). These processes are mathematically represented within a forward stratigraphic model used by the inverse model. The inverse model systematically searches for the set of forward model simulations that best match a set of stratigraphic observations. These parameters must be used for forward modelling in order to predict stratigraphic attributes in places where data are lacking. The main differences between inversion and other methods is that an inverse method gives information about accuracy, error and uncertainty of the results (Bornholdt et al., 1999; Lessenger and Lerche, 1999).

Because carbonate modelling is in a period of growth, scientists are still experimenting with a wide variety of approaches. Models of current use can be classified either as stochastic or deterministic. Stochastic simulations model the dynamic interaction of processes (e.g. input) to create a known or unknown response; that is, a process may or may not result in the same response each time, depending on an element of chance. In contrast, deterministic simulations involve experiments that model the dynamic interaction of processes (e.g. input) to create known, defined responses.

The number of spatial dimensions involved in numerical modelling ranges from one to three. Most models presented herein are 2-D (two-dimensional) in their formulation. The growth in conceptual understanding of 3-D (three-dimensional) geologic systems and processes through interpretation of increasingly large databases, rapid increases in cost-effective computer speed and memory, and increasing demand...
for more precise results and predictions from modelling, allows and favours development of models in 3-D.

**METHODS**

Designing models for natural or physical processes commonly involves the task of estimating and adjusting large sets of parameters. Discrimination and quantification of controlling parameters may be obtained from numerous feedbacks between field observations and numerical modelling (Figure 2). This double approach is really an optimization tool, which allows a better understanding of the geological processes. Numerical modelling requires knowledge of principal parameters used in modelling. Field analysis is undertaken in order to develop a geological model (Figure 2) based on facies and depositional environments, diagenesis, biological associations, sedimentary and biological structures, which allow paleodepths to be estimated along with other relevant parameters. Biostratigraphical analysis leads to an accurate estimation of the time involved. After having made a detailed analysis of the geological model conditions and processes, simulations may be developed.

![Diagram](image)

**Figure 2.** Establishment of a geological model and parameterization of main geological data. Better understanding of controlling parameters needs feedback between geological and numerical models.

The set of estimated input parameters of the geological model (e.g. antecedent topography, sea-level change or eustasy, subsidence, time) are parameterised (Figure 3). The influence and validity of variables on a simulation run can be examined through qualitative comparisons, sensitivity and error analyses (Watney et al., 1999).
Qualitative analysis includes a visual comparison of model runs with a geological model. Sensitivity analysis involves systematic variation of parameters to assess their interaction and expected value or range of possible values. Usually values of the parameters are modified and adjusted until one obtains an accurate numerical model consistent with the geological model. When the numerical model reproduces precisely the geometry and facies distribution observed in the field, the model is validated (Figure 3). These numerous feedbacks allow one to gain a better quantification of parameters, which cannot be evaluate directly from geological observations, such as erosion, carbonate production rates and pelagic sedimentation.

Figure 3. Framework for numerical modelling. A given model should be accepted when comparison between two models gives reliable results. The influence and validity of variables on a simulation runs can be examined through qualitative comparisons, sensitivity and error analysis. Iterative simulations optimized quantification of controlling parameters.

Thus, optimised quantification of controlling parameters may be integrated in a forward model using an inverse procedure in order to quantify model parameter fitting. Furthermore, it is important to remember that modelling is an iterative process that can be forever improved.
### Table 1. Comparison between accuracy of parameters programmed in the following models: CARBONATE 7.0, CARBPLAT, DYNACARB, FUZZIM, PHIL and SEDPAK

<table>
<thead>
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<th>Simulation</th>
<th>CARBONATE</th>
<th>CARBPLAT</th>
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<th>FUZZIM</th>
<th>PHIL</th>
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(A) = absent, (-) = low accuracy, (+) = medium accuracy and (++) = high accuracy.
NUMERICAL MODELLING OF NERITIC CARBONATE SYSTEMS

Numerical models allow one to simulate (1) carbonate sedimentation, with CARBONATE (Bosence and Waltham, 1990), CARBPLAT (Bosscher, 1992), KANMOD (French and Watney, 1997), STRATAGEM (Bosscher and Newall, 1997); (2) siliciclastic and carbonate sedimentation SEDPAK (Kendall et al., 1991), FUZZIM (Nordlund, 1999), PHIL (Bowman, 1997). Models simulating carbonate sedimentation have been created in order to answer to specific questions, concerning for example:

- deposition of elementary sequences – Goldhammer et al. (1993), Read et al (1991), CYCOPATH (Demicco, 1998), Read (1998), Burgess et al. (2000); Chang et al. (2000); Harper Jr (2000);
- faulting – den Bezemer et al. (1999), Cowie et al. (2000), De Donatis (2001);
- tidal currents – Nakayama et al. (this volume);

In the present paper six numerical models are compared: CARBONATE (Bosence and Waltham, 1990), FUZZIM (Nordlund, 1999), CARBPLAT (Bosscher, 1992), DYNACARB (Li et al., 1993), PHIL (Bowman, 1997) and SEDPAK (Kendall et al., 1991). CARBONATE, CARBPLAT, DYNACARB, PHIL and SEDPAK are deterministic models. FUZZIM is the only stochastic model used here. The reliability of the models CARBONATE, DYNACARB, FUZZIM and SEDPAK was estimated from numerous tests that we made. The CARBPLAT and PHIL models were estimated only from the literature. The availability of different models addresses two main questions, namely: (1) what are the advantages and disadvantages of various types of models? (2) how well do models perform?

The comparison, testing and evaluating of these models permits one to gain a better knowledge and understanding of controlling parameters of carbonate platform development that are necessary for modelling. Evaluating numerical models, critically comparing results from models using different approaches, and pushing experimental tests to their limits, provide an effective vehicle to improve and develop new numerical models. A comparison of CARBONATE, CARBPLAT, DYNACARB, FUZZIM, PHIL and SEDPAK is shown in Table 1. The main characteristics of each model are analysed below.

CARBONATE

Main characteristics: CARBONATE is a 2-D, geometric model designed for simulating carbonate stratigraphy (Bosence and Waltham, 1990; Bosence et al., 1994; Aurell et al., 1998). The main input parameters are the rate of carbonate production, rate of erosion, the depth of deposition, textural characteristics of the sediments, and relative sea level changes. The neritic production on the platform and the sediment supply from pelagic organisms are each modelled by a distinct curve. The curves are
user-defined. The platform production depends on the rate of erosion and water depth. Pelagic sedimentation and shallow-water carbonate production vary with time. Marine erosion is simulated with an exponential algorithm. The sediment deposition and slope geometry are modelled by a diffusion algorithm.

Advantages: The program is one of the most realistic among carbonate 2-D modelling reviewed here.

Disadvantages: There are a number of disadvantages related to the absence of parameters such as isostacy, thermal subsidence, crustal flexure, interaction of porosity and permeability, compaction, diagenesis. In addition, possible changes in carbonate production across a platform cannot be reproduced. Subsidence is not easy to simulate. Regarding the erosion parameter, a problem of algorithm formulation exists.

CARBPLAT
Main characteristics: CARBPLAT is a 2-D, geometric modelling program. The main parameters taken into account are carbonate production, slope sedimentation, sea level change, development of platform geometry and subsidence. Bosscher (1992) had an interesting approach of modelling slope evolution and carbonate production. The latter is regarded as dependent on light intensity required for photosynthesis, since scleractinian corals are assumed to be the main reef-building organisms. The slope develops according to the angle of repose. Water-depth appears to be the most important factor controlling carbonate production. CARBPLAT is designed to model reef complexes only.

Advantages: CARBPLAT allows to realistically simulate the slope angle, e.g. the angle of repose of sediments with different grain sizes. The carbonate production decreases with increasing depth as a function of the reducing photosynthetic activity.

Disadvantages: Since CARBPLAT assumes that scleractinian corals are the main reef-builders; it cannot be applied successfully to carbonate environments that are dominated by different groups of non-symbiotic organisms. CARBPLAT does not simulate facies and palaeowater depths. The final geometry is defined only by time lines.

DYNACARB
Main characteristics: The main parameters included light, salinity, sea surface temperature, dissolved oxygen contents, sea-level changes (Li et al., 1993).

Advantages: DYNACARB simulates the effects of physical and chemical conditions on the rates of carbonate deposition. Carbonate production is dependent on light, salinity, dissolved oxygen, sea surface temperature and latitude.

Disadvantages: DYNACARB does not include irregular subsidence, diagenesis, pelagic production, depositional depth and sediment texture. Given that the mathematical formulations of parameters (such as salinity, temperature...) are not very easy to obtain, difficulties arise concerning the reconstruction of platform geometry.

FUZZIM
Main characteristics: FUZZIM generates 2-D and 3-D stochastic models and can
simulate carbonate, siliciclastic and mixed depositional environments (Nordlund, 1999). This program is based on a fuzzy logic approach to include quantitative geological data and simulates large-scale marginal deposition.

**Advantages:** A quantitative description using mathematical functions, however, is often much more problematic because we usually do not have the detailed knowledge required. There also have problems incorporating the uncertainty inherent in natural systems. Fuzzy rules simulated are based on our field knowledge about the system we want to model, or, as in the geological case simulated here, on both knowledge about the system and data.

**Disadvantages:** In its 3-D formulation, FUZZIM simulates depositional facies belts parallel to the coastline. This picture is more restrictive when using a 3-D view.

**PHIL**

**Main characteristics:** PHIL (Bowman, 1997; Bowman and Vail, 1999) is a 2-D geometric model and simulates deposition of carbonate, siliciclastic and mixed sediments. This model is build upon concepts of sequence stratigraphic developed by the Vail/EXXON school. PHIL permits one to simulate stratal geometries and lithofacies distribution. The main factors appreciated are tectonic and crustal subsidence, sea level change, compaction, carbonate and pelagic production and erosion.

**Advantages:** PHIL includes flexure loading, compaction and erosion. This model express tectonic processes on passive margins and foreland basins. PHIL determines lithologies (corresponding to depositional environments) and transport mechanisms.

**Disadvantages:** PHIL is a very complex modelling tool and provides a tool to simulate only long-term system.

**SEDPACK**

**Main characteristics:** SEDPAK generates 2-D geometric models and can simulate sedimentation in carbonate, siliciclastic and mixed environments (Kendall et al., 1991). Accommodation, subsidence, sediment production and sea-level change are interactive. The carbonate production depends on water depth and on the basin slope angle.

**Advantages:** SEDPAK can quantify irregular subsidence rates and eustatic movements. It provides a good tool to simulate long-term functioning of systems.

**Disadvantages:** It is not possible to model diagenesis and crustal rigidity and time spans less than 1 Ma. This model requires too many parameters, such as crustal rigidity, thermal gradient, oil maturation and isostasy.

From the foregoing, it appears that FUZZIM, CARBONATE, PHIL and SEDPAK are the most reliable models for carbonate systems, although the development of carbonate platforms is controlled by numerous auto- and allocyclic parameters. Managing too large a number of parameters reduces the reliability of models. We believe that it is important to distinguish two groups of parameters, which may be input from two distinct model packages: (1) the first group includes isostacy, thermal subsidence, crustal flexure, porosity, permeability… (2) the second package includes carbonate production, pelagic sedimentation, transport (tidal and marine currents),...
deposited and redeposited sediments, salinity, temperature, light, fluvial storage… The first group provides a tool to understand the development of geological systems at large scale, while the second group allows the development of sedimentary systems to be understood at a small scale and to better constrain sedimentary processes interacting during deposition. So, evaluating these six models leads to classify PHIL and SEDPAK models into the two model packages, and CARBONATE, CARBPLAT, DYNACARB and FUZZIM in the second category. As this paper is focused on the modelling of shallow-water carbonate platforms, we have decided to use CARBONATE and FUZZIM models. This choice is based on two principal features: (1) CARBPLAT and DYNACARB appears to be more restrictive in carbonate facies modelling; (2) geological models have been already used to test the ability and the complementarity of CARBONATE and FUZZIM models; (a) reefal Miocene system on Mallorca (Nordlund, 1999), (b) Tithonian/Berriasian Basse-Provence Platform (Southeast France) (Dalmasso, 2001), and (c) Great Barrier Reef of Australia (Dalmasso, 2001). The relevant reconstructions are quite consistent with the geological data. Thus one of the main objectives of this paper is to closely compare the results obtained from the two forward models CARBONATE (deterministic and geometric model) and FUZZIM (stochastic model). Such an approach must allow an optimisation of the parameters used for modelling. The carbonate system we use to test the validity of these two numerical models is that of the Holocene coral reef located at Mauritius Island, Indian Ocean.

**Figure 4.** carbonate production functions for shallow–water carbonate sedimentation. (a) Sedimentation rates expressed in dimensional units, showing the range of rates used, and (b) rates normalized to the maximum showing variation with depth. GC: Gildner and Cisne, 1990; Bice: Bice, 1991; BS: Bosscher and Schlager, 1992; R: Read et al, 1991; Demicco: Demicco, 1998 (after paola 2000)
PRINCIPAL INPUT PARAMETER: CARBONATE PRODUCTION

One of the most important parameters in simulating carbonate systems is carbonate production, which is the result of allochthonous sediment supply and in-situ production, less export through bypassing or erosion. Carbonate production rates vary greatly in magnitude as a response to various controlling factors. A common feature of current models is that rates of carbonate production depend primarily on depth (Figure 4). Since light attenuation is the basic cause of the depth-dependence of carbonate production, more analytical forms can be obtained by relating carbonate sedimentation to known light functions (Bice, 1991; Enos, 1991; Bosscher and Schlager, 1992; Paola, 2000). Additional driving factors of carbonate production are turbidity, sea surface temperature and rates of sea-level rise (Watney et al., 1991). Lerche et al. (1987) explored the impact of some major controls on carbonate production rates and modelled their influence on the anatomy of carbonate bodies. They introduced depth- and distance-dependent functions for food supply, light («photosynthetically active radiation»), temperature, salinity and oxygen concentrations. A regime of positive depth dependence is included by Demicco and Spencer (1989), Bosence and Waltham (1990), Read et al. (1991) and Demicco (1998). These models, and that of Gildner and Cisne (1990), express a strongly decreasing production function below a depth of maximum production (Figure 4). Depths of maximum carbonate production range typically within a few metres. The increasing-production regime is absent from the semi-empirical reef model of Bosscher and Schlager (1992).

Accumulation rates were generally calculated by dividing sequence thickness by incremental duration (Enos, 1991; Bosscher, 1992). These rates therefore are underestimated, because non-depositional or erosional events may have occurred. Tables 2 and 3 present rates of carbonate deposition in various marine environments through time. However, most 2-D models simulate a constant carbonate production rate on a platform. They do not distinguish allochthonous and reworked deposits, which are integrated into the accumulation rates. Lateral displacement of sediments is necessary for progradation of the slopes of carbonate platforms. Numerical models have accounted for such features by including geometric treatment of sediment redistribution due to physical transport.

APPLICATION OF TWO NUMERICAL MODELS: CARBONATE AND FUZZIM

The choice of combining CARBONATE and FUZZIM models in simulations of carbonate platform development allows one to determine the accuracy or the level of match of the output with field observations. If the evaluation of a particular geological process were the desired outcome of a given simulation, opting for a numerical model that is able to express this process would be a better choice than using the other model. When one model appears limited in its applications, the second might be used in order to answer the question asked. The utilization in a complementary way of both models permits one to quantify different parameters that would not be estimated based on the use of a single model.

Carbonate Model

CARBONATE 7.0 was developed by D. Bosence, D. Waltham, S. Hardy and Y. Hague at Royal Holloway University of London (Bosence and Waltham, 1990; Bosence et al., 1994; Aurell et al., 1998). CARBONATE is a 2-D simulation for Unix systems and
Macintosh computer. This model is used to generate synthetic stratigraphies closely replicating real stratigraphies that, through modelling, are attempting to bracket the rates of the different controlling processes operating in carbonate platforms. The simulation starts from an initial topography and reproduces the depositional geometry in a series of time steps forward to the final geometry (Figure 5).

### Table 2: Carbonate production rates in various recent depositional environments

<table>
<thead>
<tr>
<th>Location</th>
<th>Rate</th>
<th>Period</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Supratidal environment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average rate</td>
<td>3 mm.ka⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sebkhas environment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Persique Gulf</td>
<td>0.3 to 1 m.ka⁻¹</td>
<td>Holocene</td>
<td>Purser (1973)</td>
</tr>
<tr>
<td>Persique Gulf</td>
<td>1 m.ka⁻¹</td>
<td>Holocene</td>
<td>Wilson in Enos (1991)</td>
</tr>
<tr>
<td><strong>Intertidal environment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average rate</td>
<td>0.4 to 1 m.ka⁻¹</td>
<td>Holocene</td>
<td>Schlager (1981)</td>
</tr>
<tr>
<td>Trucial Coast Barrier (Florida)</td>
<td>0.2 m.ka⁻¹</td>
<td>Holocene</td>
<td>Tucker and Wright (1990)</td>
</tr>
<tr>
<td>Cap Sable (Florida)</td>
<td>11 m.ka⁻¹</td>
<td>?</td>
<td>Gebelein in Enos (1991)</td>
</tr>
<tr>
<td>Netherlands</td>
<td>10 to 20 m.ka⁻¹</td>
<td>modern</td>
<td>Kirkhan (1998)</td>
</tr>
<tr>
<td>Abu Dhabi</td>
<td>10 m.ka⁻¹</td>
<td>Holocene</td>
<td>Schlager (1981)</td>
</tr>
<tr>
<td>Oolitic complex (Bahamas)</td>
<td>0.5 to 2 m.ka⁻¹</td>
<td></td>
<td>Belpiero et al., in Enos (1991)</td>
</tr>
<tr>
<td>Oolitic complex</td>
<td>2 m.ka⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Algal zone (Bahamas)</td>
<td>2 m.ka⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Algal zone (Australia)</td>
<td>0.9 to 1.5 m.ka⁻¹</td>
<td></td>
<td>Boreen and James (1993)</td>
</tr>
<tr>
<td>Stromatolites (Shark Bay)</td>
<td>10 m.ka⁻¹</td>
<td>Holocene</td>
<td>Logan et al. (1974)</td>
</tr>
<tr>
<td>Stromatolites (Cap Sable, Florida)</td>
<td>5 m.ka⁻¹</td>
<td></td>
<td>HoloceneGebelein in Enos (1991)</td>
</tr>
<tr>
<td>Stromatolites (Bermudes)</td>
<td>1.46 m.ka⁻¹</td>
<td>24 hours</td>
<td>Kukal in Enos (1991)</td>
</tr>
<tr>
<td><strong>Reefal environment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mauritius Island</td>
<td>1.5 to 9 m.ka⁻¹</td>
<td>Holocene</td>
<td>Montaggioni (1981)</td>
</tr>
<tr>
<td>New-Caledonia</td>
<td>1.5 to 6.4 m.ka⁻¹</td>
<td>Holocene</td>
<td>Cabioch et al. (1995)</td>
</tr>
<tr>
<td>Mayotte Island</td>
<td>4.3 to 7 m.ka⁻¹</td>
<td>Holocene</td>
<td>Camoin et al. (1997)</td>
</tr>
<tr>
<td>Tahiti Island</td>
<td>9.3 to 20.6 m.ka⁻¹</td>
<td>Holocene</td>
<td>Montaggioni et al. (1997)</td>
</tr>
<tr>
<td>Great Barrier Reef of Australia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average rate</td>
<td>8 to 12 m.ka⁻¹</td>
<td>Holocene</td>
<td>Davies and Hopley (1983)</td>
</tr>
<tr>
<td>Windward coral reef</td>
<td>2 to 10 m.ka⁻¹</td>
<td>Holocene</td>
<td>Davies et al. (1985)</td>
</tr>
<tr>
<td>–branching corals</td>
<td>1 to 16 m.ka⁻¹</td>
<td>&quot;</td>
<td>Davies and Hopley (1983)</td>
</tr>
<tr>
<td>–massive corals</td>
<td>&lt; 7 m.ka⁻¹</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>–coralline red algae</td>
<td>2 m.ka⁻¹</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>–rubble reef zone</td>
<td>7 to 18 m.ka⁻¹</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>Leeward coral reef</td>
<td>3 to 16 m.ka⁻¹</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>(branching coral)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fringing coral reef</td>
<td>1 to 4 m.ka⁻¹</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>
This model has the capability for simulating rates of carbonate production and pelagic sedimentation, erosion, wave base, offshore transport of coarse to fine-grained sediments, and the coarse/fine ratio. The modelled geometries are expressed from ‘pseudo-facies’ (Figure 5), which, in turn, are the reflection of depositional depths, depositional processes (deposited vs. redeposited sediments) and depositional dip angles. Between sea level and a defined wave-base (e.g. fair-weather wave base, see Figure 6) deposits are reworked and redeposited along the modelled section; they are referred to as ‘redeposited’ sediment (Figure 6). This removed material is identified as ‘coarse’ in the case of sand- and gravel-sizes sediments, and ‘fine’ in the case of clay- and silt-sized particles. Because coarse- and fine-grained sediments are transported respectively different distances, redeposition is considered to occur at exponentially decreasing rates from a sediment source.

Table 3: Carbonate production rates of ancient carbonate platforms

<table>
<thead>
<tr>
<th>Location</th>
<th>Rate</th>
<th>Period (Ma)</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical to subtropical platforms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cretaceous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basse-Provence Platform</td>
<td>0.1–0.4 m.ka⁻¹</td>
<td>Tithonian/Berriasian = 13</td>
<td>Dalmasso (2001)</td>
</tr>
<tr>
<td>(Southeast France)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urgonian (Provence, France)</td>
<td>0.05 m.ka⁻¹</td>
<td>12</td>
<td>Masse and Alleman in Bosscher (1992)</td>
</tr>
<tr>
<td>Bahamas (Upper Cretaceous)</td>
<td>0.04 m.ka⁻¹</td>
<td>100</td>
<td>Tucker and Wright (1990)</td>
</tr>
<tr>
<td>Golden Lane Platform</td>
<td>1.4 m.ka⁻¹</td>
<td>22</td>
<td>Wilson in Bosscher and Schlager (1992)</td>
</tr>
<tr>
<td>Jurassic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haynesville Formation, Texas</td>
<td>0.1 m.ka⁻¹</td>
<td>2</td>
<td>Sarg (1988)</td>
</tr>
<tr>
<td>Morocco platform</td>
<td>0.09 m.ka⁻¹</td>
<td>19</td>
<td>Ranke et al. in Bosscher and Schlager (1992)</td>
</tr>
<tr>
<td>Caucasian</td>
<td>0.16/0.17 m.ka⁻¹</td>
<td>Oxfordian</td>
<td>Wilson in Bosscher and Schlager, (1992)</td>
</tr>
<tr>
<td>Paris Basin</td>
<td>0.01 m.ka⁻¹</td>
<td>Callovian</td>
<td>Gaumet et al. (1996)</td>
</tr>
<tr>
<td>Paris Basin</td>
<td>0.01/0.05 m.ka⁻¹</td>
<td>Bathonian</td>
<td>Gaumet et al. (1996)</td>
</tr>
<tr>
<td>Iberian Basin</td>
<td>0.16/0.20 m.ka⁻¹</td>
<td>Kimmeridgian</td>
<td>Aurell et al. (1998)</td>
</tr>
<tr>
<td>Trias</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dolomites, Italia</td>
<td>0.3 to 0.5 m.ka⁻¹</td>
<td>Lower Carnian = 4</td>
<td>Schlager (1981)</td>
</tr>
<tr>
<td>Latemar platform (Italia)</td>
<td>0.15 m.ka⁻¹</td>
<td>18</td>
<td>Goldhammer and Harris (1993)</td>
</tr>
<tr>
<td>Pleistocene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Great Barrier Reef (Australia)</td>
<td>6 m.ka⁻¹</td>
<td>0.7</td>
<td>Dalmasso (2001)</td>
</tr>
<tr>
<td>Temperate platform</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>0.01/0.05 m.ka⁻¹</td>
<td>Cenozoic</td>
<td>Nelson (1978)</td>
</tr>
<tr>
<td>Australia</td>
<td>0.02/0.05 m.ka⁻¹</td>
<td>Oligo-Miocene</td>
<td>Boreen and James (1993)</td>
</tr>
<tr>
<td>Quebec</td>
<td>0.14 m.ka⁻¹</td>
<td>upper Ordovician</td>
<td>Lavoie (1995)</td>
</tr>
</tbody>
</table>
Numerical Modelling of Carbonate Platforms and Reefs: Approaches and Opportunities

Figure 5. Flow diagram for computer program CARBONATE 7.0.

Figure 6. Sedimentary model showing a CARBONATE simulation with higher neritic carbonate production, wave erosion and resedimentation (modified, from Aurell et al., 1998).
Fuzzim Model
This model is a 2-D/3-D stratigraphic program written in fuzzy logic for Macintosh, developed by Nordlund and Silfversparre (1994) at Uppsala University (Sweden). A comprehensive description of Fuzzy logic is given in Nordlund (1996, 1999). Here we give only a short description of the process for creating a fuzzy system in order to simulate the Holocene coral reef at Mauritius Island.

Fuzzy logic is based on the concept of fuzzy sands. Fuzzy sands are those that allow one to define a range between 0 and 1, regarded as «true» values (Figure 7). It relies on IF/THEN rules, so-called fuzzy rules. These may involve the logic operators AND and OR (conjunction and disjunction) combining two or more sands in the premise. A simple example could be the following system: «IF shallow THEN deposit_much AND carb_sand» (Figure 7).

**Figure 7.** Graphic representation of evaluation of a fuzzy rule based on fuzzy sets.

The given carbonate production curve (Figure 8) is a suitable starting point for constructing a fuzzy system. The easiest way of recasting the curve into a fuzzy system is to simply describe it into words, and then extract the rules directly from this qualitative description. Given that carbonate is produced mainly in shallow-waters, carbonate production decreases as depth increases (Figure 8). Furthermore, erosion may take place at the surface.

The concepts of ‘depth (shallow, intermediate depth and deep for example), at_surface, erosion and carbonate production rates, grain size’ are defined by the fuzzy sets, as explained above. If some general assumptions about grain sizes vs. depth are added, then some rules can be extracted as follows:

1. IF land THEN erode_little
2. IF at_surface THEN erode_some
3. IF shallow THEN deposit_much AND carb_sand
4. IF deep THEN deposit_some AND carb_mud.

FUZZIM model allows one to produce pseudo-facies, the colours of which represent lithologic composition (carbonate, siliciclastic, reef), grain size, depositional depths, porosity, and accommodation…
Figure 8. Examples of fuzzy sets defined on the basis of the qualitative description of carbonate production curve (modified, from Nordlund, 1999).

Figure 9. Location of the studied reef area on the western coast of Mauritius (Western Indian Ocean) (a). The rectangular box shows the surface biozonation and locations of the three boreholes S1, S2 and S3 (b) (modified, from Montaggioni and Faure, 1997).
A CASE STUDY: A HOLOCENE CORAL REEF AT MAURITIUS ISLAND
Geological and stratigraphical setting
Applying a numerical modelling to a Holocene coral reef from Mauritius Island (Western Indian Ocean, Figure 9) enables us to show how numerical models can be used to quantify reef growth. The dataset used in the present study comes from previous works Montaggioni (1978; 1981) and Montaggioni and Faure (1997). Assuming that the subsidence of Mauritius Island was negligible (0.03 mm.year\(^{-1}\) for the past 125 kyr; Montaggioni, 1978), compared to the rate of Holocene sea-level rise (4 mm.yr\(^{-1}\); Montaggioni and Faure, 1997), rapid increase in accommodation is considered to be mainly controlled by eustatic changes. Thus, the studied fringing reef at Pointe-au-Sable (Figure 9) was used to examine the effects of Holocene sea-level rise on coral growth. This reef is about 1000 m wide and comprises a forereef slope (30 m maximum depth), a narrow reef crest and a very shallow backreef zone (1 to 5 m maximum depth). Three cores were drilled through the major reef-top biozones (Figure 9).

Parameterization of geological data
The main parameters used in modelling are the following: time, antecedent topography, sea-level curve, neritic carbonate production, erosion and pseudo-facies (depth of deposition).

Time
The phase of reef initiation started approximatively at 7000 \(^{14}\)C years B.P. (Montaggioni and Faure, 1997). In numerical models, black vertical lines are 1000 years increment time lines.

Antecedent topography
The cores extracted show that the reef has a maximum thickness of 20.3 m and has developed on weathered basaltic bedrock. The basaltic topography (Figure 10) is locally capped by Pleistocene reefal deposits, 2.4 m in maximum thickness and partially altered by meteoric diagenesis.

Figure 10. Cross-section of Pointe-au-Sable reef along the core-hole transect, extending from forereef to backreef zones. The position of the four coral assemblages identified and the time–growth surface lines (in 1000 year intervals) are shown (modified from Montaggioni and Faure, 1997).
Sea-level changes curve
The sea-level curve indicates that the position of sea level at 7500 years B.P. was around 18 m below present sea level. Sea level rose at an average rate of 4 m.ka\(^{-1}\) and stabilized close to its present position at about 2500 years B.P.

Parameterization of coral assemblages
In the cores, on a generic to specific level scleractinian and non-scleractinian corals were identified (Montaggioni and Faure, 1997). Their depth and water-energy requirements were defined by analogy with the distribution patterns of their modern analogs. Four major coral facies have been recognized (Figure 10):

(I) robust branching coral assemblage dominated by robust branching acroporids. By reference to the modern coral zonation at Mauritius, this coral assemblage is considered to be diagnostic of medium-energy, reef crest or upper forereef zones, thus indicating a palaeowater depth of 0–6 m.

(II) tabular-branching coral assemblage dominated by tabular and/or branching corals. By analogy with the distribution pattern of its present-day analogs, this coral assemblage is interpreting as representing open, low-water energy settings (e.g. middle parts of the forereef zone), at depths between 6 and around 15 m.

(III) robust branching-domal coral assemblage dominated by abundant dome-shaped colonies and some robust forms. By analogy with the zonation of its modern counterparts, this coral assemblage is regarded as reflecting a semi-exposed habitat, such as the inner part of the present-day reef crest and the outermost section of the backreef. The growth palaeodepth was presumably < 6 m.

(IV) foliaceous coral assemblage. By analogy with the modern zonation, this coral assemblage is thought to have grown on the middle part of a former backreef in < 10 m of water-depth.

Coral biofacies were parameterized differently according to the models applied. Using CARBONATE, the pseudo-facies were established from the coral record. Four palaeobathymetric ranges were differentiated: 0–6 m, 6–10, 10–15 and more than 15 m. Using FUZZIM, each coral assemblage was defined by a fuzzy rule:

(I) robust branching coral assemblage
1. <IF shallow AND wavedepth THEN deposit_much AND branching_corals>

(II) tabular-branching coral assemblage
2. <IF intermed_depth THEN deposit_some AND massive_corals>

(III and IV) robust branching-domal and foliaceous coral assemblages
3. <IF shallow AND NOT wavedepth THEN deposit_little AND massive_corals>

In order to simulate grainstone sediment, we wrote the following rule:
4. <IF deep AND NOT wavedepth THEN deposit_very_littke AND carb_sand>.

It is noteworthy that the FUZZIM model takes into account only the coral branching
and massive shapes. The tabular coral form is likened to the massive coral form in this modelling pattern. The notions of carbonate production rate and depositional water-depth are described below.

**Neritic carbonate production and erosion**

We use the terms “shallow” as indicating shallow-water environments between 0 and 6 m, “intermediate_depth” as relating to a depth of 10 m, and “depth” as indicating a depth interval from 15 to 20 m. The selection of these depth ranges is based on the habitat depths defined for each coral assemblage. Furthermore, the fair-weather wave base was located at 6 m, to simulate an environment subject to high water energy within the 0–6 m interval, characterized by coral association (I). Below the strong wave-base, an environment occurs characterized by moderate to low water agitation at depths greater than 6 m and by the coral assemblage (II).

The maximum neritic carbonate production rate is assumed to occur within the 0–10 m depth interval. Production decreases linearly below 10 m depth until approximately 50 m deep. The mean rates of reef aggradation can be estimated reliably from the 14C dates (Montaggioni and Faure, 1997), between the base and top of each core. The rate of vertical accretion varied between 3.6 to 4.3 m.ka⁻¹. But abrupt changes in growth rates can occur within a given cored sequence that coincides with changes in the composition of coral assemblages. The robust branching coral assemblage exhibits accumulation rates ranging from 0.8 to 15.5 m.ka⁻¹. The robust branching-domal coral and the tabular-branching coral assemblages have been developed within a similar range of growth rates from 4.1 to 6.4 m.ka⁻¹.

In modelling, a carbonate production rate of 5 m.ka⁻¹ is simulated between 1 to 10 m (for details see Figure 8). This maximal rate corresponds to the membership value «deposit_much». Decrease in production rate with increasing depth (CARBONATE) is simulated with the membership «deposit_some, deposit_little and deposit_very_little» (FUZZIM). Several iterative simulations allow one to optimize and to select a carbonate production rate about 5 m.ka⁻¹.

Two rules were applied to simulate the erosion process: aerial erosion <IF land THEN erode_more> (fuzzy rule n°5) and subaerial erosion <IF at_surface THEN erode_more> (fuzzy rule n°6). Iterative simulations allow one to estimate and optimize erosion rates equally.

**Patterns of reef growth and geological model**

Detailed analysis of the internal structure and facies distribution of the reef has revealed the following growth history (Figure 10). Flooding of the antecedent topography occurred around 8000–7000 years B.P. The time lag between inundation and reefal growth was less than 1000 years.

The initial coral communities were dominated seaward by wave-resistant, robust branching acroporids associated massive forms. At this stage, the reef tract formed a mound-shaped body.

From 6000–5500 years B.P., changes in reef profile occurred, passing from hydraulically exposed to more protected conditions. Water depth is around 8–10 m at this time. The mound was capped primarily with plate-like, thinly branching acroporid
colonies, associated with other branching and domal growth forms that developed vertically until about 5500 years B.P. Then, it was replaced by a robust branching coral assemblage, adapted to higher water energy conditions in shallower waters.

Around 4000 years B.P., the depth below the reef top did not exceed 6 m. Reef geometry was flat-topped and steep-sided. From 3500–3000 years B.P., the reefal system prograded towards the ocean. At this time, sea level began to stabilize close to its present position. The modern fringing reef anatomy and biozonation was developing. The reef was flat-topped and continued shoreward to accrete as a shallow submerged area.

During the last 2500 years B.P., the reef was growing to a static sea level. Vertical growth is limited due to the lack of vertical space available. The fact that the isochron lines are approximately parallel to the present-day topography can be explained by a prevalence of the aggradational over the progradational regime.

**Figure 11.** Simulated 2-D stratigraphies from CARBONATE (a) and FUZZIM (b). Time lines occurred at 1000 years increment. FUZZIM model reproduce more accurately initial reef growth (coral assemblage I) than CARBONATE model.

**Comparison between modelling and field data**
Modelling realized with both CARBONATE (Figure 11a) and FUZZIM (Figure 11b) are consistent with the modern morphology of the fringing reef and the distribution of the time lines. The results concerning the distribution of coral assemblages are realistic. The first growth phase corresponding to the appearance of the mound-shaped body was not simulated in a satisfactory way. Using CARBONATE, neritic carbonate production rates depend on depth only. As a consequence, carbonate production rates vary vertically and not laterally, thereby precluding the building of a «mound body.»
Regarding the later growth phases, both deterministic and stochastic numerical models are able to reproduce reef geometry and distribution of coral assemblages consistently.

From 7000 to 6000 years, using FUZZIM coral communities are composed of branching coral assemblage I (e.g. fuzzy rule 1), determining a keep-up growth pattern. Using CARBONATE, this time interval is typified by the occurrence of the 0–6 m pseudo-facies.

From 6000 to 4500/4000 years, changes in coral communities occurred, passing from hydraulically exposed (assemblage I) to more protected conditions (assemblage II). Along the forereef slope, FUZZIM simulates intermediate and massive coral growth forms (e.g. fuzzy rules 2 and 3) and CARBONATE simulates water-depth range from 10 to 15 m. At this location the reef growth is of catch-up style. At shoreward side, the reef system is dominated by shallow-water coral assemblage I; reef growth is of keep-up style.

Figure 12. Simulated 3-D stratigraphy FUZZIM. Two Stages, respectively at 4000 and 2500 years., defined a morphological change of the fringing reef characterised by a progradational pattern

Around 4000 years, the depth interval between the reef top and sea surface did not exceed 6 m. In the inner areas, the reef system is dominated by branching coral assemblages I, III and IV (fuzzy rules 1 and 3; FUZZIM), adapted to higher hydraulic energy in shallower waters (CARBONATE). Along the forereef slope, intermediate and massive forms were prevailing. At this time, the reef tract underwent changes in
growth processes, passing from aggradational to progradational patterns. At this time, the reef growth followed sea-level rise and caught up with decelerating, then stabilizing sea level. Three-dimensional modelled views of the depositional surfaces at 4500 yr and 2500 yr respectively (Figure 12; FUZZIM) present the distribution and the zonation of coral assemblages across the reef. These 3-D models illustrate well changes in stacking patterns and facies distribution.

DISCUSSION AND PERSPECTIVES
Comparison of the results obtained from the Mauritius Holocene reef provides a good test of the accuracy of the two numerical models CARBONATE and FUZZIM. Evaluating these two models has allowed a comparison between input variables, algorithm, and geological and numerical models. The models used here have produced reconstructions of reef development satisfactorily and complementarily. Even though the models are limited in their application, the numerical modelling appears to be a tool necessary for a better understanding of the parameters controlling reef development and more widely functioning of carbonate platforms.

Testing variables is only one approach in model assessment. In order to examine the validity of algorithms, it is also necessary to test if models are good approximations of the sedimentary system that is designed to be simulated. There are many reasons for studying sedimentary systems, academic and economic as well. The fossil oil and gas, derived from the maturation of organic matter in sediments, have migrated to a suitable reservoir rock. It is necessary to simulate all of these sedimentary processes. But managing a large number of parameters reduces the reliability of models. Numerical models must be used to answer specific questions concerning for example (1) oil maturation, (2) system evolution (on larger scale) in response to subsidence or eustasy, (3) sedimentary system evolution (on a smaller scale) in response to changes in carbonate production controlled by climatic condition. But a numerical model must provide for simulating various geological systems. Accordingly, the principal roles of numerical modelling include: (1) encouraging accuracy and precision in data collection and interpretation of processes; (2) quantitatively testing interpretations concerning the control of various mechanisms in producing sedimentary packages; (3) predicting or extrapolating results into areas of limited control; (4) gaining new insights to offer new intuitive results regarding the interaction of parameters; (5) helping focus on future studies to resolve specific problems.

Simulation runs result in non-unique solutions due to the numerical model limitations, and the inherent approximations of the geologic input parameters. But modelling permits ongoing experimentation as data quality and understanding of processes improvement. The results should serve as guide for hypothesis formulation and rejection. Critical examination of these results and of their implications can lead to better understanding of geological models and of process interactions. If a simulation does not represent well geological models, is it the input parameters that are not reflecting the natural variability of the geological systems, or does the fault lie with the model itself? Providing the most accurate result needs iterative simulations,
and numerous feedbacks between geological and numerical models. This method leads to a better understanding of the sedimentary system development and related processes.

The development of ‘a high-value numerical model’ must require: (1) a coherent and cooperative effort of the sedimentologic-stratigraphic modellers and geologists in order to determine optimal algorithms and parameters; (2) feedback between geological data (outcrops, seismic lines…) and numerical models; and (3) principally, funding for stratigraphic modelling to permit the necessary effort to be exerted. There are many factors which control carbonate systems and determine products (Figure 13). Sediments can be deposited from a wide range of processes including winds, streams, tidal and storm currents, waves, turbidity currents and debris flow, in-situ growth of skeletons, direct precipitation of minerals. Water-depth, degree of water agitation, salinity, nutrients are important physical attributes of environments that govern the behaviour of organisms. As a consequence, it is difficult to imagine how a scientist may create graphical descriptions or algorithms that have the capacity to reproduce natural systems accurately.

Figure 13. Discrimination of parameters interacting during the development of carbonate systems

Models are written essentially in 2-D and more recently in 3-D (Nordlund, 1999; Warrlich et al., 1999, 2000; Seiffert et al., 2000). The most important next step to be reached in stratigraphic modelling is the development of 3-D models, which, for instance, requires integration of fluid flows responsible for current-driven sediment transport and changes in carbonate production rates on a platform (Baker and Waltham, 2000; Warrlich et al., 2000; Nakayama et al., in this volume). Erosion is an important controlling parameter, which needs new algorithm formulation in order to gain more accuracy. We have seen that generally lithofacies are represented by depositional depth-intervals (CARBONATE, FUZZIM, PHIL, SEDPAK), textures (CARBONATE), grain-sizes (FUZZIM). Further improvement would be simulation
of depositional environments directly from depth-intervals. Evaluating a deterministic and a stochastic model (e.g. CARBONATE and FUZZIM respectively) shows that stochastic approach is more realistic and accurate, and could permit simulation of sediments displacement (in three-dimension) that the deterministic approach does not allow.

Models used and developed by academics usually are less performance driven than those developed by petroleum companies (Aminzadeh, 2000; Dodds, 2000; Hoggetts et al., 2000; Ouenes, 2000; Tye and Hickey, 2000; Borgomano et al., 2001 among others). A significant number of individuals, from oil industry or universities, suggested that «academic models» add little or nothing to interpretative or predictive capability; instead, in their view, such an academic modelling serves as no more than a simple drafting tool which reproduce perfectly the geological model. This misconception can probably be attributed partly to the way some models have been used. In the early development of models, scientists wanted to simulate exactly what they have observed and accurately to predict all other characteristics of the geological system (Aigner et al., 1990; Bosence and Waltham, 1990; Lawrence et al., 1990; Kendall et al., 1991). More recently, models are used to better understand depositional processes and to quantify parameters controlling the development of systems. Better prediction of reservoir geometry requires better constraints on the factors influencing the development of carbonate systems. These two research (petroleum companies and universities) objectives are complementary. Indeed, in the aim of predicting the distribution and geometry of reservoirs more precisely, modelling approaches by petroleum engineers have taken into account «natural» parameters such as fair-weather wave base, storm wave base and wind direction (Massonnat, 2001).

Numerical models can be used as teaching tools (PHIL; Bowman, 1997), to answer fundamental research questions or as predictive tools for hydrocarbon exploration. Simulation models must be definitively incorporated into academic courses; geologic processes could be observed in action and students could explore the complex interdependencies between processes and responses. All models used must be applicable to more geological systems. It is important that model users should not be forced to convert their data to match numerical models. Recently, model packages such as FUZZIM or STRATA (Flemings and Grotzinger, 1996) are distributed freely on the Internet. This distribution allows one to receive source code that may be used to develop new free models. Making new stratigraphic more realistic models must be based on flexibility and capacity of scientists to couple new sophisticated mathematical techniques. Finally, increasing awareness of stratigraphic modelling can be addressed by holding conferences that deal collectively with numerical modelling and carbonate sedimentology.

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