Computer Simulation of Sedimentation and Ecological Environment at Nobi Alluvium Delta, Central Japan*

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Abstract

Geologic history of formation of Nobi alluvium delta is simulated by high-speed computer. Material supply by the river Kiso, deposition of sediment as delta, winnowing of sand and mud, and tectonic tilting are taken into consideration. Ecological behavior of organism community is also simulated in which several species of shell are concerned. It is concluded that geodetic information on crustal movement is compatible with geologic information.

§ 1. Introduction

Natural phenomena are apparently complicated in which various physical, chemical and even biological processes are interacted each other. Owing to its large scale, a synoptic view is difficult to obtain. These unit processes, in many cases, are progressing under a rather simple law. However, their coupling is so complicated that an over-all feature is difficult to analyze. One of the aims of the earth science is to investigate the history of the earth. Apparently its evolitional path is irreversible, and therefore the ancient state cannot be reproduced. The best way to reproduce the ancient state is to perform experiment based upon a model procedure. Development of high speed computer enables us to perform the model experiment of the complicated natural phenomena through a technique of simulation. We may regard a simulation as a means of exploring interactions among a series of different sets of assumptions. Application of computer simulation to the earth science was presented by the present authors in which several examples were included [SHIMAZU et al. (1970)]. The present paper consists of a part of our simulation project.

Simulation models are classified into two types: deterministic and stochastic. The former is meant that the process is expressed by a set of definite formulae, e.g. simultaneous differential equations. Therefore, the deterministic simulation is generally equivalent to solve equations numerically. Many examples can be found in geophysics. The stochastic model, on the contrary, includes a degree of uncertainty. In geological simulation, which is our present theme, a general approach is to imitate major geologic processes and to cause these processes to interact with each other through time, producing geologic events. A sequence of events is often of a character of chance, and therefore the model becomes stochastic. The objective is to create a mathematical model that behaves realistically.

The test of a geological simulation model is empirical. If results produced by the model accord with the observed features to a reasonable degree, the model may be considered to be more or less successful. A simulation model is neither hypothesis nor theory. Un-
like a scientific hypothesis, it is not verified directly by experiment or observation. Most simulation models are both true of false. Some of the relationships embodied in a model are likely to be true in the sense that they occur in nature. The validation of a simulation model is not that it is true, but that it helps to generate hypotheses that, in turn, perhaps may be rigorously tested.

After we obtain a reasonable model, in a sense described above, it might be possible to find which factor is more essential by applying a virtual change of parameters. It is usually called a sensitivity analysis, which is our final object of simulation. This kind of experiment will serve to set up strategy to prevent undesirable consequence in natural system which might be expected to occur in future, especially by human activity.

§ 2. Outline of Sedimentation Simulator (SEDSIM)

HARBAUGH and WAHLSTEDT (1967) developed a mathematical model for simulating sedimentation and interaction between communities of marine organism in shallow sea. The model represents, through use of a grid of rectangular geographic cells; a depositional basin in three-dimensional space, accommodating a sea of varying depths, shorelines, beaches, river deltas, and land areas. The model provides for transportation and deposition of sediment, for tectonic movement of basement, and for population of land areas and sea floor with organism communities that respond dynamically to environmental changes. The model is advanced through increments of time. Here a brief description of the simulator is given.

Various physical processes are considered. Tectonic movement is simulated by columns, square in cross section, that are moved upward or downward during each stage. At each time vertical motion may take place. Depending on the contrast between values in adjacent columns and their algebraic signs, conditions can be simulated that range from uniform downwarping or upwarping to complex folding and faulting. Deposition of sediment also takes place by time increments. Several factors and processes affect sediment increment rates. Sediment deposition is simulated by adding the value of the sediment increment to the preexisting sea floor or land elevation. Water depth is calculated as the difference between the sea floor and sea level. Elevations on land are denoted by negative signs with reference to sea level.

Processes of deltaic sedimentation are simulated by varying the rate of supply of terrestrially derived sediment to mimic the effect of a river bringing sediment to the sea and spreading it out. The rate of deposition of terrestrially derived sediment, however, is not necessarily the same as the rate of supply. If the depth of water is less than some specified value, the proportion of sediment deposited is proportionally less than the rate of supply. The proportion deposited reduces to zero when some specified elevation (which may be above or below sea level) is reached. The effect of winnowing of fine particles at beaches is treated as a function of both water depth and proportions of sand and mud. The relative intensity of the winnowing process reaches a maximum at sea level and decreases linearly to zero at some specified depth. Amounts of sand and mud supplied by the river are specified at each stage as input data. Only one river is allowed to consider, and the geographical position of river mouth can be migrated by specifying as input data. The geometrical form of delta is also specified.

The simulator provides for continuously populating the sea floor and adjacent land areas with organism communities. Aggregation of organisms to form communities, rather than individual organisms are used. The sea floor (or land area) is divided into square cells; a single organism community, represented by a integer, occupies each cell at a given stage. Organism communities in the simulator are endowed with properties that affect their ability to compete with the other organism communities. The means by which competition and ecologic succession are simulated are probabilistic in nature and
center about the selection of communities chosen to occupy cells at each new stage. This involves the geographic distribution of organism communities in preceding stage and the relative vitality of the different organism communities. Vitality is a function of the relative fitness of each organism community for the local environment at a specific moment and place.

The influence of organism communities that occupied geographic cells during previous stages is a three step Markov process, in
which matrices of the transition probability values influence the selection of the next organism community to occupy a given geographic cell. The transition probability values are nonstationary with respect to time, being progressively modified at each stage. Environmental factors including depth of water and proportions of mud and sand, as well as the occupants of neighboring cells, affect the transition probability values. The random aspect of selection is simulated by use of random number generator.

The transition probability value developed in the simulator is such that, moving toward through time increments of short duration, the most probable organism community to occupy a cell is the same community that occupied that cell immediately before. This assumes that other factors in the environment are relatively unchanged, and that adjacent cells do not harbor communities that would have a strong overpowering influence if present. The occupation of the cell by a community that is next in an ideal ecologic succession, however, is the second most probable event. Occupation of the cell by community that is progressively farther removed in an ideal ecologic succession are of progressively lower probabilities. Given sufficient time increments, a pioneer community should replace gradually by other communities involved, so as to simulate the effect of the muddy water on them.

Physical environment factors that are internal with respect to the model are water depth, sand/mud ratio, and rate of influx of terrestrially derived sediment. The rate of supply of sediment is assumed to have no influence on the community until a specified threshold level is reached. Above this level, increase in rate of supply causes relative vitality to decrease until an intolerable level is reached.

An outline of low chart is given in Fig. 1. The original program by HARBAUGH and WAHLSTEDT is rewritten for FACOM 230-60 at Kyoto University. Several revisions are included, e.g. the redundant 300 statements are omitted. The program listing is given in a separate paper [SHIMAZU et al. (in press)].

§ 3. Simulation of Formation of Nobi Alluvium Delta

Nobi plain, Central Japan, is one of the largest alluvium delta. It is formed by the deposition due to three major rivers, Kiso, Nagara, and Ibi, among which the Kiso has an overwhelming effect. The Kiso flows from east toward west and then turns its direction toward south as is seen in Fig. 2. The turning is dependent upon a tectonic tilting of the basement which has been continuing since the Tertiary. A synoptic pattern of westward down tilting and southward slope determines a rather complicated structure of Nobi plain. One of the objects of simulation is to find a ratio of significance of the above two effects quantitatively.

The description of geologic history of Nobi plain by MATSUZAWA and KUWAHARA (1964) is referred to specify the input data. The grid points of 13×16 are used, where a unit interval is 2.5 km. Here the EW and NS directions are called row and column respectively. A configuration of grid system is shown in Fig. 2.

The following items are taken into consideration.

(1) Judging from the description by Ma-
Fig. 2. Representation of grid system.

Table 1. Sand and mud increment values (Unit: m).

<table>
<thead>
<tr>
<th>Stage</th>
<th>SM-1</th>
<th></th>
<th>SM-2</th>
<th></th>
<th>SM-3</th>
<th></th>
<th>SM-4</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sand</td>
<td>mud</td>
<td>sand</td>
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<td>sand</td>
<td>mud</td>
<td>sand</td>
<td>mud</td>
</tr>
<tr>
<td>1</td>
<td>10.0</td>
<td>0.5</td>
<td>2.0</td>
<td>0.2</td>
<td>15.0</td>
<td>0.5</td>
<td>8.0</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>5.0</td>
<td>0.1</td>
<td>1.0</td>
<td>0.5</td>
<td>19.5</td>
<td>8.0</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>10.0</td>
<td>5.0</td>
<td>0.4</td>
<td>0.5</td>
<td>19.5</td>
<td>0.5</td>
<td>25.0</td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>18.0</td>
<td>0.5</td>
<td>30.0</td>
<td>0.2</td>
<td>10.0</td>
<td>0.5</td>
<td>25.0</td>
</tr>
<tr>
<td>5</td>
<td>24.5</td>
<td>0.5</td>
<td>10.0</td>
<td>0.5</td>
<td>18.5</td>
<td>0.5</td>
<td>20.0</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>5.0</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
<td>5.0</td>
<td>0.1</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Table 2. Organism communities.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Organism</th>
<th>Favorable depth (most favorable) (m)</th>
<th>Favorable environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>Land plant</td>
<td>above sea level</td>
<td>—</td>
</tr>
<tr>
<td>¥</td>
<td>Anadara granosa bisensis</td>
<td>0~10 (2)</td>
<td>mud</td>
</tr>
<tr>
<td>/</td>
<td>Corbicula japonica</td>
<td>0~3</td>
<td>sand</td>
</tr>
<tr>
<td>+</td>
<td>Macoma toryoensis</td>
<td>0~30 (15)</td>
<td>mud</td>
</tr>
<tr>
<td>M</td>
<td>Venerupis</td>
<td>0~10 (2)</td>
<td>sand</td>
</tr>
<tr>
<td>=</td>
<td>Batillaria multiformis</td>
<td>0</td>
<td>sand</td>
</tr>
</tbody>
</table>

Table 3. Combinations of parameters.

<table>
<thead>
<tr>
<th>Model</th>
<th>Position of river mouth</th>
<th>Sand &amp; mud</th>
<th>Tectonic movement</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>R-1</td>
<td>SM-1</td>
<td>TCT-1</td>
</tr>
<tr>
<td>B</td>
<td>R-2</td>
<td>SM-1</td>
<td>TCT-1</td>
</tr>
<tr>
<td>C</td>
<td>R-1</td>
<td>SM-1</td>
<td>TCT-1</td>
</tr>
<tr>
<td>D</td>
<td>R-1</td>
<td>SM-3</td>
<td>TCT-1</td>
</tr>
<tr>
<td>E</td>
<td>R-1</td>
<td>SM-4</td>
<td>TCT-1</td>
</tr>
<tr>
<td>F</td>
<td>R-1</td>
<td>SM-2</td>
<td>TCT-1</td>
</tr>
</tbody>
</table>

TSUZAWA and KUWAHARA, six stages or six time increments are considered.

(2) Since the transported materials by the Nagara and Ibi are less than 1/10 of those by the Kiso, only the effect by the Kiso is concerned. Migration of the river mouth is considered, and its position is read as input data.

Case R-1: river mouth at (8,-1) in Fig. 2.
Case R-2: river mouth at (3,-1) in Fig. 2.

(3) Amounts of sand and mud supplied from the river during each stage are rather difficult to specify. They are expressed in terms of depth (m) referring to the maximum thickness of each stratum shown by MATSUZAWA and KUWAHARA. Actually they are regarded as adjustable parameters in input data. Five cases shown in Table 1 are considered.

(4) Roughly speaking, tectonic movement of the basement is upward at the eastern half and downward at the western half. The contour map of the recent crustal movement inferred from precise levelling are referred.

Three cases are considered:
- TCT-1 the present rate is assumed to be continued during the whole stage
- TCT-2 TCT-1×1/2
- TCT-3 no movement

It is concluded that Case TCT-3 is far from the actual history of Nobi plain.

(5) Six types of organism communities are used as shown in Table 2. All of them appear to have little ability of organic sedimentation.

Here results for seven models described in Table 3 are discussed. Before obtaining these models, many steps of trial and error are needed. Here, only the models which can give reasonable results are presented. Stratigraphic sections at the sixth stage (=present state) are shown in Figs. 3, 4, 5. Column 5, for example, represents the east-west section at a position column 5 in Fig. 2. Section EW-3 is the corresponding observed cross section compiled by MATSUZAWA and KUWAHARA. Similarly EW-8 and NS-3 are the observed cross sections corresponding to Column 14 and Row 4 respectively.

Model G is omitted from Figs. 3, 4, 5 because it is far from the actual state. It is noticed that the effect of position of river mouth is not significant (See Model A and B). A local feature such as an interfinger cannot be simulated because the grid size is not small enough. It is inferred that Model A appears to be optimum. The maps of water depth for Model A and C are shown in Figs. 6(A) and 7(A) respectively. The numbers represent depths in unit of 10 m (i.e. 5 means 50 m). The negative value denotes the land...
Fig. 3. Stratigraphic cross sections for Column 5. EW-3 is the corresponding observed cross section.

I: Ibi, N: Nagaara, K: Kiso
—: water, †: mud, ⋅: sand.
Fig. 4. Stratigraphic cross section for Column 14. EW-8 is the corresponding observed cross section.

Fig. 5. Stratigraphic cross section for Row 4. NS-3 is the corresponding observed cross section.

*: water,  : mud,  .: sand.
**Fig. 6.** (a) Water depth map for Model A (unit in meter).
(b) Organism community map for Model A (See Table 2 for symbols).

Grid point (1, 1) is located at the left-upper corner. Columns (NS direction) and rows (EW direction) extend from the left to the right and from the upper to the lower respectively.
Fig. 6(b)
elevation above sea level. The corresponding maps of organism community distribution are shown in Figs. 6(B) and 7(B). It is remarked that the distribution of organism communities is significantly different for Model A and C while their stratigraphic cross sections are similar. Unfortunately, a detailed paleontological study is not carried out for Nobi plain. Marine organism communities such as *Macoma* and *Batillaria* are found in the deeper parts of drilling core at (10.4) in Fig. 2. However their extents are not confirmed yet, and therefore a choice of model based upon the fossil distribution is a future problem. At any rate, geodetic information on the recent tectonic movement is compatible with geologic information. The mathematical model thus obtained will be served to a further study, e.g. a problem of ground water control at Nobi district.
References


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