CONSTRUCTING GEOLOGICAL CROSS SECTIONS WITH A CHRONOLOGY OF GEOLOGIC EVENTS

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Abstract

Geologists attempt to explain the current geological structure in terms of a sequence of processes in time. As an analytical tool, they frequently use cross sections. Current research in the use of geographic information systems (GISs) in geology has concentrated on 3-D modelling of geologic structure as a snapshot without reference to time. This paper is a first step toward the integration of space-time reasoning about geological processes into a GIS. It presents a method for constructing cross sections from geologic events to examine the differences between the temporal and observable characteristics of cross sections. This method closely follows the cognitive spatio-temporal models used by geologists when analyzing a cross section. Spatial and temporal relationships are defined in algebraic formalisms and implemented in an object-oriented model. The formalisms show that there is a one-to-many relationship between a cross section and the histories that may generate it, and that two histories are observably equivalent if they generate the same cross section.

1. Introduction

> "The geometry of rock bodies can easily be reproduced at a reduced scale. We need to go beyond geometry, however, to understand how structures came into being." (Dennis, 1972, p.109)

1.1 Motivation

Simple observation of Figure 1 might suggest a land use pattern to a planner, land value to an assessor, or a 2-cell space to a topologist. For a geologist, this pattern represents a cross section and is the first step in understanding the tectonic events that led to the current situation. Geologists express their interpretation of geologic cross sections as a history of the geologic events that *could* have produced the cross section.

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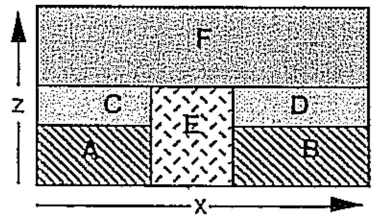


Figure 1. Geological Cross Section

If Figure 1 were interpreted topologically, we would say, among other things, that A is adjacent to C and E. In cross section, however, both axes are not equal. The z axis (depth) is naturally ordered by time, because the principal of super-imposition states that any stratigraphic layer can only *cover* what was present before it. Gravity places stratigraphic layers at the bottom of the cross section first and age decreases as you move up. Only through the expenditure of a great deal of energy in the form of folding can this natural order be reversed.

A geologic interpretation of Figure 1 translates the topologic relationships that can be observed into temporal relationships. This is performed by identifying the sequence or sequences of valid events that could generate the observed cross section. An interpretation of Figure 1 might be:

1). A-B was deposited.
2). C-D was deposited on A-B.
3). A vertical fracture developed through A-B and C-D.
4). E was intruded along the fracture.
5). A discontinuity occurs between C-D/E and F
6). F was deposited on C-D and E.

It is important to note that the geologist is creating an inferred history, based on topological relationships evident in the cross section, information about the rocks (age, composition, deposition environment, etc.), and expert knowledge about the macro-level events that effected the region.

1.2 Previous Work

Past efforts to apply geographic information systems (GISs) to geological problems have focused on modelling the three-dimensional aspects of geology (Carlson, 1987; Raper, 1989a; Raper, 1989b; Turner, 1989). A three-dimensional GIS is very effective in modeling the existing subsurface structure with a number of methods ranging from octree to voxels. These models are by their design accurate static representations of the geology in question (Carlson, 1987; Youngmann, 1988). However, these systems fall short of modelling and communicating temporal progression.

Three-dimensional GISs concentrate on capturing accurate spatial information, primarily expressed as coordinate geometry. But precision is often not available to the geologist and she is more interested in a qualitative (i.e., not spatially accurate) assessment of the situation. Primarily a geologist interprets the situation as a sequence of events that shaped the geology of the area.

Building databases that model temporal aspects is a topic of current research (Shoham and Goyal, 1988). One distinguishes between time-based databases that represent the situation at given points in time, and change-based models that concentrate on actions and states. The latter model is used here. The discussion of different time perspectives is probably less relevant for modeling geologic situations (Snodgrass and Ahn, 1985; Snodgrass, 1987).

1.3 Objectives

This work is part of a larger effort to include space and time as used by such applications as geological processes into a GIS. Our goal here is to model geological cross sections as a sequence of events and to build a tool that produces valid cross sections and properly analyzes a given cross section. This approach is different from previous work that concentrated on static 3D models. It includes temporal change in the model and is, therefore, suitable for analysis of dynamic processes in geology and other earth sciences.

In this paper, for simplicity we focus on the cross section, because it is a geologic model with which all geologist are familiar, and it is a simple model which has a history of providing understanding about the geologic structure. Geologists have used the geological cross section as a tool for modelling geologic structure, and this simple model has been the basis for many economically rewarding (and disastrous) undertakings (Simmons, 1982). We further restrict our attention to sedimentary processes, to keep our exposition within the limits imposed.

In the rest of this paper we will discuss the methods used to develop the formal models of geologic cross sections for this study, how those formal models were implemented in an object-oriented prototype, the results derived from exercising the prototype, and finally draw some conclusions about possible applications and where further study is required.

2. Geologic Principals

The basic concepts used by modern geologists are in most cases less than 200 years old. While strata, or layers of rock, were observed by Lazzaro Moro of Venice in the early eighteenth century, there was little effort made to explain why these occurred and why they often were not horizontal to the Earth's surface. In the mid-nineteenth century, geologists began measuring strata, and mapping their observations. The geological maps and cross sections became the fundamental objective of geology during this period (Dennis, 1972).

A geologic map is created by making observations over the region under study and combines the individual observed angles of contacts between stratigraphic layers to develop structure for the region. From this sampling of information a geologist with an understanding of the processes that are possible infers what the most likely sequence of geological processes is that shaped the area. This understanding of geology as a sequence of events allows her then to infer the geological situation in areas for which no direct observations were made.

For this project, we have chosen to model only sedimentary rocks and sedimentary processes. The basic process is *deposition*. Sedimentary rocks are created from small rock particles settling out of muddy water. At some point sea level changes and the rock becomes exposed to erosion. The erosion process removes rock particles, and given time can remove all evidence that a particular stratigraphic layer ever existed.

When there is an erosional surface beneath a sedimentary layer it is called an *unconformity*. An unconformity is a break in the geological history and corresponds to one or more of the following events:

- Deposition of a layer that was subsequentially eroded away;
- Erosion of the existing rock;
- Emergence above sea level;
- Submergence

For the purposes of this project we chose to model only deposition and erosion. More complex processes such as folding are not handled in the present model.

3. Formalizing a Cross Section Model

We start with a very simplified model of a cross section (Figure 2), which has three components. The basic component is the *layer*. The layer represents a single homogeneous geologic unit. Layers are organized in *columns*, which contain an ordered stack of layers. Finally, columns are ordered by a *cross section*.

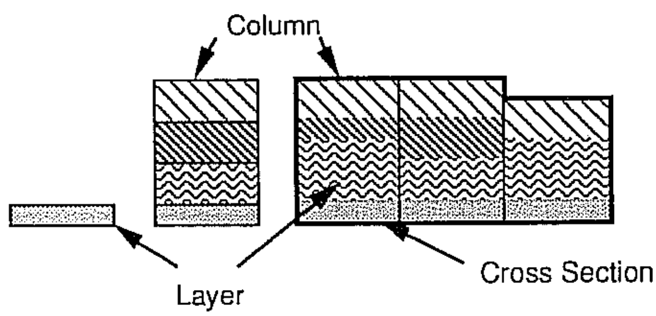


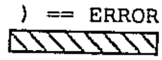
Figure 2. Elements of the Cross Section Model

To define the behavior of each of this three components, we have used an algebra based on the formal specifications of Liskov and Guttag (Liskov and Guttag, 1986) to describe our cross section model. This method defines each *sort* (class in object-oriented programming languages) in terms of its attributes and operations. Table 1 shows the definition of the Layer in its first iteration.

Operations are classified into *constructors* and *observers*. An operation is a constructor if its result includes the sort for which it is defined. For example, in Table 1 the operation Create results in a Layer1 and is a constructor (shown by prefix 'C'). Observer operations act on the sort and return a value or some other sort. The Thickness observer in Table 1, for instance, returns an integer value for the thickness of the Layer.

```
sort: LAYER1
    introduces
    C    Create: ∅ → LAYER1
    C    Erode: LAYER1 → ∅
    O    Thickness: LAYER1 → BOOL
    O    History: LAYER1 → list of OPERATIONS
    O    Draw: LAYER1 → DRAWING

axioms constrain Create, Erode, Thickness, History, Draw
    so that for all [s1: LAYER1]
    (1)  Thickness( Create ) == TRUE
    (2)  Thickness( Erode(s1) ) == ERROR
    (3)  History( Create ) == "CREATE"
    (4)  History( Erode(s1) ) == ERROR
```

(5) Draw(Create) == 

```
    (6)  Draw( Erode(s1) ) == ERROR

    sort: COLUMN1
    introduces
    C    Create: ∅ → COLUMN1
    C    Deposit: LAYER1, COLUMN1 → COLUMN1
    C    Erode: COLUMN1 → COLUMN1
    O    TopLayer: COLUMN1 → LAYER1
    O    History: COLUMN1 → TEXT
    O    Draw: COLUMN1 → DRAWING

axioms constrain  Create, Deposit, Erode, TopLayer,
                  History, Draw
    so that for all [s: LAYER1, c: COLUMN1 ]
    (1)  TopLayer( Create ) == ERROR
    (2)  TopLayer( Deposit (s, c) ) == s
    (3)  TopLayer( Erode( Deposit(s, c) ) == TopLayer(c)
    (4)  History( Create ) == "CREATE"
    (5)  History( Deposit(s, c) ) == History(c)+"DEPOSIT" x s
    (6)  History( Erode(c) ) == History(c) + "ERODE"
    (7)  Draw( Create ) == — — — —
    (8)  Draw( Deposit(s, c) ) == Layer1::Draw(s) + Draw(c)
    (9)  Draw( Erode( Deposit(s, c) ) == Draw(c)
```

Table 1. Formal Specifications for Layer and Column (First Iteration).

This specification method leads immediately to object-oriented design and implementation:

- Operations permitted on a sort are clearly defined and translated directly into class methods.
- Test conditions for implementation are defined in the axioms.

Higher order objects may inherit behavior, methods, and attributes from other objects. A simple model can be implemented first and then be expanded by increasing the complexity of one or more of the objects. For example, we selected as a basic model Layer1 and Column1: all layers have the same thickness and erosion removes the entire layer. The model also has observers for drawing and reporting history for each sort. The second model (Layer2, Column2) adds the concept of individual thicknesses to the layers. The columns can have a specified thickness eroded from them. In both of these models the columns have been undimensioned horizontally. Column3 introduces bounds to the column and Column4 provides methods to cut the column at a specific point. Finally, a cross section sort was defined to maintain and order a set of Column4s (Figure 3).

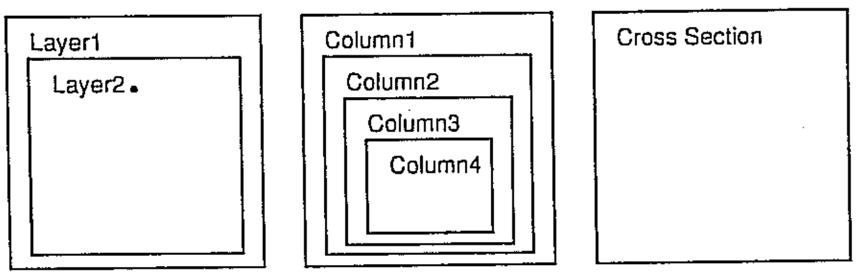


Figure 3. Sorts Used in Modelling Geologic Cross Sections

4. Analysis of the Formalism

This difference between a History and Cross Section can be seen in the specifications for the History and Draw axioms in the Column sort when applied to an Erode (Table 2).

```
     ...
(6)  History( Erode( c ) ) == History( c ) + "ERODE"
     ...
(9)  Draw( Erode( Deposit( s, c )  ) == Draw( c )
```

Table 2. Axioms for Draw and History from Column1

Because the Erode destroys the evidence of the Deposit, drawing the Cross Section after an Erode is equivalent to drawing what was present before the Erode (Deposit) operation. History is expressed differently. History is the sum of all previous operations, and includes all Deposit and Erode, even pairs of Deposit and Erode that cancel and are thus not observable in a cross section (Figure 5).

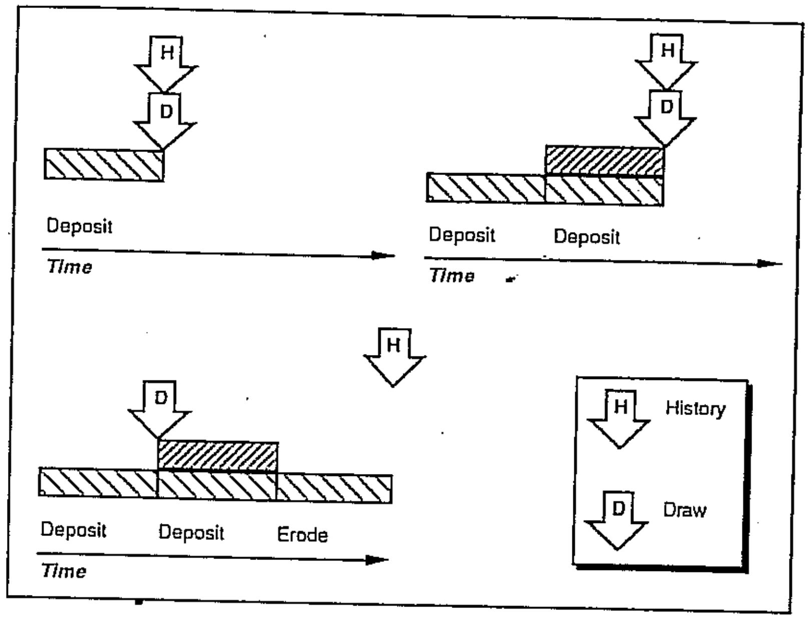


Figure 5. Temporal Discrepancies between History and Draw

Two sequences of events are *historically equivalent* if they are comprised of the same events in the same order. Historically equivalent histories will produce cross sections which are *observably equivalent.* Because cross sections are the end result of a set of processes and some of those processes destroy evidence of the cross section's history, we cannot conclude that two observably equivalent cross sections have historically equivalent histories.

For Example, Histories A and B in Figure 6 are not historically equivalent because History A has Erode(Deposit(P)) that does not exist in History B. Because the Erode and Deposit cancel each other the Cross Sections are observably equivalent.

Observable equality is a transitive relation, but there is a one-to-many relationship between Cross Sections and Histories. In other words even though it is possible for two Histories to have the same Cross Section, i.e. observably equivalent, it does not follow that they are historically equivalent.

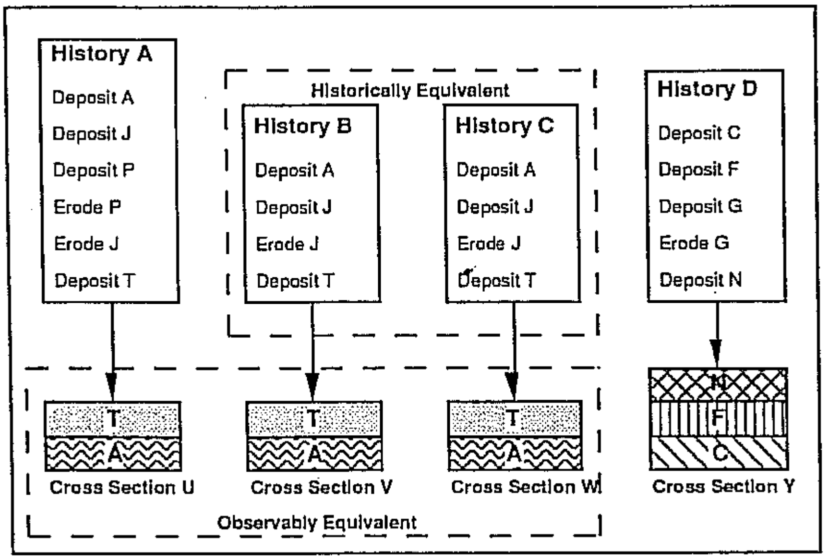


Figure 7. Equivalency in Cross Sections and Histories

5. Implementation

The implementation provided a graphic model for identifying the relationships between temporal objects and graphic objects. During implementation the sorts defined in the specifications are translated into classes in the object-oriented environment. Operations in the sorts become class member functions (to use C++ terminology).

A key element in each specification is the *History* observer. Each sort can be asked to give a history of the events which have acted on it. In addition, each sort also has a *Draw* observer which will provide a graphic representation of its current state. These observers lead to defining two abstract classes (*Historian* and *GraphicHistorian*) that provide a framework to implement classes which track their history as a set of states. Simply stated, a *Historian* records what action brought it into being and knows from which state it came. The *GraphicHistorian* simply adds a *Draw* member function and inherits all the functionality of its superclass Historian. The Layer, Column and Cross Section classes are subclasses of *GraphicHistorian*..

The models defined in the specifications where implemented in Think C for the Apple Macintosh and used the Think Class Library. The implementation of the formal specification proved that the specifications were internally consistent and that it was successful in modelling the behavior of Layer1 and Column1 sorts.

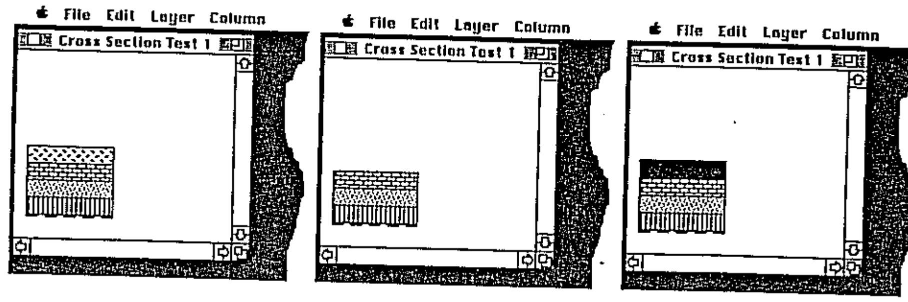


Figure 4. Eroding and Depositing with the Cross Section Modeler

6. Conclusions and Further Work

The analysis of the cross section geometry and the history that it implies, is only one of many techniques used by geologists to visualize their data. Complete analysis of the geologic structure requires additional information, such as bedrock age and chemical composition, to provide other clues needed to solve geologic cross sections. These attributes are usually incorporated into the geologic cross section, when available.

The erosion process (among others) leaves behind evidence (ex. sandstone from eroded granite) of what was there before, though that evidence may have to be found at a different location. For instance, an understanding of the structure of the Swiss Alps came about by correlating observations from several different sites. Unconformities in one region could be explained by making observations where strata on both sides of the unconformity are separated by a different stratigraphic layer.

With this tool, geologically valid cross sections can be produced and we can show what the interdependencies are. Such a tool may be valuable for students to study geological events. Of more interest is extending this model to parse a given cross section and to determine all possible (minimal) sequences of operations that could have produced it. The problem with the existing model is that there can be an infinite number of Erode(Deposit(s, c)) operations at any point in the History, which are all observably equivalent. One can select the shortest (minimal) sequence of events and consider this the canonical representative for the equivalence class.

Cross section analysis along the lines sketched here may provide an economical means of developing hypotheses before investigating the site in detail. One potential application of this technology could be in core drilling plan development. The model would be able to determine where the existing evidence permits a divergence in histories. By identifying the nature of the missing information, the model could be used to select a location most likely to provide information that will verify one line of reasoning or another.

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Discussions with Keith Turner, John Herring, Marco Casanova and the participants of the NATO Workshop on 3D modelling for GIS in Santa Barbara in 1989 were influential in our understanding of the topic. Funding from NSF for the NCGIA under grant SES 88-10917 and from Intergraph Corporation is also gratefully acknowledged.

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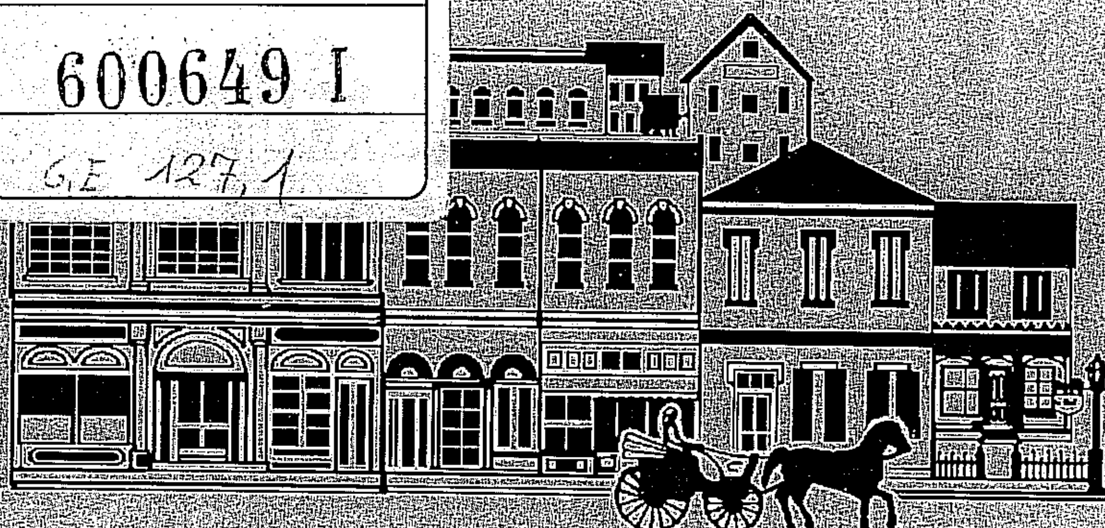

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