SIMULATING SEDIMENTARY BASINS : AN OVERVIEW OF THE SEDSIM MODEL AND ITS RELEVANCE TO SEQUENCE STRATIGRAPHY

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Abstract : SEDSIM is a series of computer program modules that simulate the main processes that create sedimentary basins. The representation is three dimensional, except that representation of flow processes are not fully 3-D, with geographic variations in flow velocity in open bodies of water being represented, but variations with depth are not. Processes include wave action, erosion, transport and deposition of clastic sediment, compaction, pore-fluid expulsion, and isostatic compensation. Experiments that linking processes together document the versatility of SEDSIM's procedures to produce highly realistic stratigraphic sequences under controlled conditions, including responses to changing sealevel and wave climate. Experimental results involving stratigraphic sequences produced by falling sealevel followed by rising sealevel are briefly described and compared with the Yegua Formation.

Key words : Geologic processes, 3-D simulation, Waves, Navier-Stokes equations, Potential flow, Fluid elements, Sealevel change

INTRODUCTION

Procedures or "models" for simulating sedimentary basins have advanced rapidly in the past five years. All use computers and all employ computer-generated graphic display to show details of simulated features. Most older models are two dimensional and represent basins by means of vertical sections, whereas newer models are partially or fully three dimensional. Advantages of 2-D models include simplicity of programming, rapidity of computation, and ease of graphic display, but a major disadvantage is that they are inherently unrealistic. For example, a river system that creates a deltaic complex at the edge of a basin can only be represented realistically in 3-D. Lateral shifting of meandering rivers that create deltaic deposits and attack by waves at the seaward margin cannot be represented effectively in a vertical section.

Most sedimentary basin simulation models attempt to represent major geologic processes that create basins, but means for their representation vary widely. For example, in a 2-D basin model, transport of clastic sediment may be represented simply by the diffusion equation. While useful for some purposes, the diffusion equation is not very realistic for representing sediment transport. By contrast, other equations can represent currents in rivers and the sea and can be linked with equations for sediment transport.

Truly effective basin models should incorporate all major geologic processes that govern creation of basins, including flow of water, wave activity, erosion, transport and deposition of clastic sediment, deposition of carbonates and evaporites, compaction and expulsion of porefluids, diagenesis, isostatic compensation, and tectonic deformation. Additional processes include hydrocarbon generation and migration, eolian transport, and mass movement of sedi-

ment. Some of these processes are included in "SEDSIM", Stanford University's SEDimentary Basin SIMulation model discussed below.

FLOW, TIME, SEDIMENT TRANSPORT, AND WAVE ACTIVITY

A central issue in basin simulation involves flow in surface waters and in pores in rocks and unconsolidated sediments. Most geologic processes involve flow, directly or indirectly. Flow in surface waters can be represented in several ways. The simplest involves the Laplace equation for potential flow represented by flow fields with smooth gradients. Numerical solutions of the Laplace equation in two or three dimensions are easy to obtain, although complications at boundaries of flow fields may require much detail in computer programs. Once a numerical solution is obtained, the flow field does not change unless the boundary conditions change, requiring a new solution. An alternative involves numerical solutions of the Navier-Stokes equations to represent individual fluid elements whose locations, velocities, and directions are continuously tracked. Their use in representing flow in SEDSIM is described by Tetzlaff and Harbaugh (1989).

The conventional concept of a fluid element involves a finite but very small mass of fluid. The concept may be extended to fluid elements containing hundreds or thousands of cubic meters of fluid, permitting realistically large volumes of fluid to be represented in simulation experiments. By using a large number of fluid elements, the quasi-random motions of a fluid moving from higher to lower potential can be represented, with fluid elements interacting with each other in complex fashion, producing more realistic representation than potential flow.

A flow field composed of fluid elements constant

Fig.1. Schematic diagram showing ranges of time scales in simulation experiments.

ly changes, requiring that numerical solutions be up-dated frequently, sometimes at intervals as short as a few seconds. The computational effort is therefore much greater than for potential flow, although today's computers can carry out the arithmetic. Unfortunately the arithmetic labor for full 3-D representation is usually far too great, requiring that representation of flow in a river or in the sea be 2-D in form. This representation permits velocities to vary geographically, but not with depth. Depth still can be represented, however, to make the flow's representation partially 3-D in form. When much faster computers become available, these constraints should be progressively eased.

Time scales in simulation experiments can range from fractions of seconds to millions of years (Figure 1). Such large ranges are challenging to represent, but ranges of 12 or 13 orders of magnitude may be desirable. For example, numerical solutions of the Navier-Stokes equations may need updating at intervals of a few seconds in an experiment spanning a million years geologic time. Such disparate time scales require care in selecting parameters that control experiments, and computational shortcuts are required to reduce arithmetic labor, which otherwise may be too great for even the fastest computers.

As currents move, they transport sediment available at the water-sediment interface, provided that their velocities are enough to move sediment grains present there. Transport distances depend on velocities and on sizes and densities of grains. In SEDSIM's representation of sediment transport, strict attention is paid to the conservation laws to ensure that all sediment is accounted for, including that which moves into, within, and beyond the boundaries established for an experiment. Sediment transported beyond the boundaries and thus "lost" must be accounted for with equal rigor, as described by Tetzlaff and Harbaugh(1989).

Wind-induced waves may have large localized effect on currents and exert major influence on sediment transport. While currents induced by waves are

Fig.2. Diagrams prepared by Martinez(1992) illustrating SEDSIM's ability to simulate nearshore currents induced by waves in area of moderately complex submerged topography. Area is along coast in southwestern Oregon. (A) Perspective diagram showing generalized current motions. (B) Map showing depth contours (in meters) and currents generated by waves.

complex and are poorly understood, SEDSIM represents directions and intensities of waves as they shoal and approach shore, and calculates velocities and directions of wave-induced currents at the water-sediment interface. Martinez(1992) describes SEDSIM's representation of waves, and Figures 2 and 3 document SEDSIM's ability to represent wave motions in an area of complex submerged topography. With its ability to represent waves, SEDSIM can produce experimental sequences containing complex facies relationships where nearshore sediments (as in a delta complex, for example) are subjected to strong wave activity. Other major influences also can be studied experimentally, such as effects of changing sea level.

EXPERIMENTS INVOLVING STRATIGRAPHIC SEQUENCES

A petroleum geologist may explore for hydrocarbon reservoir facies in an ancient delta complex. At the outset the geology may be poorly understood, with information provided only by scattered exploratory wells and widely spaced seismic lines. A continuing challenge is to interpret the geology in accord with available information, with focus on selecting loca-

Fig.3. Maps prepared by Martinez(1992) of area in Figure 2 showing submerged topography and wave and current directions : (A) Directions of refracting waves are shown by vectors representing wave orthogonals.(B) Directions of wave -induced currents shown by vectors.

Fig.4. Cross-sections perpendicular to shore showing features produced by changes in sealevel. (A) Sedimentary facies produced in simulation experiment extending over 2000 years in which sealevel fell uniformly for five meters during first 500 years, followed by uniform rise of 15 meters in remaining 1500 years. Lighter gray patterns represent coarser materials (fine sand) and darker gray represent finer sediment (silt and clay). Section is hypothetical so that vertical and horizontal scales are generalized, although horizontal dimension of section is roughly 20 km and vertical dimension is about 100 m. Sealevel at close of experiment is shown by horizontal boundary that separates light and dark gray. (B) Section that corresponds to section A, but instead shows ages of beds. Each band represents sediment deposited during 50 - year interval. Experiment was conducted by Martinez, Lee, and Ramshorn (unpublished). (C) Diagrammatic cross-section, with no scale implied, of features of Yegua Formation in Texas and Louisiana shown for comparison with sections A and B. Yegua is interpreted to have formed during fall and subsequent rise of sealevel.

tions for additional wells and seismic lines. When additional information becomes available, the interpretation is revised to accord with the new information. Such a sequence of interpretation, acquisition of new information, and re-interpretation is familiar, regardless of procedures utilized. Simulation helps in such an interpretive sequence because it can link assumptions about geologic processes operating in the past with the geologic features being interpreted.

Results of an experiment involving a delta created by two rivers that debouched side by side into a receiving basin are shown in Figure 4. The experiment spans 2,000 years and involves a uniform fall of sealevel of five meters during the first 500 years, followed by uniform rise of sealevel of 15 meters during the remaining 1500 years. Sections A and B in Figure 4 are perpendicular to shore, with section A representing variations in sediment type (light gray represents coarser sediment) and section B representing ages (each alternating band represents sediment deposited in a 50-year interval.) Figure 5 shows positions of ancient shorelines as the sea progressively transgressed during rise of sealevel.

In the experiment, thick foreslope beds formed during falling sealevel, whereas thinner overlying beds were formed as sealevel rose. The resulting sequence, while hypothetical, can be compared with actual sequences formed during similar changes in sealevel. By contrast, section C of Figure 4 represents the Yegua Formation of Tertiary age of the Gulf

Coast in Texas and Louisiana, where shelf-edge deltas and turbidites that formed close to the center of the basin during a sealevel lowstand were succeeded by stable-shelf deltas deposited progressively farther from the center of the basin during subsequent sealevel rise and transgression. It is suggested that adaptation of three-dimensional simulation for analyzing the geologic history of sedimentary basins represents a technological advance of potential importance.

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Fig.5. Map prepared by Martinez, Lee, and Ramshorn (unpublished) showing locations of shorelines during part of simulation experiment in which sealevel was rising. Lines represent shorelines from 600 to 2000 years after outset of experiment. Geographic dimensions of area are roughly 12 by 12 km, although dimensions are hypothetical. Map corresponds to sections A and B in Figure 4.