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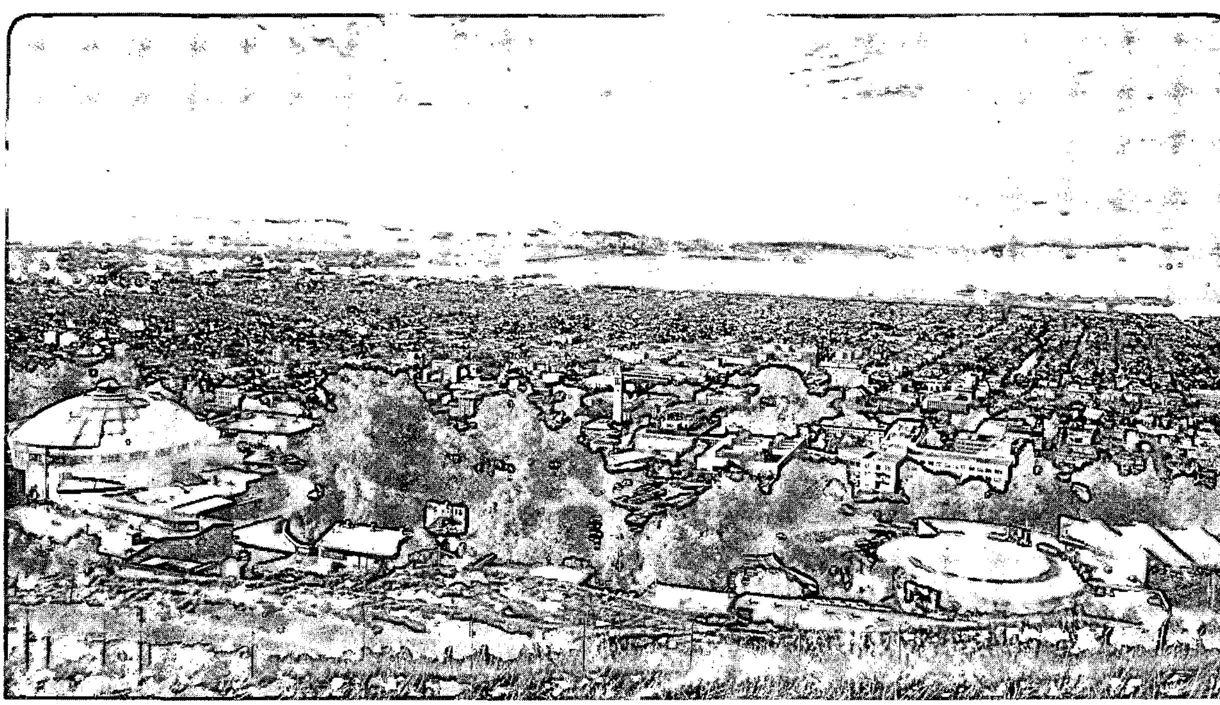

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Contents

Abstract

Most geoscience applications, such as assessment of an oil reservoir or hazardous waste site, require geological characterization of the site. Geological characterization involves analysis of spatial distributions of lithology, porosity, etc.. Geoscientists often rely on two-dimensional visualizations for analyzing geological data. Because of the complexity of the spatial relationships, however, we find that a three-dimensional model of geology is better suited for integration of many different types of data and provides a better representation of a site than a two-dimensional one. Being able to easily manipulate a large, complex data set provides the geoscientist with the opportunity to detect and visually analyze spatial correlations and correlations between different types of data, thus leading to an increased understanding of the data.

A three-dimensional model of geology is constructed from sample data obtained from field measurements, which are usually scattered. To create a volume model from scattered data, interpolation between points is required. The interpolation can be computed using one of several computational algorithms. Alternatively, a manual method may be employed, in which an interactive graphics device is used to input by hand the information that lies between the data points. For example, a mouse can be used to draw lines connecting data points with equal values. The combination of these two methods presents yet another approach.

In this study, we will compare selected methods of three-dimensional geological modeling. We used a

flow-based, modular visualization environment (AVS) to construct the geological models computationally. Within this system, we used three modules, scat_3d, trivar and scatter_to_ucd, as examples of computational methods. We compare these methods to the combined manual and computational approach. Because there are no tools readily available in AVS for this type of construction, we used a geological modeling system to demonstrate this method.

Paper

Geoscientists often use two-dimensional tools to visualize and analyze their data. These tools include cross-sections, contour maps, topographic maps, etc. Because of the complexity of geological data, two-dimensional analysis is not sufficient for a complete understanding. A three-dimensional model of geology is more suitable. When viewing three-dimensional data, it is much easier to combine many different data elements for analysis in three dimensions than in two dimensions. For example, in one three- dimensional representation, a volume model of geology, tubes representing boreholes, topographic lines representing the surface and fault planes can all be viewed at the same time. Two-dimensional tools such as detailed cross-sections also can be considered when building a three-dimensional model. With advanced visualization tools, it is possible to view a geological model in a variety of ways. A model can be viewed as a whole, just as if you were in a plane flying over it, or it can be viewed in part by cutting away parts of it to see inside.

We have chosen to create a volume model of our geological data because of the flexibility of visualization in three dimensions. A volume model of geology is constructed from data collected in the field, usually from boreholes. Because boreholes are often separated by quite a distance compared to the distance between sample points down a hole, the data is very scattered. There are several ways of looking at this type of data. The simplest form in which this data can be viewed in three dimensions is as "scatter dots". A small sphere is placed at each point in space where data occurs and is colored according to the data value at that point. (See figure 1.) The dimension of the sphere may also be proportional to the data value. Another simple way to look at geological scatter data is in the form of tubes. If the data are borehole data, each well becomes a tube which has segments colored according to the data values. (See figure 2.)

It is possible to obtain more complex representations by interpolating between the data points to get a three-dimensional volume model of the data. Three-dimensional interpolation routines "fill out" the data in places where the data are scarce and generate a three-dimensional volume of data. This type of representation is very useful and there are many ways to view it. It can be sliced and cropped, and isosurfaces may be extracted from it.

We have used three different methods for creating a three-dimensional model from sample data. The first method is one in which the points are resampled to obtain a three- dimensional, rectangular volume of data. This is a type of numerical interpolation in which the interpolation is based on the data at the coordinates. In AVS, there are two modules that we use to perform this type of interpolation, scat_3d and trivar. Each module uses a different algorithm for numerical interpolation. These modules convert scatter data that is essentially a one-dimensional field in three coordinates to a three-dimensional field in three coordinates. This type of rendering is best observed by taking two dimensional slices or three-dimensional isosurfaces. (See figure 3.)

The numerical interpolation method is useful because it is possible to vary the degree of interpolation.

We can view the data in a very raw state, where the data is interpolated to a small search radius. Alternatively, we can fill in the sparsely sampled areas by choosing a large search radius to gain a better understanding of the spatial relationships. This method is useful also because it provides us with more ways to view the data than if it were just represented as scatter dots or tubes. For example, we would not be able to take a two- dimensional slice (with AVS) if data are represented as scatter dots or as tubes.

Interpolation is not very useful for data sets that are structurally complex or poorly sampled. In this case, interpolation does not describe the data much better than scatter dots or tubes do. It is also possible to over-interpolate and, therefore, make incorrect analyses of the data. In geological applications, the interpolation method is not very useful for showing layered data such as stratigraphy because the field data are qualitative and structural, not quantitative and continuous.

Structural interpolation is another method in which the interpolation is based only on the coordinates. This method uses triangulation to create tetrahedral cells whose vertices are the scatter points. The cells are connected to form a three-dimensional volume. (See figure 4.) In AVS, this type of cellular structure is called Unstructured Cell Data (UCD), and the module used to make the conversion is scatter_to_ucd. Each cell vertex or node keeps the data value that was at the corresponding data coordinate. There are no parameters to adjust, so there is essentially only one UCD model that can be built from a particular data set.

UCD representation is much more useful than numerical interpolation. It can quickly turn a fairly simple geological data set into a three-dimensional volume showing layered data such as rock type. This type of modeling gives a good first representation of any geological data set. If the data are fairly complex, UCD rendering will give the scientist some idea of the degree of complexity. In general, there are many useful ways to look at a cellular structure. A two-dimensional slice may be extracted from the volume, and in this way, a geological cross-section can be obtained. Several cross-sections may be combined to form a fence diagram. (Refer to figure 6b for an example of a fence diagram.) These are two tools that geoscientists are quite familiar with and can be obtained very easily from a three-dimensional model. UCD models also are more realistic than three-dimensional models constructed from numerical interpolation. The boundaries of a cellular structure are defined by the outermost data points so the shape of the structure is more confined. Another advantage is that this type of cellular structure allows several different types of data to be represented in the same volume because the structure is defined by the coordinates, not the underlying data.

There also are problems associated with this type of three-dimensional model. In most cases, the model that is created by scatter_to_ucd is too simple. Discontinuities, such as fracture planes, and other complex elements can not be accounted for in a model constructed in this manner. We have limited control over the interpolation rendered by scatter_to_ucd. The only way to change the outcome of this module is to change the input data. In other words, we cannot sculpt the model to make a better fit or to make it more pleasing to view.

The most useful method that we have employed for building a three-dimensional geological model is to construct a cellular structure from the scatter data using an application-specific modeling system and then visualize that structure in an advanced visualization system. The software we chose to build the model with is Lynx Geoscience Modelling System (GMS) by Lynx Geosystems, Inc. This system uses two methods for building volume models. The surface generation method builds a surface from a predefined subset of data points using triangulation. This surface usually describes one boundary of a geological layer. (See figure 5.) After creating a second boundary, the software will interpolate between the boundaries (assigning the same value to all points in that space) to form a cellular structure much like that created by scatter_to_ucd. The surface generation mechanism can be controlled by the user by deleting and creating triangles that make up the surface. This process can be repeated for several layers, and each layer may have its own area boundary or may be made to conform to one area boundary. The volume model is output in AVS UCD format and read into AVS. It then can be manipulated in the same ways as the scatter_to_ucd model described above.

In the second method, the interactive method, the scatter data is used to build elements that are combined to form a volume model. These elements include cross-sections that are created "by hand" by using a mouse to draw lines that connect points with similar values, surfaces created by projecting two-dimensional lines into a third dimension, and volume elements created by projecting surfaces into three-dimensional space. (See figures 6a and 6b.) As with the previous method, the volume model that is constructed using the interactive method can be exported to AVS, as described above. (See figure 6c.)

The benefits of using this method over the previously described methods are obvious. The flexibility of the modeling program allows fairly complex and realistic models to be constructed. (Refer to figure 7 for a cross-section of a more complex geological model built with Lynx GMS.) A complete three-dimensional model can be built from many different elements, taking into consideration complexities such as faults, folded layers, and heterogeneous data. Given increased control over the data interpolation, the user can fine- tune the model.

The disadvantages also are obvious. This method is very time-consuming. Also, as with the scat_3d and trivar modules, it is possible for the modeler to interpolate too much and to possibly add elements to the model that do not actually exist. In general, however, building a geological model by any method requires much analysis and redefinition and is not a fast or simple process.

The process of building a geological model is an iterative one. First, the geoscientist builds a model from the field data using the available tools. Next, the model is analyzed and a more refined model is built using that analysis. This process may continue indefinitely. Because of the iterative nature of the building process, it is appropriate that the geoscientist use tools that will facilitate the process. It might be easier to draw a two- dimensional cross-section by hand, but it is nearly impossible to construct a three- dimensional model by hand. A computer is a necessary tool for doing the interpolations required to construct a three-dimensional model of geology.

There are many computational methods for building three-dimensional geological models, three of which were discussed in this paper. Of the methods discussed above, software like Lynx GMS provides the most useful and intuitive approach for constructing a three- dimensional model. If additional data are obtained, it is much easier to modify the existing computer model in a system like Lynx GMS rather than to create an entirely new model using the numerical and structural interpolation methods discussed in this paper or than to modify an existing "on paper" model. Why do we need a three-dimensional model of geology? Because nature is three-dimensional, and geological data sets are three- dimensional, a three-dimensional model seems the most appropriate model to use.

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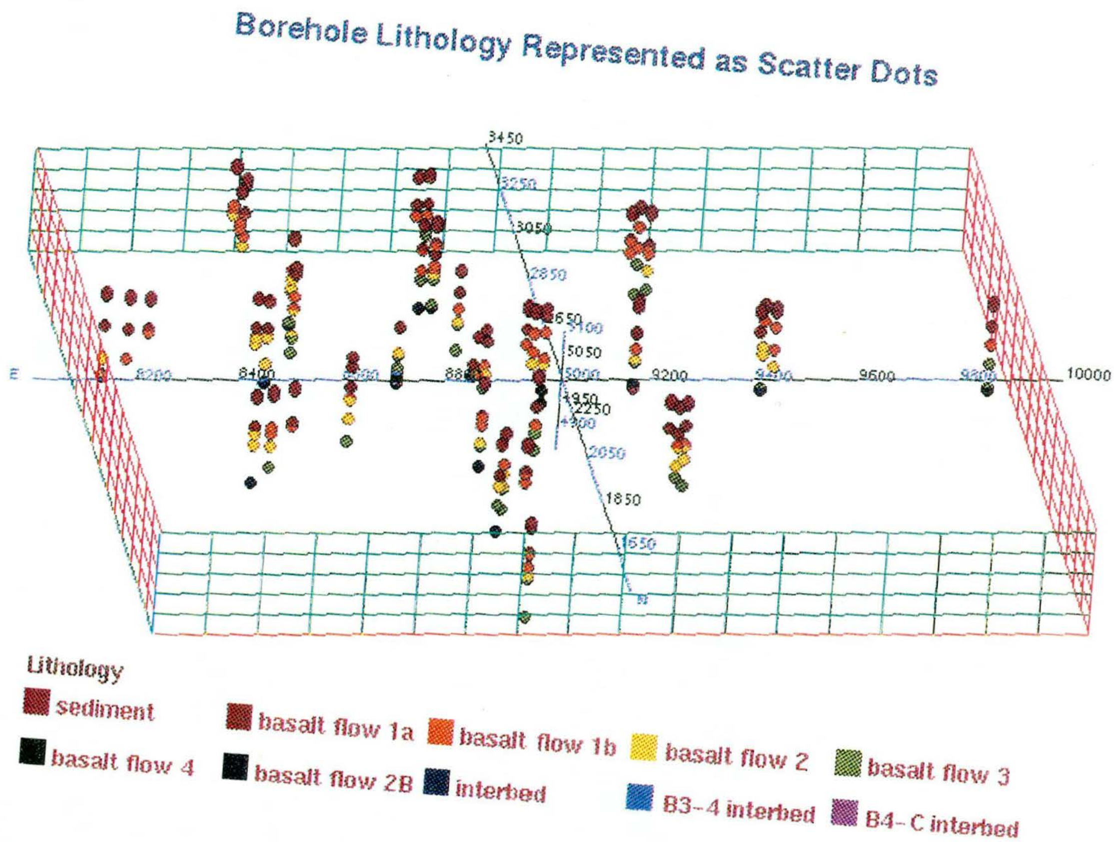

Borehole Lithology Represented as Scatter Dots
3450
3250
3050
2850
1650
5100
5050
5000
1950
2250
4900
2050
1850
1650
N
E
8200
8400
8800
9200
9600
10000
Lithology
sediment
basalt flow 1a
basalt flow 1b
basalt flow 2
basalt flow 3
basalt flow 4
basalt flow 2B
interbed
B3-4 interbed
B4-C interbed

Figure 1

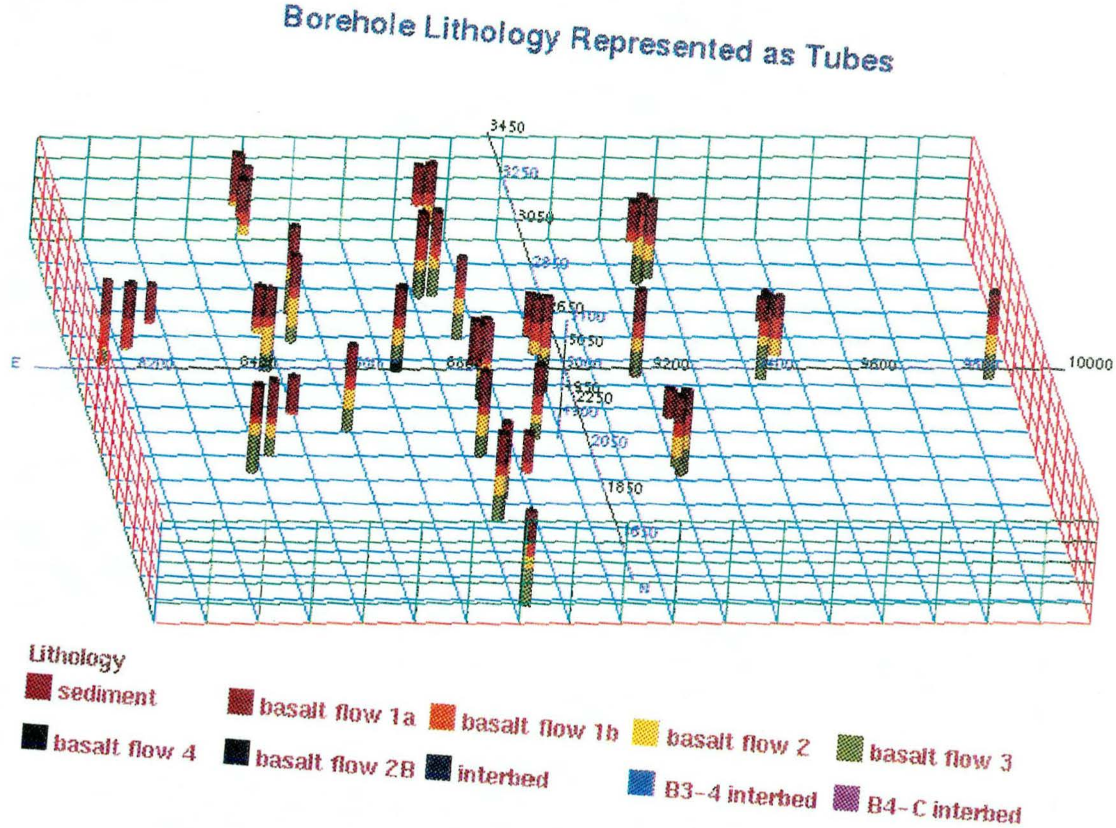
Borehole Lithology Represented as Tubes
Lithology
sediment
basalt flow 1a
basalt flow 1b
basalt flow 2
basalt flow 3
basalt flow 4
basalt flow 2B
interbed
B3-4 interbed
B4-C interbed
10000

Figure 2

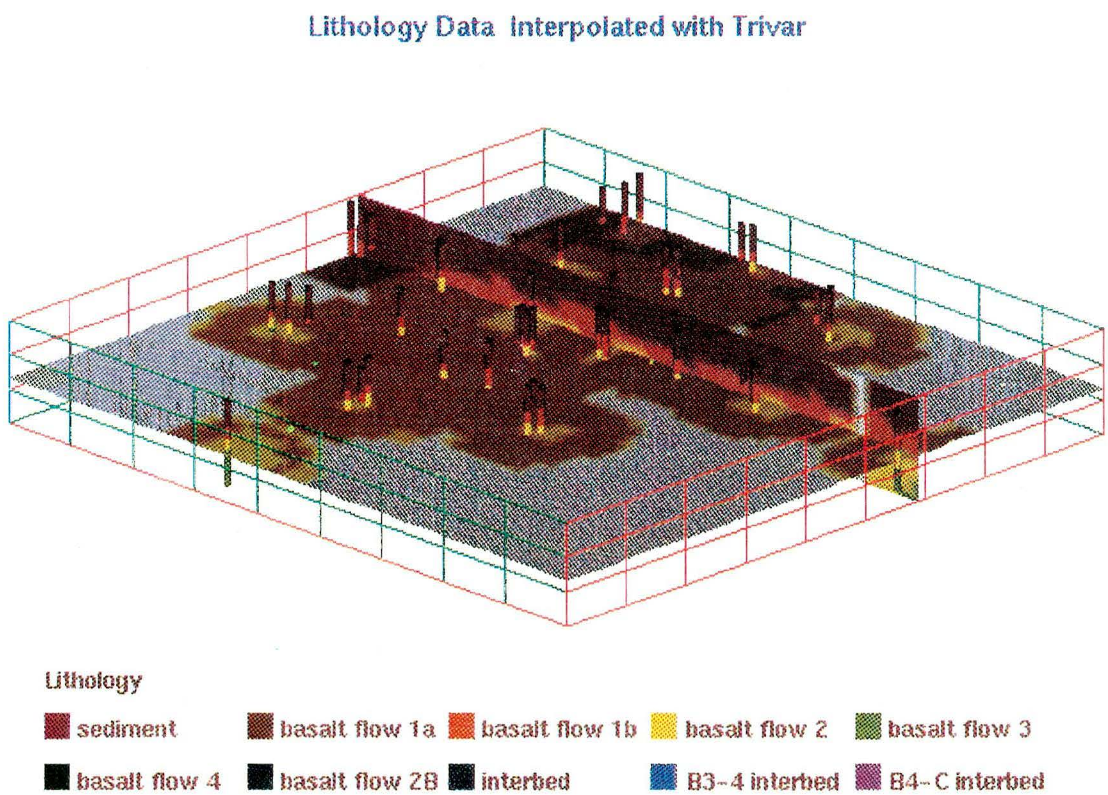
Lithology Data Interpolated with Trivar
Lithology
sediment
basalt flow 1a
basalt flow 1b
basalt flow 2
basalt flow 3
basalt flow 4
basalt flow 2B
interbed
B3-4 interbed
B4-C interbed

Figure 3

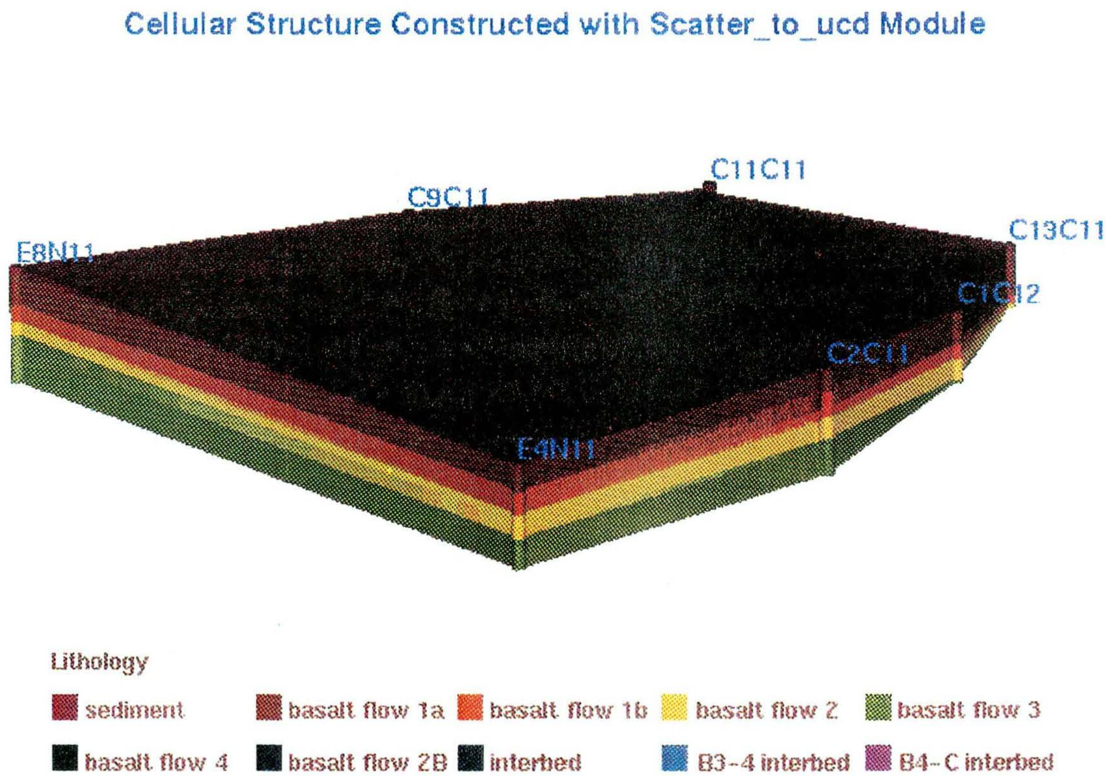
Cellular Structure Constructed with Scatter_to_ucd Module
C11C11
C9C11
E8N11
C13C11
C1C12
C2C11
E4N11
Lithology
sediment
basalt flow 1a
basalt flow 1b
basalt flow 2
basalt flow 3
basalt flow 4
basalt flow 2B
interbed
B3-4 interbed
B4-C interbed

Figure 4

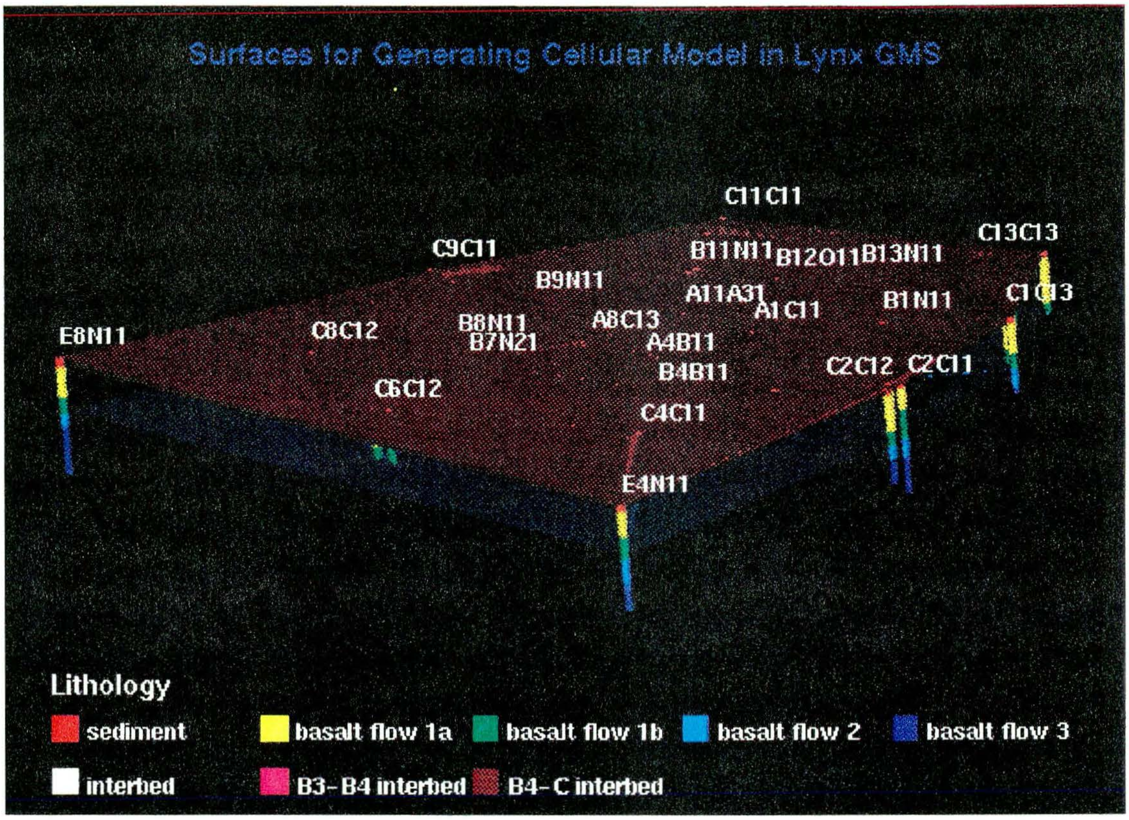
Surfaces for Generating Cellular Model in Lynx GMS
C11C11
C13C13
C9C11
B11N11
B12O11
B13N11
B9N11
A11A31
A1C11
B1N11
E8N11
C8C12
B8N11
B7N21
A8C13
A4B11
B4B11
C2C12
C2C11
C6C12
C4C11
E4N11
Lithology
sediment
basalt flow 1a
basalt flow 1b
basalt flow 2
basalt flow 3
interbed
B3-B4 interbed
B4-C interbed

Figure 5

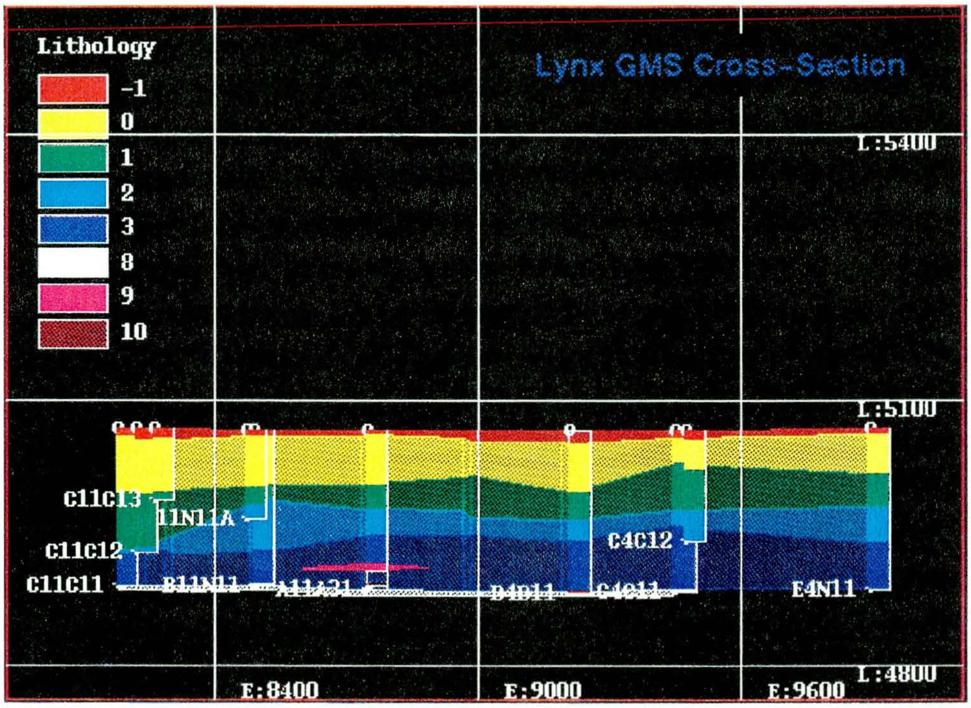
Lithology
-1
0
1
2
3
8
9
10
Lynx GMS Cross-Section
L:5400
L:5100
L:4800
C11C13
11N11A
C11C12
C11C11
C4C12
D4D11
E4N11
E:8400
E:9000
E:9600

Figure 6a

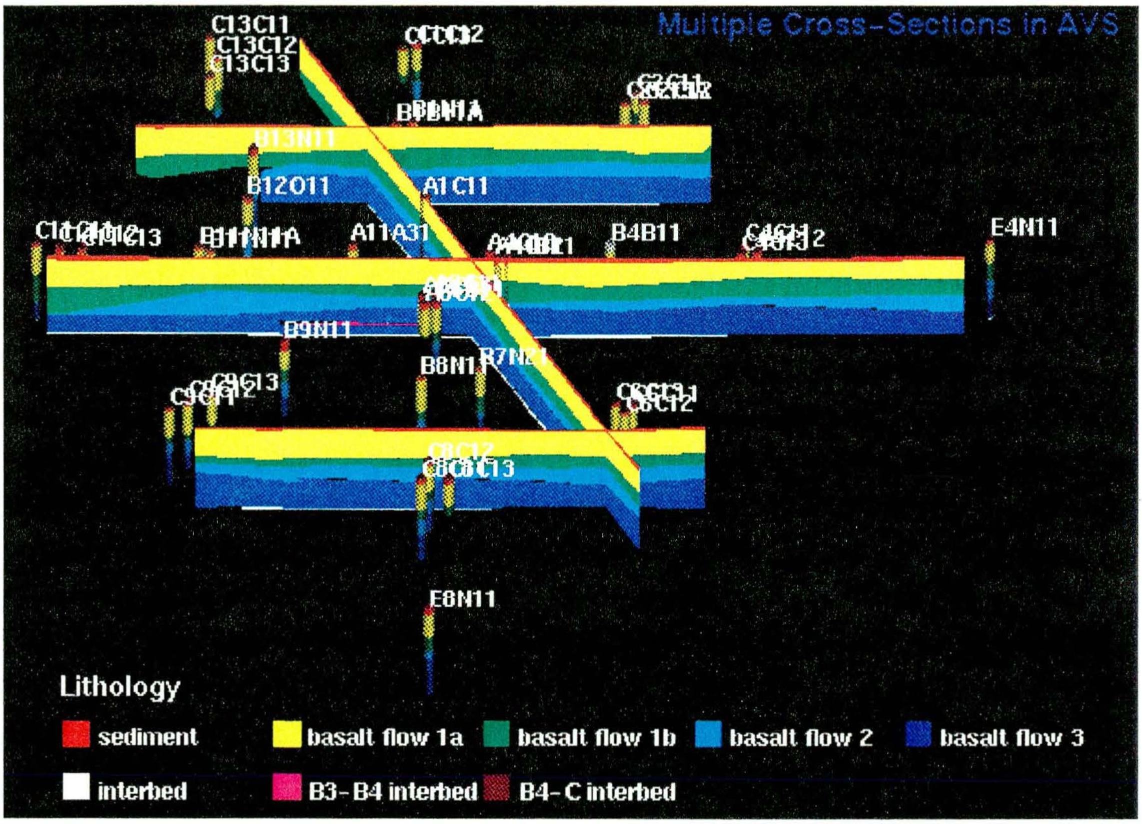
Multiple Cross-Sections in AVS
C13C11
C13C12
C13C13
B13N11
B12O11
A1C11
A11A31
B4B11
E4N11
B9N11
B8N11
E8N11
Lithology
sediment
basalt flow 1a
basalt flow 1b
basalt flow 2
basalt flow 3
interbed
B3-B4 interbed
B4-C interbed

Figure 6b

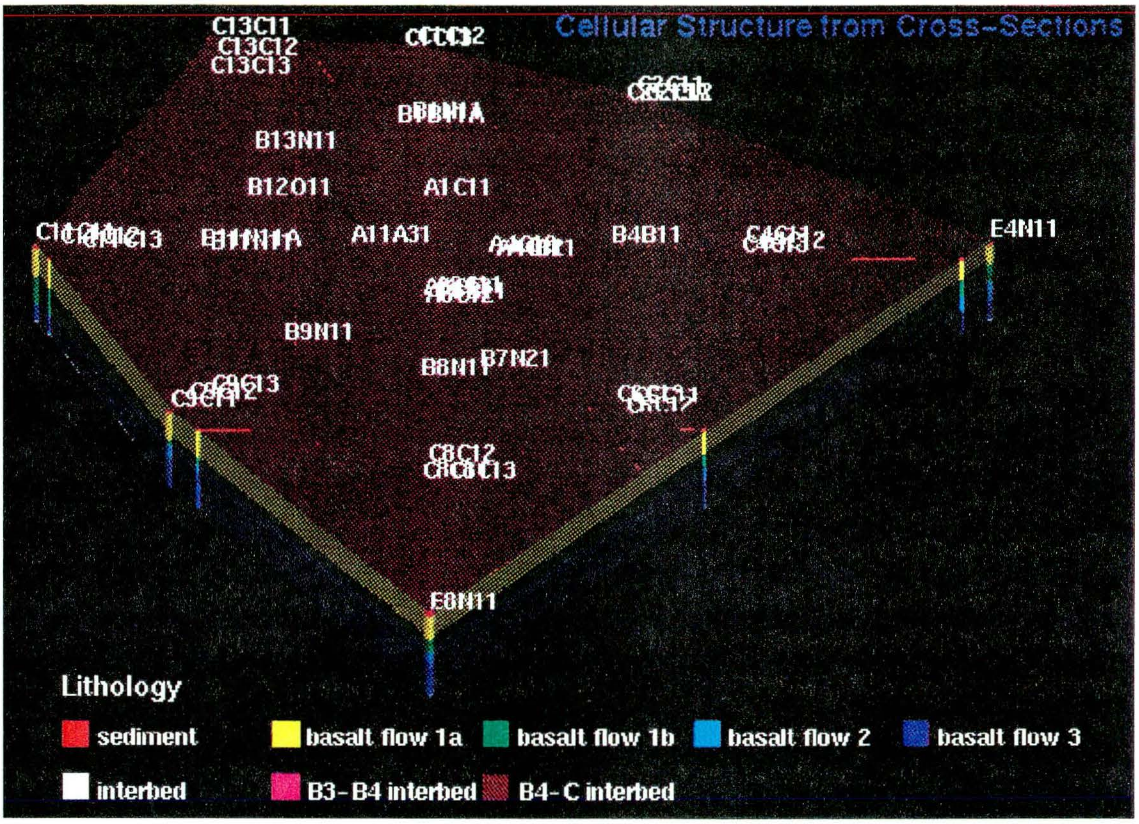
Cellular Structure from Cross-Sections
C13C11
C13C12
C13C13
B13N11
B12O11
A1C11
A11A31
B4B11
E4N11
B9N11
B8N1
B7N21
E8N11
Lithology
sediment
basalt flow 1a
basalt flow 1b
basalt flow 2
basalt flow 3
interbed
B3-B4 interbed
B4-C interbed

Figure 6c

Figure 7

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