[PS]A Qualitative Computer Simulation for Understanding Sequence Stratigraphy Concepts and Parameters*

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Abstract

Sedpak, a sedimentary computer simulation developed at the University of South Carolina, assumes clastic transport based on slopes and carbonate production based on water depth. Output geometries display a sequence stratigraphic framework of erosional and depositional surfaces of the simulated section. Sedpak extends interpretation of depositional setting and predictions of lithofacies geometries away from the studied areas. It aids prediction of facies likely to contain both hydrocarbon and water resources and their characteristic fabrics. Redesign of Sedpak incorporates open source software applications and tools. New design continues to provide a platform for understanding how different geometries are produced by varying sea level, sedimentation, and subsidence.

Computer modeling of sedimentary geometries that match interpreted sections is a repetitive exercise in parameter estimation, viewing of resulting geometries and adjusting of parameters to converge on a best match. Intuitive model parameters based on physical processes, including rates of clastic sediment accumulation and transport distance down slope in a two dimensional simulation space, offer valuable insight into a more quantitative modeling approach. Further information on the fabrics of the deposits can be obtained by means of coupling computer models of sedimentary geometries with physically based submodels that describe the spatial and temporal evolution of relatively small portions of the entire system. The origins of sediment geometries and facies are interpreted by comparison with observations of similar features in modern sedimentary systems and their processes and then the interpretations are tested with the Sedpak simulation. The question is: do input parameters match those inferred from current field observations parameters set to create basic sequences stratigraphic systems tracts, including prograding low-stand and high stand systems tracts, and retrogradational transgressive systems tracts? The same applies to in-situ carbonate accumulation. Are the depth-production rates reasonable?

Sedpak provides a work setting to tune initial conditions and model parameters producing 2-D sedimentary geometries that intuitively 'make sense' to new and experienced stratigraphic modelers. A new open source design will eliminate collaboration barriers and offer easier access to model data and depositional algorithms.

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ABSTRACT

Sedpak, a sedimentary computer simulation developed at the University of South Carolina, assumes clastic transport based on slopes and carbonate production based on water depth. Output geometries display a sequence stratigraphic framework of erosional and depositional surfaces of the simulated section. Sedpak extends interpretation of depositional setting and predictions of lithofacies geometries away from the studied areas. It aids prediction of facies likely to contain both hydrocarbon and water resources and their characteristic fabrics.

Redesign of Sedpak incorporates open source software applications and tools. New design continues to provide a platform for understanding how different geometries are produced by varying sea-level, sedimentation, and subsidence.

Computer modeling of sedimentary geometries that match interpreted sections is a repetitive exercise in parameter estimation, viewing of resulting geometries and adjusting of parameters to converge on a best match. Intuitive model parameters based on physical processes, including rates of clastic sediment accumulation and transport distance down slope in a two dimensional simulation space, offer valuable insight into a more quantitative modeling approach. Further information on the fabrics of the deposits can be obtained by means of coupling computer models of sedimentary geometries with physically based submodels that describe the spatial and temporal evolution of relatively small portions of the entire system. The origins of sediment geometries and facies are interpreted by comparison with observations of similar features in modern sedimentary systems and their processes and then the interpretations are tested with the SEDPAK simulation. The question is: do input parameters match those inferred from current field observations parameters set to create basic sequences stratigraphic systems tracts, including prograding low-stand and high stand systems tracts, and retrogradational transgressive systems tracts? The same applies to in-situ carbonate accumulation. Are the depth-production rates reasonable?

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SEDPAK

What is SEDPAK?

SEDPAK provides a conceptual framework for modeling sedimentary fill of basins by visualizing stratal geometries as they are produced between sequence boundaries. The simulation is used to substantiate inferences drawn from the potential for hydrocarbon entrapment and accumulation within a basin. It is designed to model and reconstruct clastic and carbonate sediment geometries which are produced as a response to changing rates of tectonic movement, eustacy, and sedimentation. The simulation enables the evolution of the sedimentary fill of a basin to be tracked, defines a chronostratigraphic framework for the deposition of these sediments and illustrates the relationship between sequences and systems tracts seen in cores, outcrop, and well and seismic data.

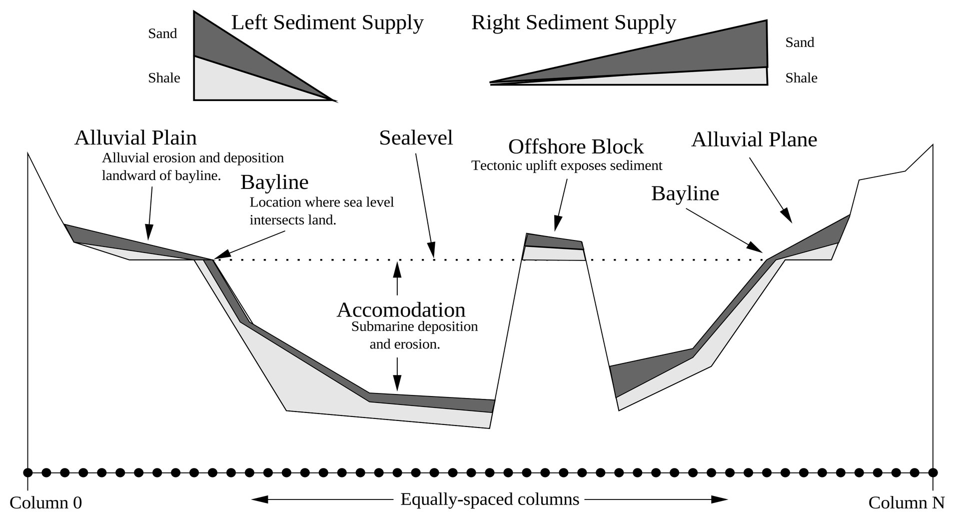
What assumptions are made in the simulation algorithms?

- Sea level position, tectonic movement and sedimentation all vary independently.
- Tectonic movement is vertical only but SEDPAK accounts for combined effects of crustal cooling and isostatic response to sediment loading.
- Subsidence due to compaction is handled separately from tectonic subsidence.
- Clastics are deposited first followed by carbonate deposition.
- Clastic sediments first fill the accomodation of the shelf landward of the bayline break as alluvium and shallow marine sediments. Sediment is then deposited in the submarine environment downslope from the bayline break to a prescribed distance on the underlying surfaces that are inclined below a specific angle.
- Sediment is deposited as lithologic ratios.
- Simultaneous with deposition, sediment is returned to sediment supply after erosion.
- Benthic carbonates accumulate as a function of water depth and time.
- For all time and location data, SEDPAK linearly interpolates values between given input values and extrapolates from intermediate values if start or end values are not defined.

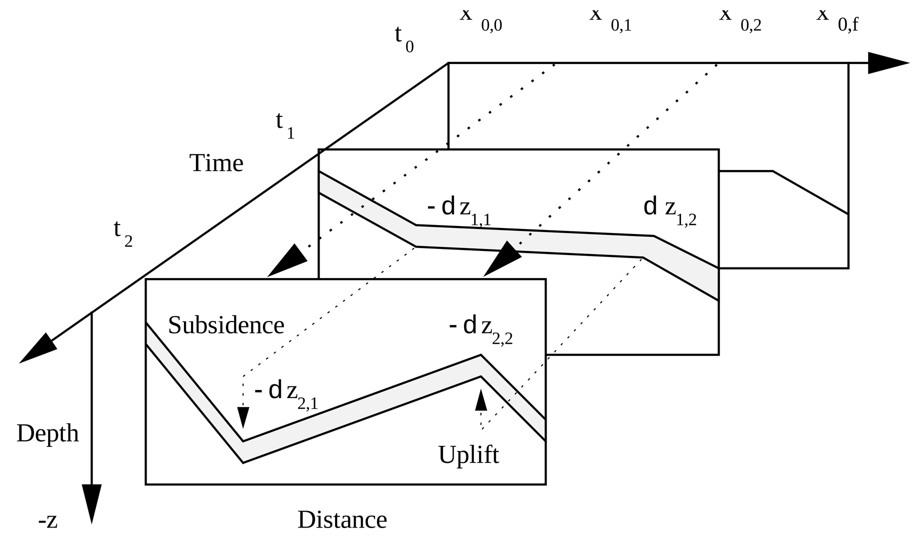
What are major controls of sedimentary fill in SEDPAK's simulation algorithms?

- **Subsidence**
  - The thermal and mechanical properties of the lithosphere exert important controls on the formation of sedimentary basins (Steckler, 1990).
  - Thermal subsidence rates and the magnitude and distribution of subsidence due to loading vary in basins of different tectonic settings (Steckler and Watts, 1978; Stephenson, 1990).
- **Eustasy (global sea level)**
  - Eustasy refers to the sea level relative to a fixed datum, such as the center of the earth. Global sea level variations results form changes in either oceanic basin volume or water volume. Eustasy combined with subsidence results in relative sea level variations, which control accomodation for sediment deposition (Posamentier et al., 1988; Posamentier and Vail, 1988).
- **Sediment Supply**
  - The role of sediment supply in transgressions and regressions is a fundamental one… (Schlager, 1994). When the rate of sediment supply is greater than the rate of relative sea level rise, accomodation space will be filled.

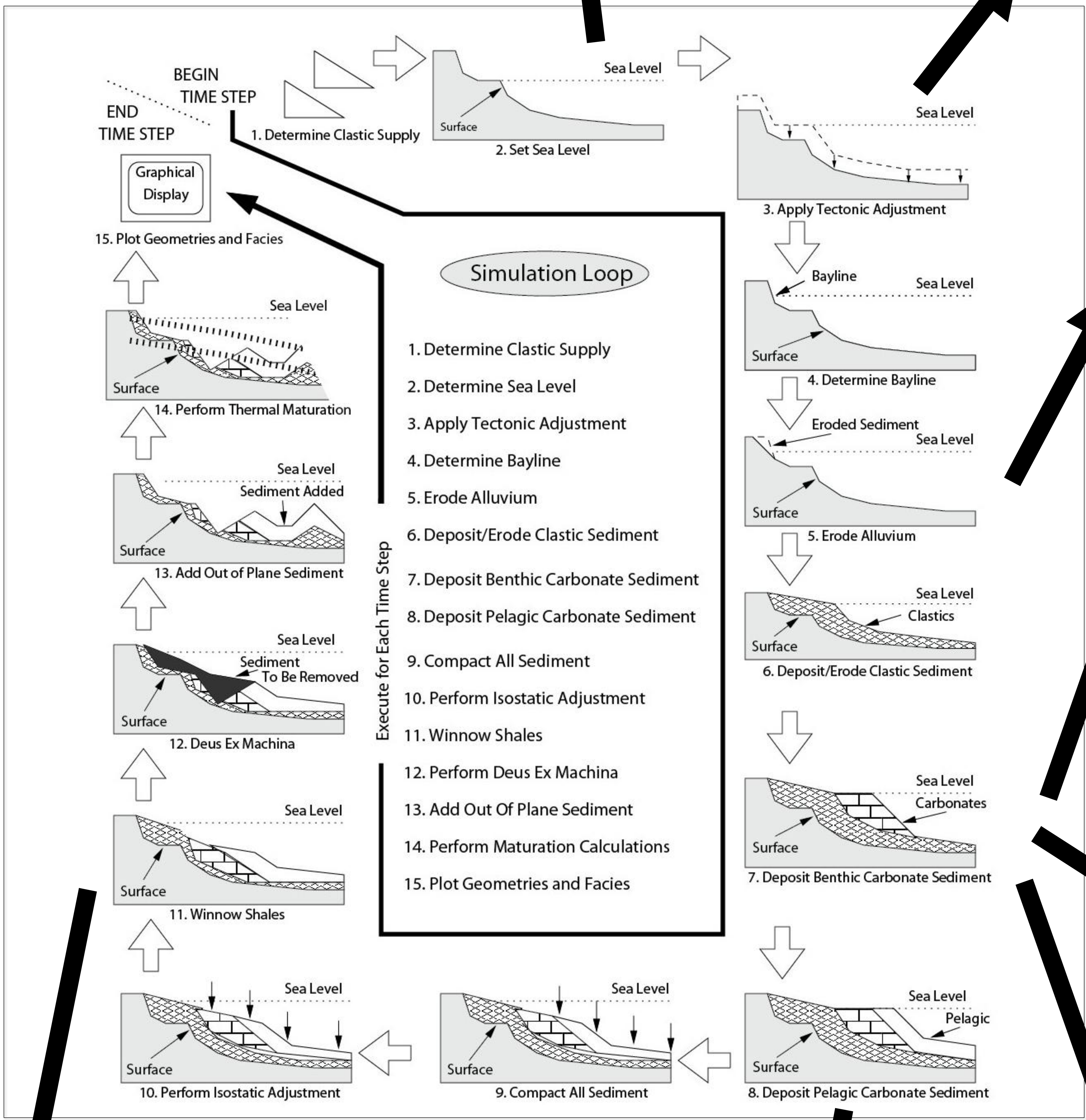
SEDPAK Time Step Operations

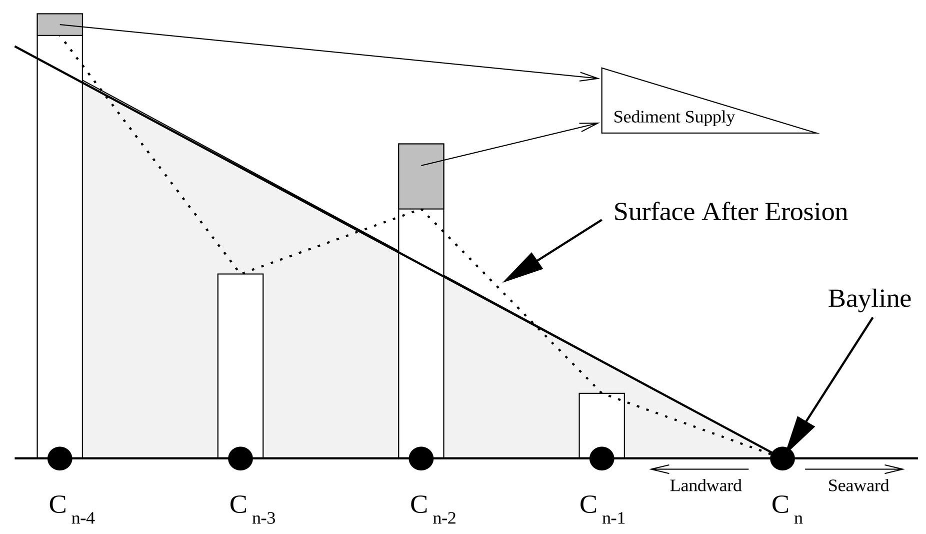


Basin Setting. The basin is divided into equally-spaced columns. After the bayline is located, alluvial sediment is eroded landward then submarine sediment is deposited or eroded. Offshore blocks created by sea level change or tectonic adjustments may be eroded to the initial basin surface.

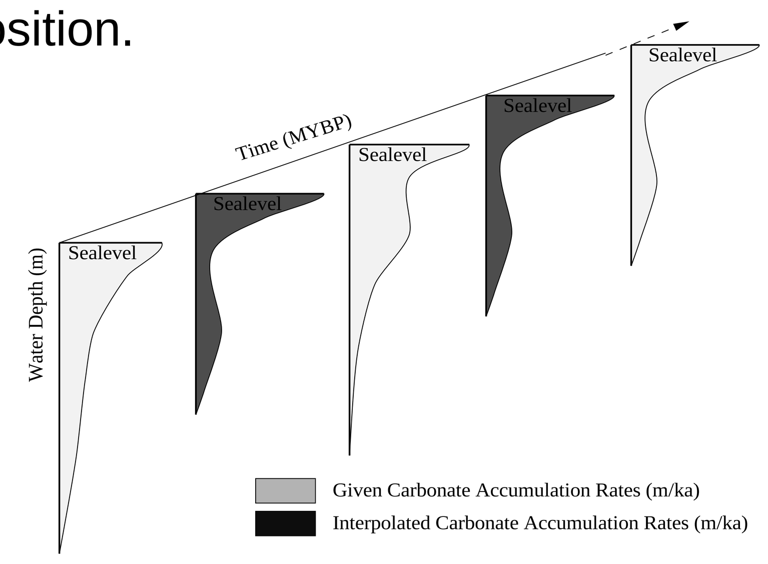


Vertical Fault Displacement. A vertical fault begins at time t_0. The vertical arrows show displacement occurring between two adjacent columns over time.

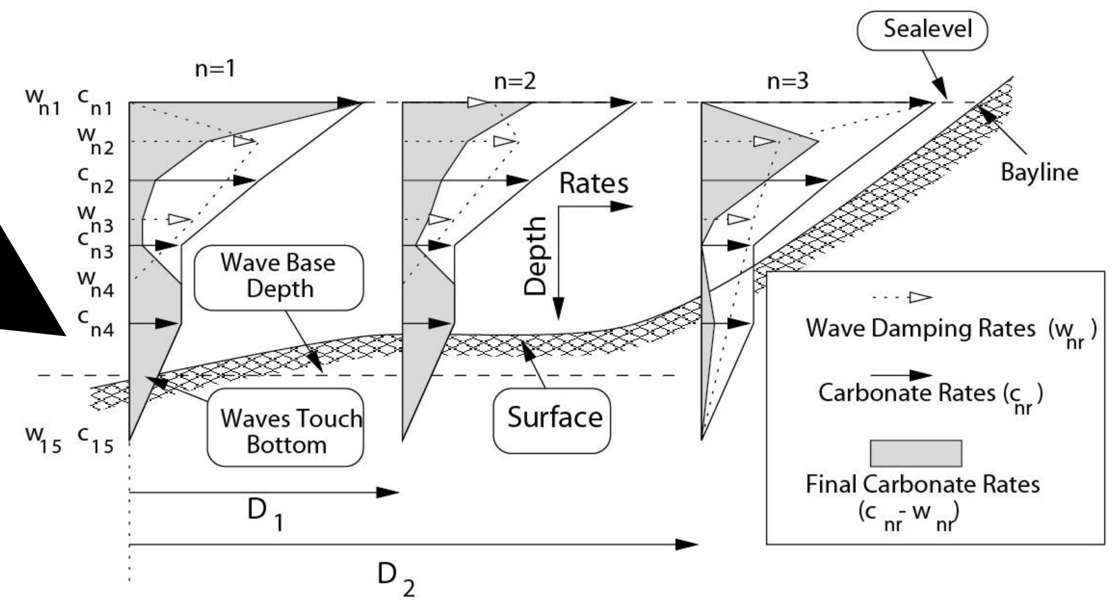




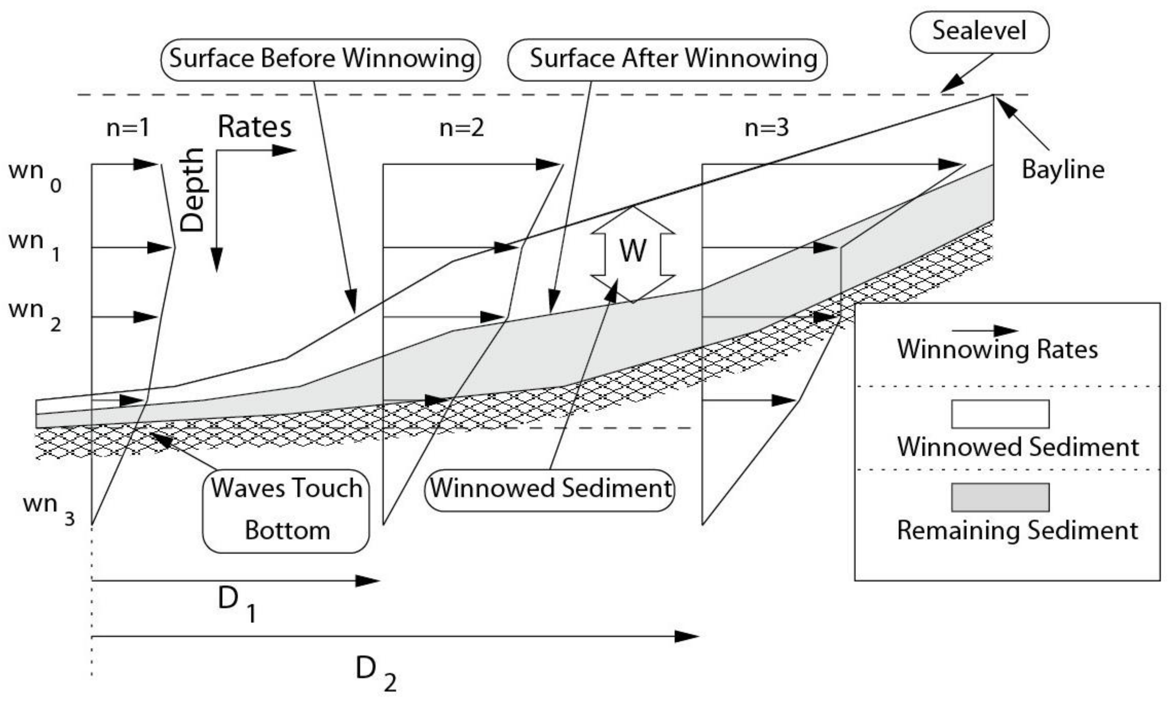
Schematic representation of Erosion. Sediment above the erosional line at columns C_{n-2} and C_{n-4} is removed. No sediment is eroded from C_{n-1} or C_{n-3}. Eroded sediment is returned to the sediment supply for later deposition.



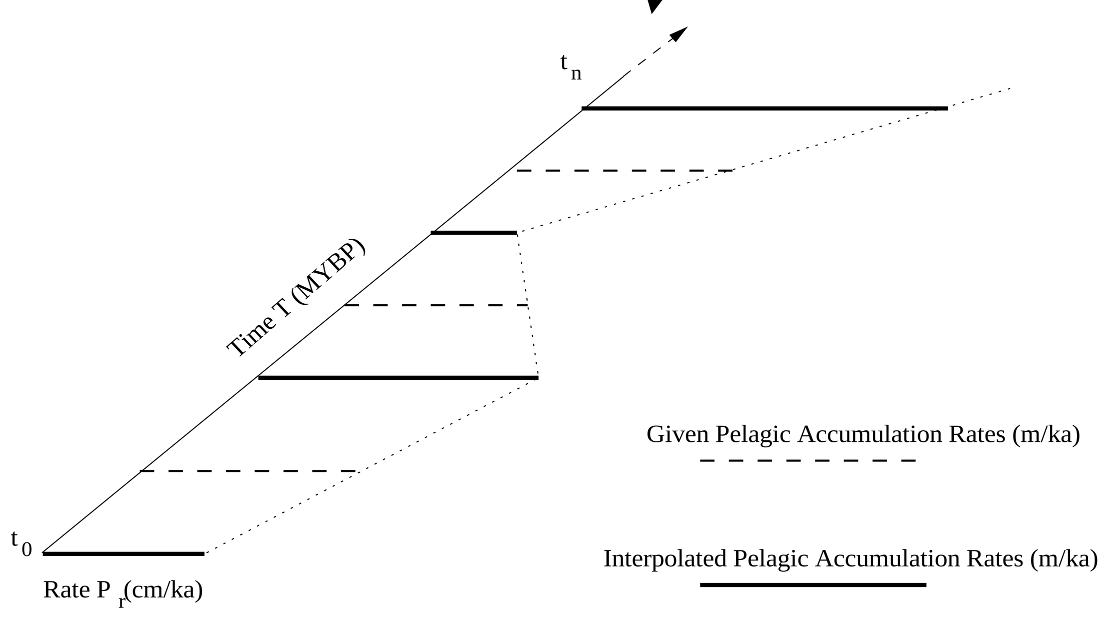
Varying Carbonate Rates. Rates are interpolated between depth-rate curves given at specified times in model parameters.



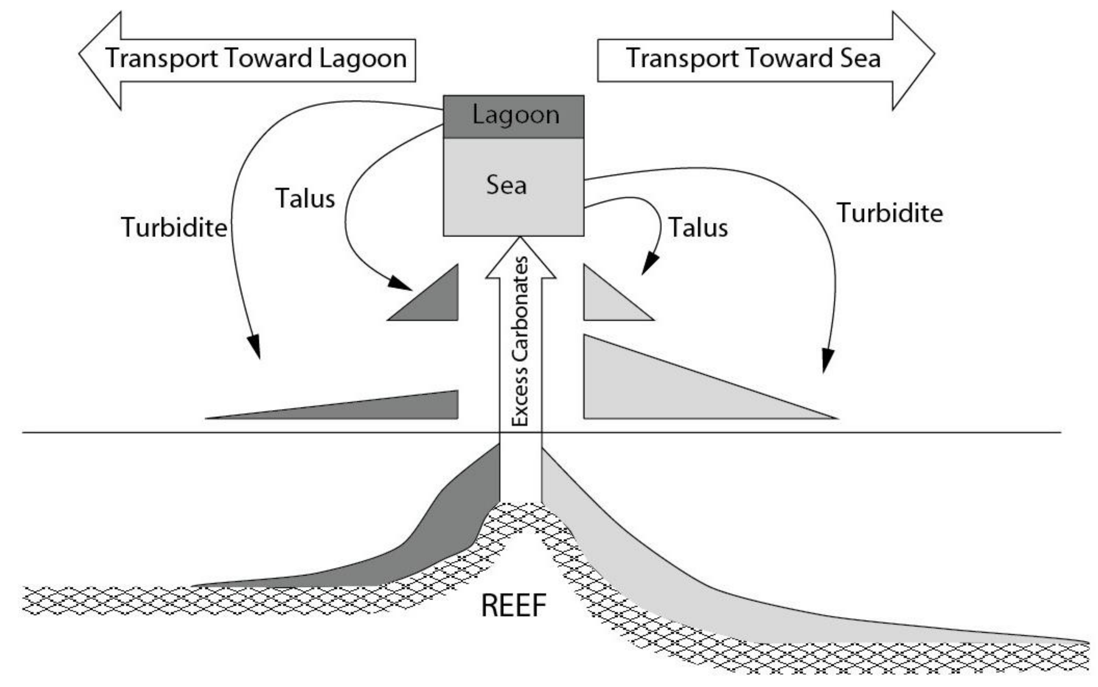
Wave damping of carbonate accumulation. From wave base in a landward direction to the right, wave damping rates (W_{nr}) are subtracted from the carbonate rates (C_{nr}) where n is the distance from wave base and r is the rate at that distance.



Winnowing of shale by waves. Waves touch bottom at left (n=1). The winnowing curves specify the percentage of shale to remove from the sediment column to the right of wave base.



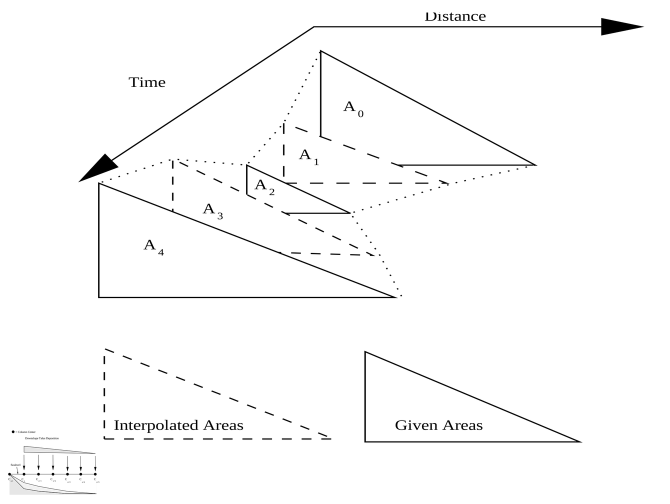
Pelagic deposition of Carbonates. Pelagic rates in meters/Ka can vary over time and are linearly interpolated between user defined rates at specific times.

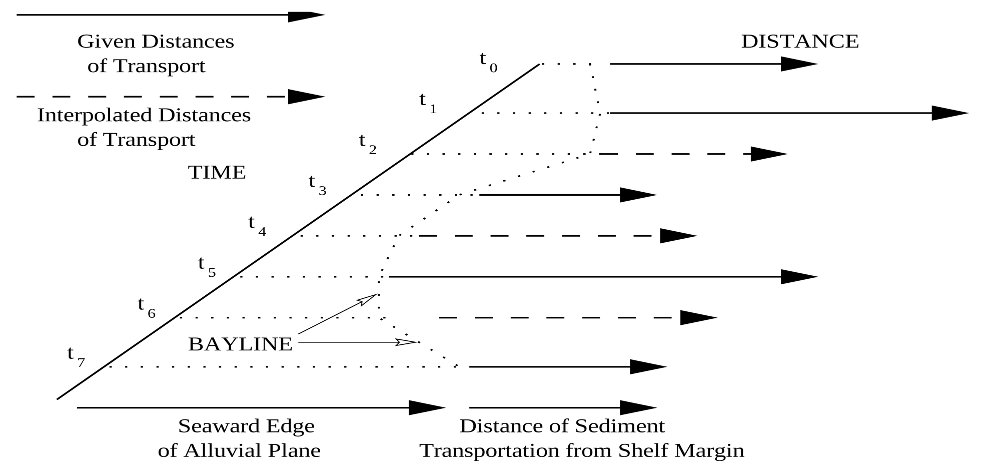


Excess carbonate production is bypassed in the the lagoon and basin. A proportion of the excess is transported either into the lagoon or basin as a percentage. For each proportion, another percentage can be specified as talus or turbidites with specified distance of penetration.

Clastic Deposition

Proscribed Clastics Areas and Distances

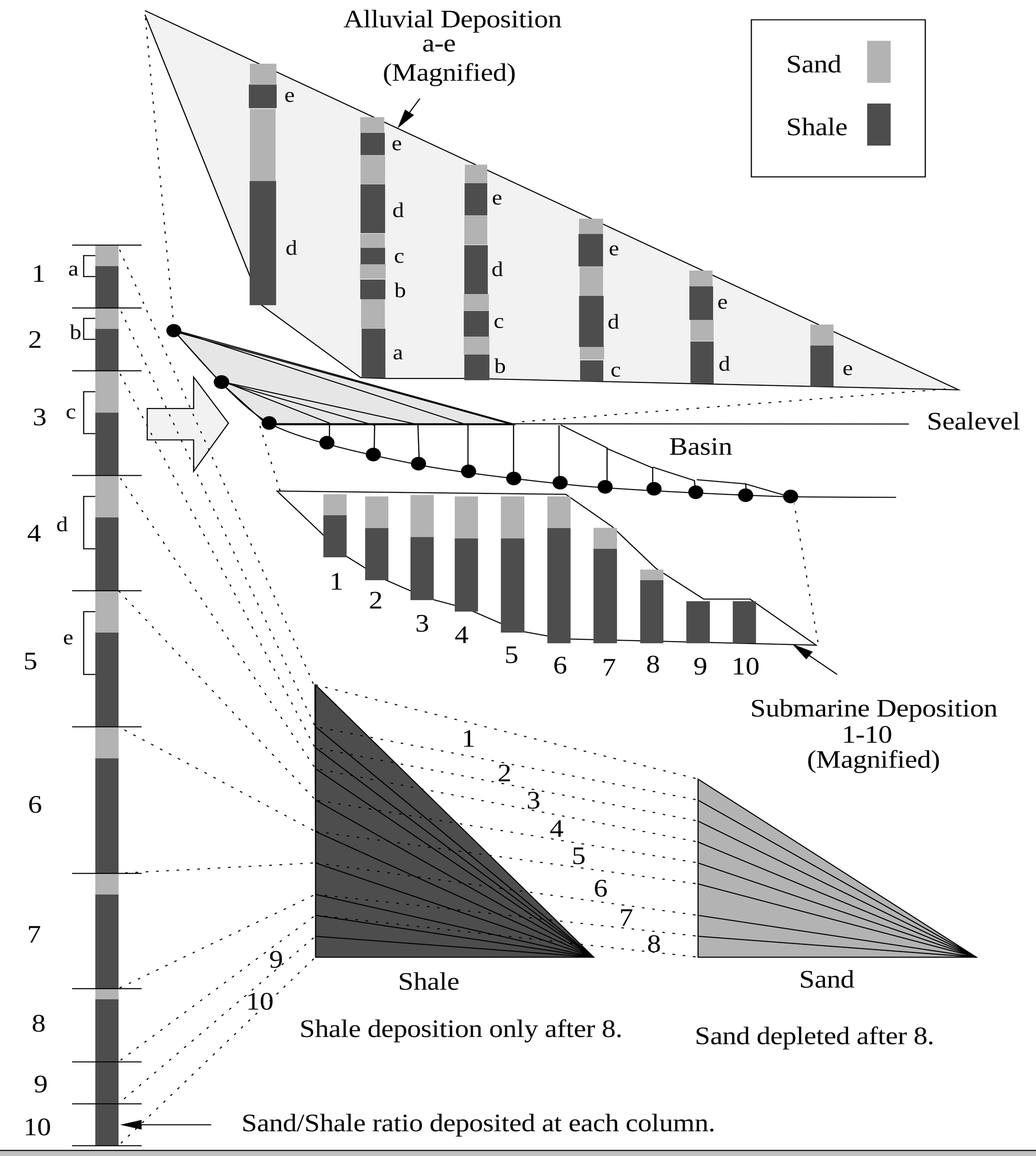




Sediment supply is given as a series of triangles which can vary areas through time. The supply is linearly interpolated between defined areas for each time step.

Sediment transport distance into the basin is equivalent to the base of the supply triangle and extends from the seaward edge of the alluvial plane which are linearly interpolated for each time step.

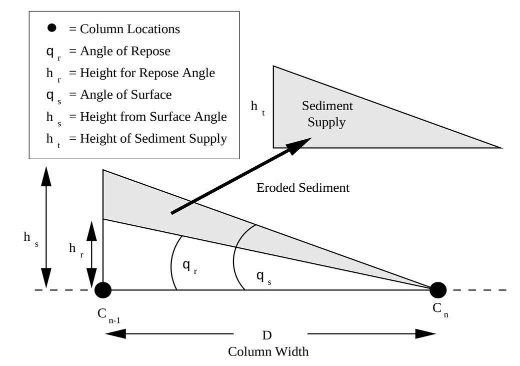
Example of Sand/Shale Ratio Deposition from Sediment Triangles



In shallow water at column 1, the basin is filled to sealevel then sediment is deposited into the alluvial plane at the angle of alluvial deposition. As accomodation increases seaward, deposition increases until maximum sediment is deposited in column 6. Given an initial supply that was shale prone, sand is depleted in column 8 then the remaining shale is deposited in columns 9 and 10.

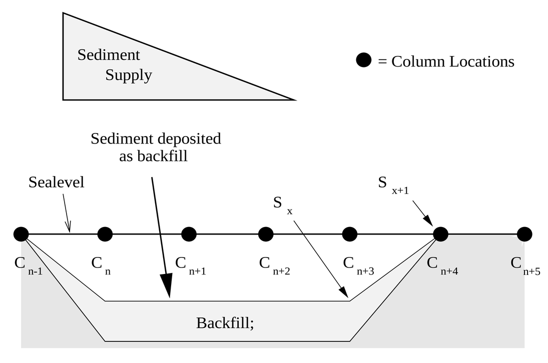
Sediment Deposition Operations

1



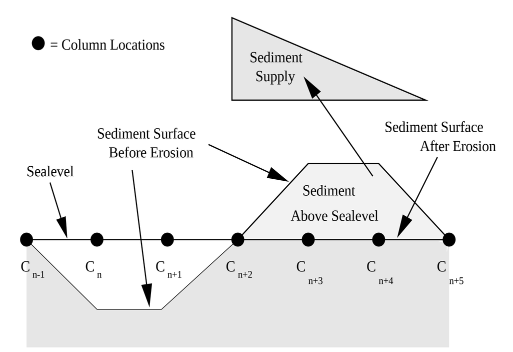
Submarine erosion. Erosion takes place when sediment in current column has height greater than projected erosional surface which is defined by the angle of repose θ_r. Sediment height in this example is removed at height h_s defined by repose height h_r. Sediment removed from column C_{n-1} is returned to the sediment supply (added to h_t) for later deposition.

2



Submarine Backfill. In this example, sediment is being deposited from the left. When the height at column C_{n+4} is greater than the height at C_{n+3}, depressions will be filled in the columns to the left of C_{n+4}.

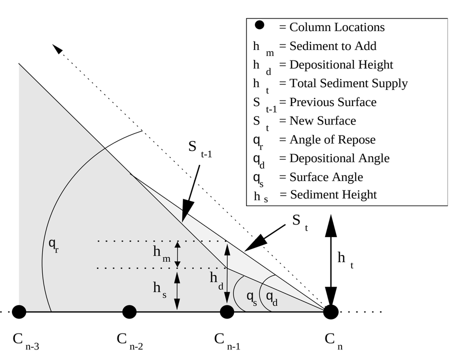
3



Erode exposed Sediment. If sediment lies above sealevel, remove and return to supply. Exposed off-shore sediment is a result of tectonics or sealevel change. No erosion can take place below the initial basin surface. In this example, sediment at columns C_{n+3} and C_{n+4} is removed at sealevel height and returned to sediment supply.

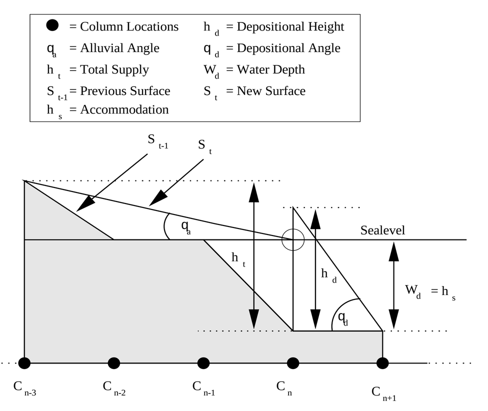
1	$h_r < h_s$	Erode submarine sediment
2	$s_x > s_{x+1}$	Backfill into depression
3	$W_d < 0$	Erode exposed sediment offshore
4	$W_d >= h_s$, $h_t <= h_s$	Deposit to hs then fill submarine backslope
5	$W_d < h_s$, $h_t > w_d$	Deposit to sealevel then fill alluvial backslope
6	Otherwise	Deposit downslope sediment wedge

4



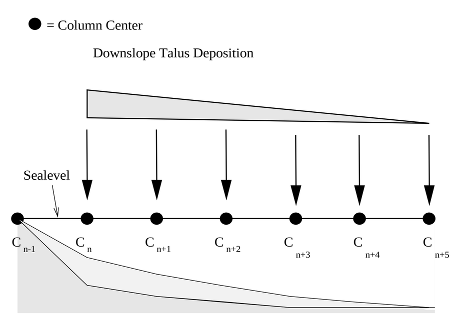
Submarine Deposition. At column C_{n-1}, an amount of sediment h_m can be deposited on S_{t-1}. The height h_d is determined by the depositional angle θ_d. The erosional surface, shown as a dotted line, is above the height at C_{n-1} where no erosion occurs. Sediment supply h_t must be available to fill to the depositional angle.

5



Deposit up to sealevel and fill onto alluvial plane. If sediment is available and the depositional angle θ_d is not exceeded, fill accomodation landward and determine new bayline. If deposition if possible, all accomodation is filled at the alluvial angle θ_a and the shoreline is shifted landward.

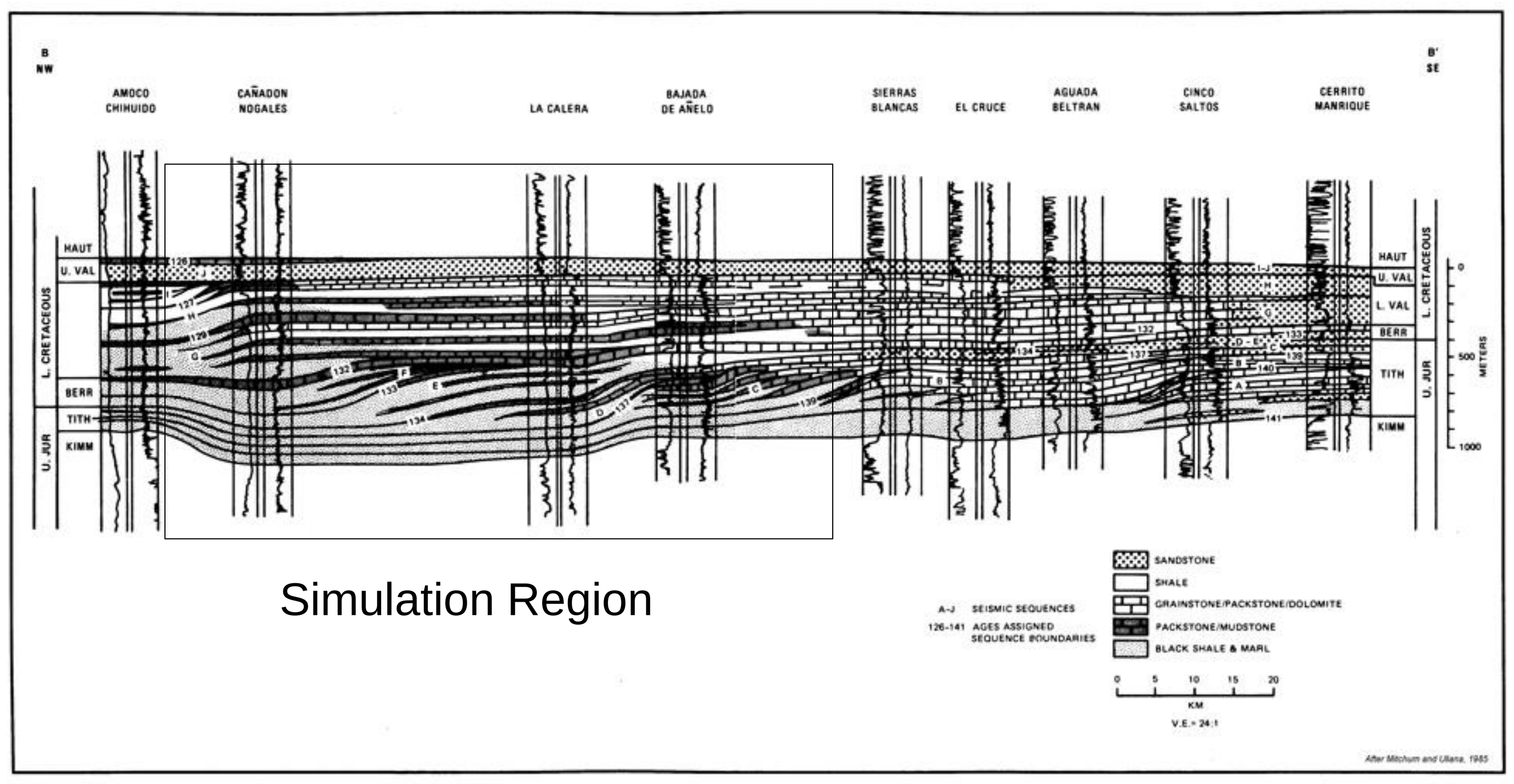
6



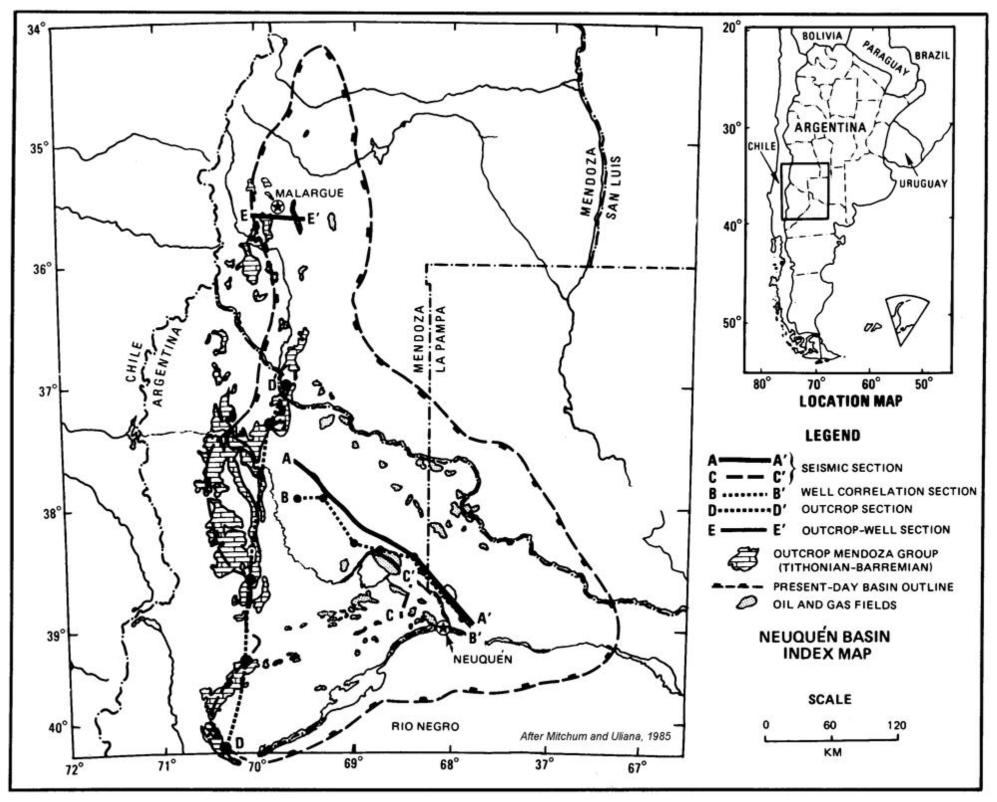
Deposit all remaining supply h_t downslope as sediment wedge.

Neuquén Basin Case Study

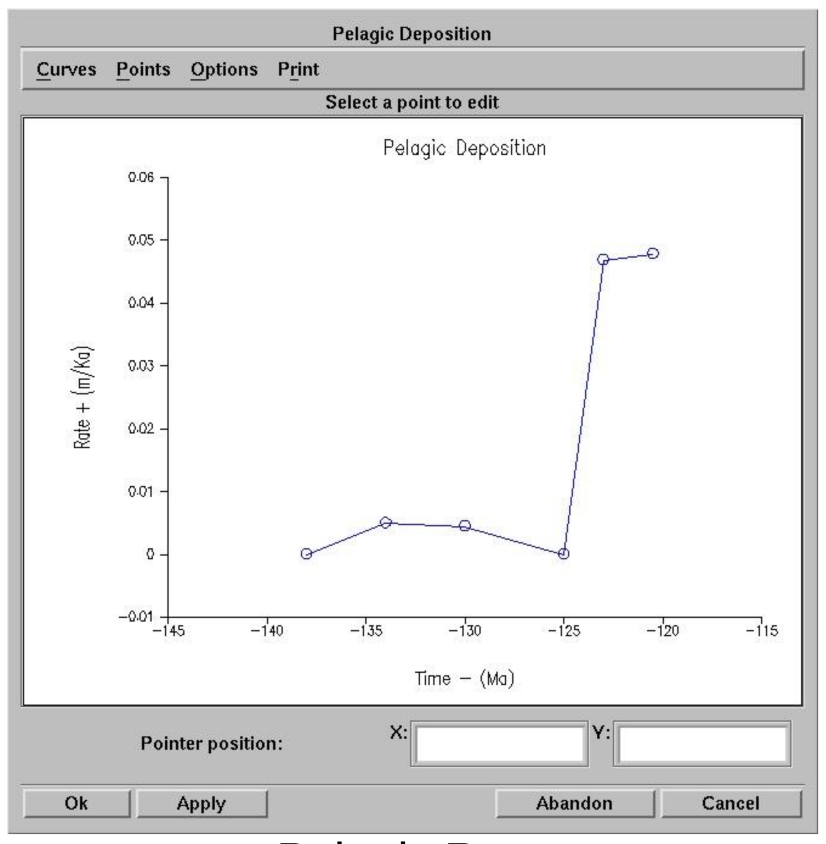
- Input Parameters
- User Interface
- Plots



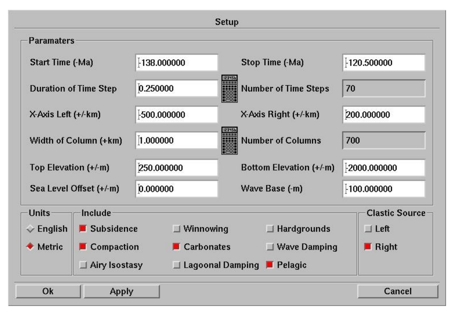
Regional Stratigraphic Diagram



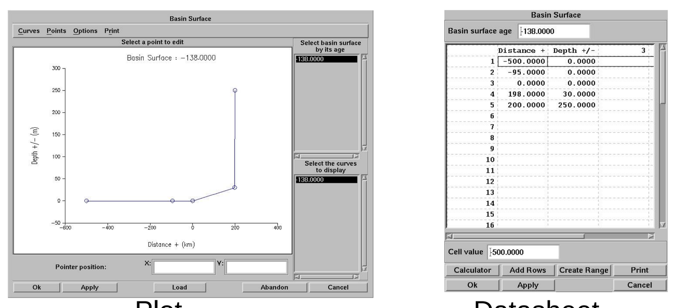
Basin Location Map



Pelagic Rates



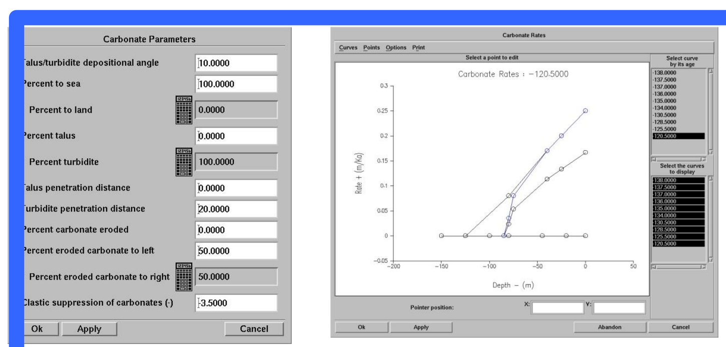
Setup Parameters



Plot

Datasheet

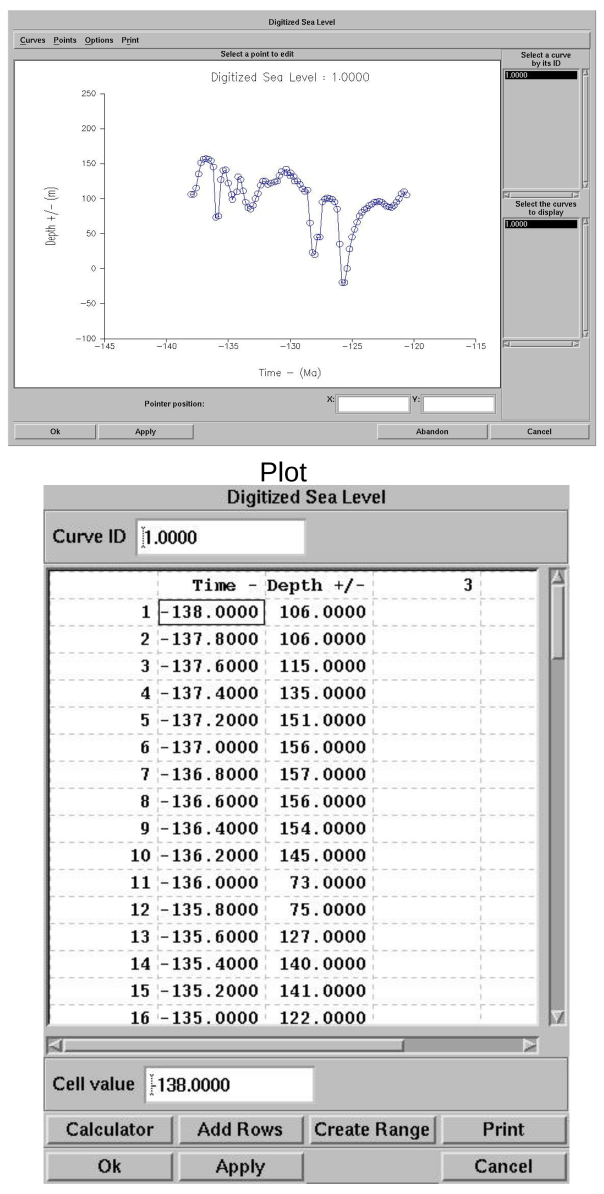
Initial Basin Surface



Parameters

Rates

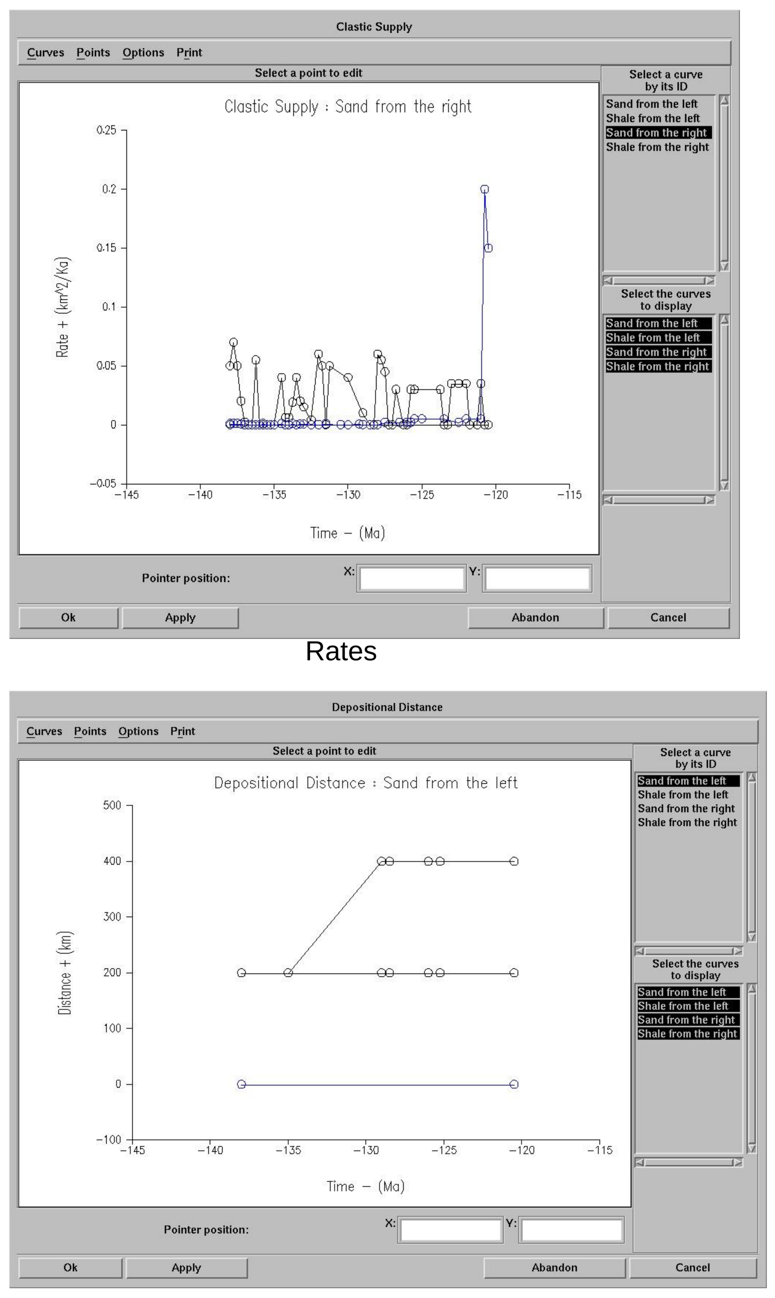
Carbonate Deposition



Plot

Datasheet

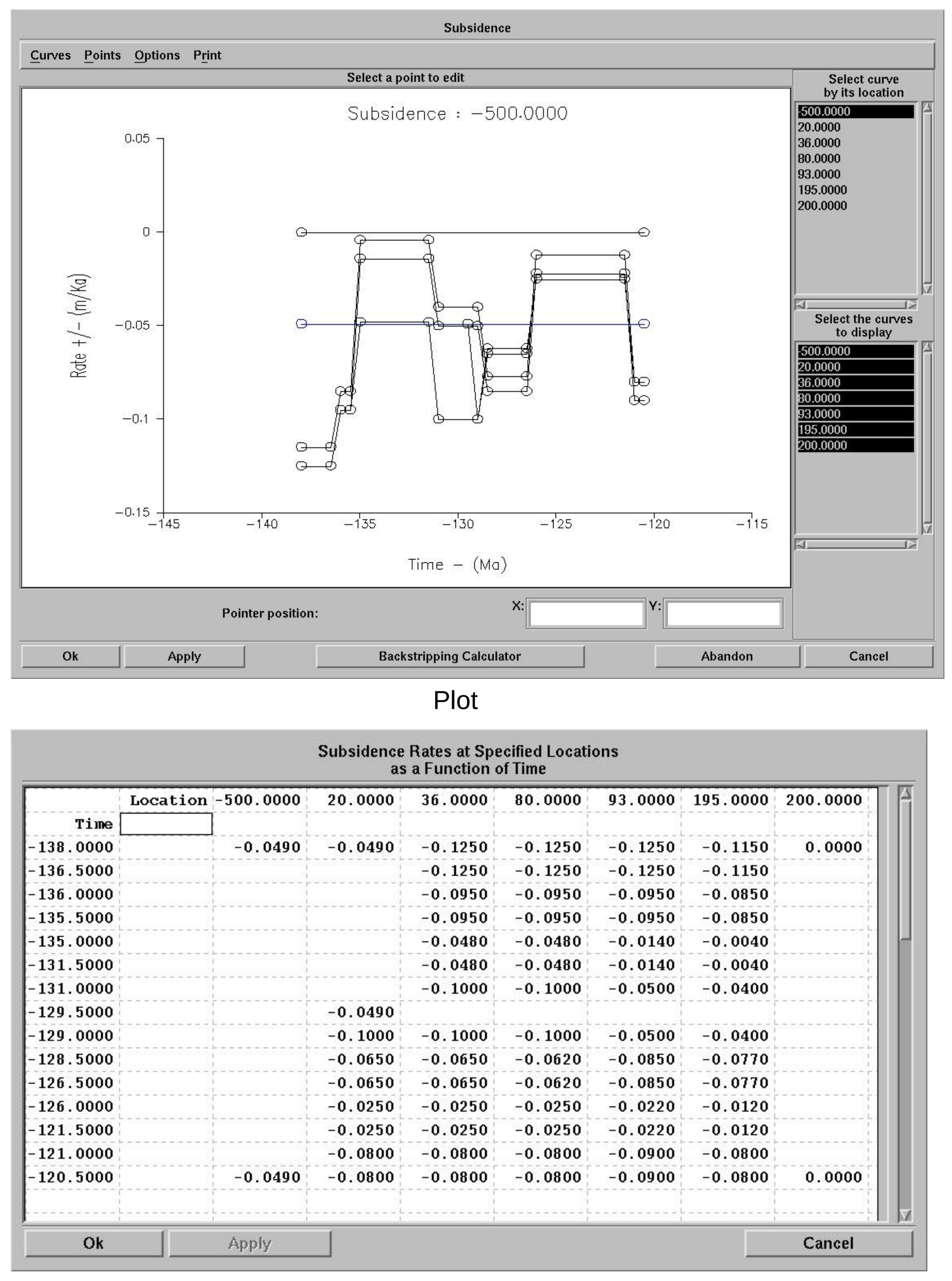
Sealevel



Rates

Distances

Clastic Deposition

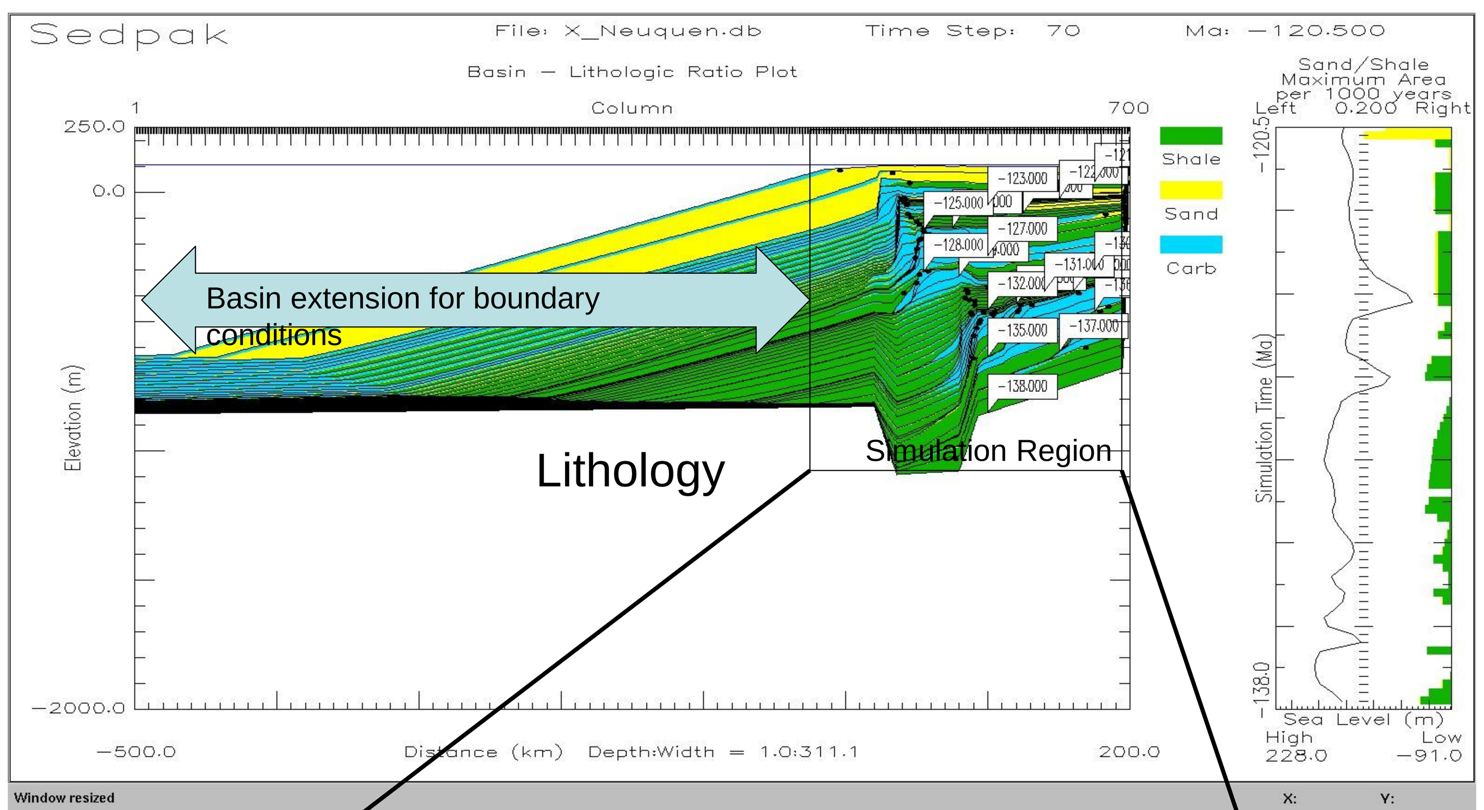


Plot

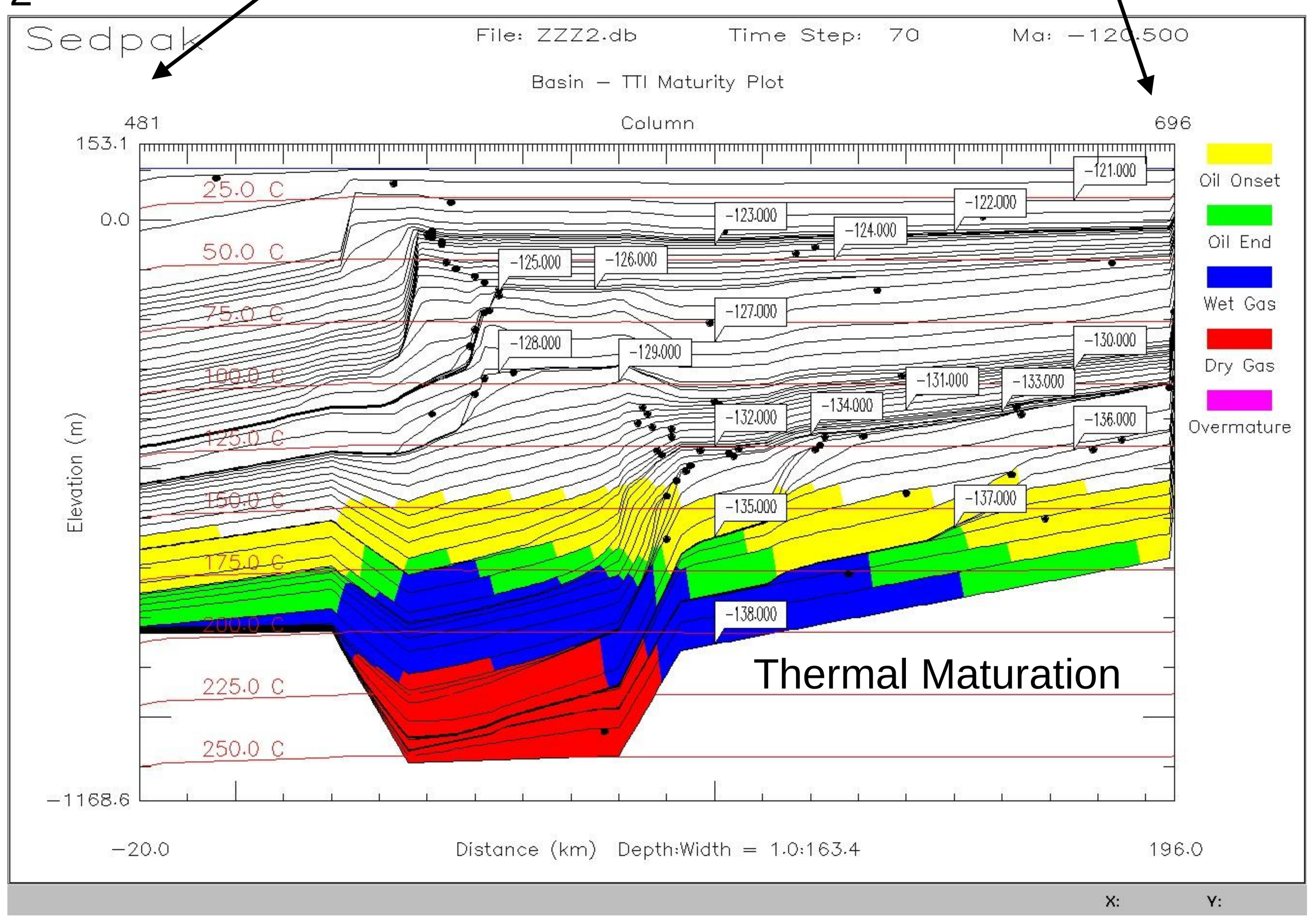
Datasheet

Subsidence Rates

1



2



1. The top plot shows the shale, sand and carbonate lithology ratios in the basin as shale, sand and carbonate ratios in the basin. The space to the left of the simulation region was needed to correct for boundary conditions. Shale, sand and carbonates are represented as ratios.

2. The bottom plot shows hydrocarbon maturation and gradient lines for input parameters having constant surface temperature of 14 degrees C and constant gradient values of 0.1 degrees C per meter.

The Cretaceous Carbonate and Clastic Fill of the Neuquén Basin

Mitchum, and Uliana (1985) made a study of the Upper Jurassic-Lower Cretaceous interval in the Neuquen basin, Argentina. This provides a good example of carbonate sedimentary response to eustatic sea-level change in a rifted basin that has produced hydrocarbons for over 50 years. We used Sedpak to analyze a well cross section taken from the area and which Mitchum, and Uliana (1985) had used in their integrated stratigraphic approach, including seismic stratigraphy for sequence identification and configuration, wells and outcrops for lithologies and porosity types, and outcrops for paleontological age, ecological data, and detailed physical stratigraphy. The SEDPAK section and that of Mitchum, and Uliana (1985) shows the Vaca Muerta, Quintuco, Lorna Montosa, and Mulichinco formations are time-transgressive lithofacies units within a series of prograding sequences that laterally filled the shallow, stable basin. There are at least nine clinoform-shaped depositional sequences, and they span the Tithonian, Berriasian, and Valanginian stages. All of them consist of seismically mappable shelf, shelf-margin. slope, and basin facies. In the wells tied to seismic data, the predominantly carbonate reservoir rocks of the Lorna Montosa and Quintuco formations represent, respectively, the inner- and outer-shelf segments of individual clinoform sequences. Hydrocarbon-source shales of the Vaca Muerta Formation occur in slope and basin positions. The youngest prograding unit is characterized by shelfal to continental sandstones of the Mulichinco Formation. The degree of shelfward restriction, lateral progradation, and vertical aggradation of the sequences appears to be strongly controlled by global trends of eustatic rises and falls. Other depositional controls, including thermal subsidence and sediment influx were modeled assuming slow, nearly constant rates in medial to late stages of basin evolution.

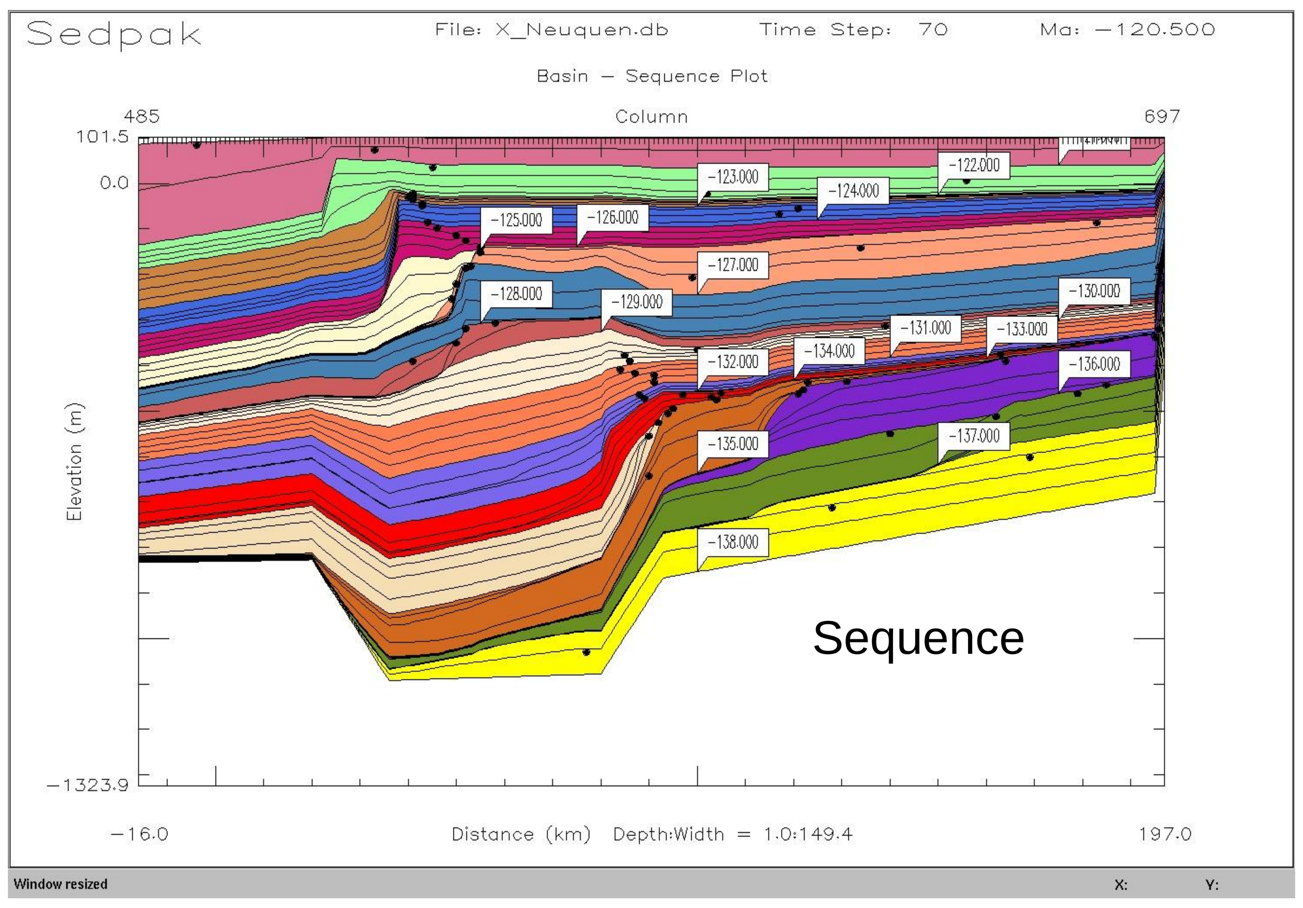
The Sedpak idealized shelf-to-basin lithologic model of a given sequence progresses from terrestrial sandstones and shales through marine inner-shelf micritic limestones, dolomites, and shales; middle-shelf oolitic and skeletal carbonates and shales; outer-shelf molluscan-micritic limestones and shales; and slope and basin dark organic shales.

Outcrops along the western basin margin exhibit depositional characteristics slmllar to those of the subsurface. In the western outcrop area. lithostratigraphic units are time-transgressive from south to north toward the basin center. In the northwestern outcrop area (Malargue) the timing and depositional response to eustatic changes can be documented through interpretation of detailed stratigraphic and paleontologic observations by Mitchum, and Uliana (1985) and other authors.

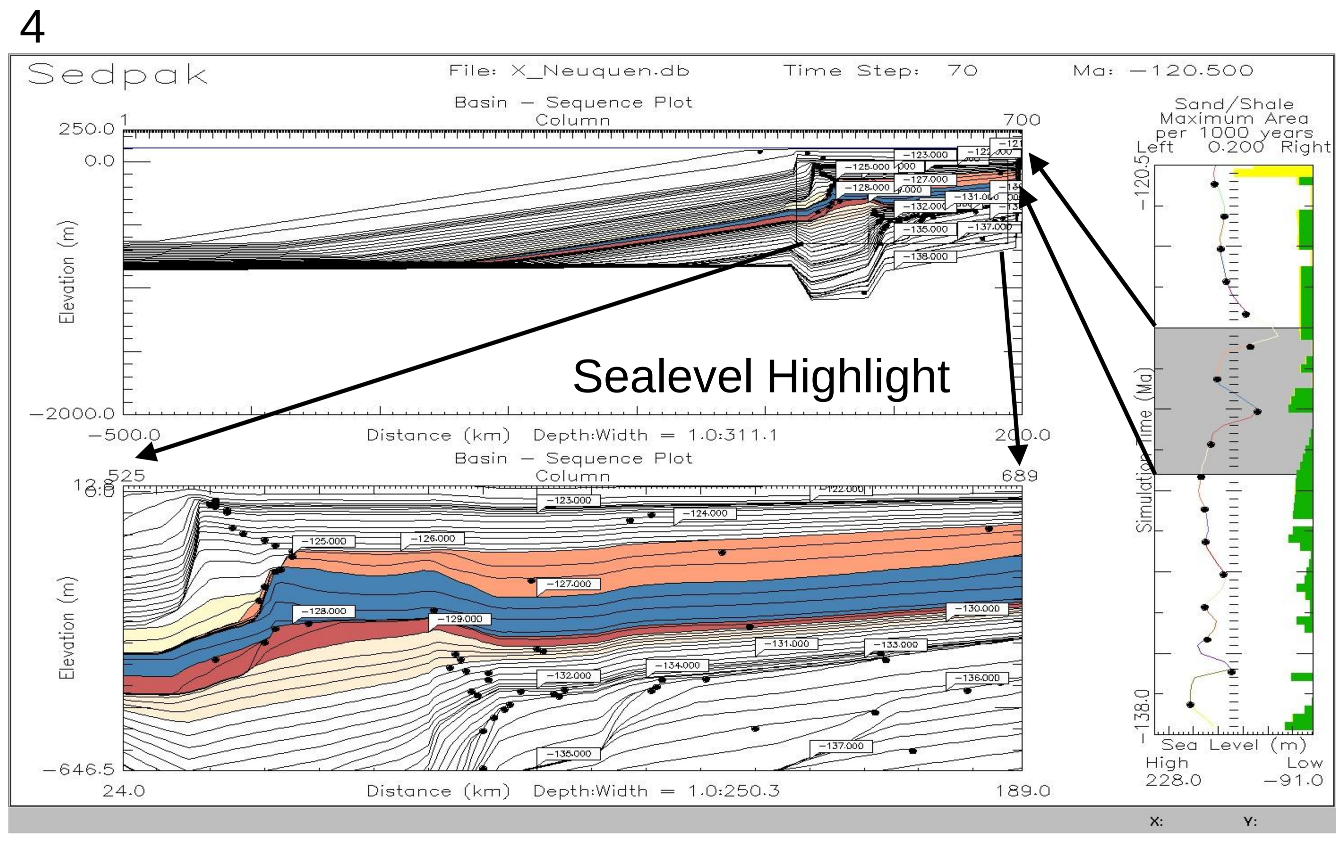
To recreate the geometries that Mitchum, and Uliana (1985) had mapped we first simulated the area as extending hypothetically beyond the area of interest. This was done to avoid unrealistic edge effects induced by the simulation.

Bibliography
Mitchum, R. M., Jr., and M. A. Uliana, 1985, Seismic stratigraphy of carbonate. II: An Integrated Approach to Hydrocarbon Exploration: AAPG Memoir 39,p 255 -274

3



4



3. The top plot shows sequences having boundaries defined at user defined points on sea level curve.

4. The bottom plot is an example of selecting a portion of the sea level curve to be highlighted in the basin plot. Also in this example, the simulation region has been highlighted then displayed as a zoomed view in the lower plot.

Information and download: sedpak.geol.sc.edu

Software Development History

- First version was written in Mainframe Fortran
- SEDFIL converted to Unix C language and renamed SEDPAK
- Real-time plotting in X-Window System
- **(Industrial Consortium funding begins**
- Keyword-Value File format (.db) for input files
- New depositional algorithms
- Motif Editor and Execution user interface
- WCL Widget and VOGLE vector graphics libraries
- Ported to AIX, BSD, Solaris, IRIX
- Includes examples and test files
- ***Industrial Consortium funding ends)***
- Ported to Linux
- Not open source yet, but free to download

Lessons Learned

- Low-level user interface development can quickly consume all resources
- Avoid operating system and compiler dependencies
- Avoid different 32-bit and 64-bit operating system releases
- Use platform independent tools and libraries

New Python Integration

- Added user functionality without major modifications to SEDPAK source code
- Python language
- Startup Menu
- Integrated Help
- Snapshot and movie files
- Line vector over scanned image overlay

Proposed Sedpak-Next Generation (Plans)

- Open Source IPython
- Interpreted, not compiled, no 32-64 bit
- Interactive
- 2-D space first
- Tight control and inspection of each time step
- Spreadsheet integration
- Capable of web hosting
- Platform independent
- Ubuntu Linux Live CD, native or virtual machine
- Avoid different 32-bit and 64-bit operating system dependencies
- Use platform independent tools and libraries