What's the Difference Among 2-D, 2.5-D, 3-D and 4-D?

It's been suggested that a geologist is a chemist who has discovered geography! Whereas many geologists share with chemists a sincere interest in the chemical composition of their samples, geologists also maintain a strong interest in the locations of their samples. Spatial relationships among the samples often provide the critical information that allows geoscientists to locate and evaluate a mineral deposit, petroleum reservoir or pollution plume. So it's not surprising that geoscientists were among the initial users and developers of GIS technologies.

However, as discussed in the January "Applied Geoscience Forum," (*GIS WORLD*, "The Best of Times or the Worst of Times?" page 64) geoscientists have specific needs that aren't fully satisfied by traditional GIS products. Many questions can be answered with 2-D maps of land-surface conditions, but a critical need is the ability to analyze conditions within Earth's subsurface in three dimensions and, in many cases, to analyze how these conditions change over time, requiring 3-D and 4-D analysis. Some confusion exists about what constitutes 3-D analysis. Many GISs treat topographic elevation as a special class of spatially varying dependent variable, an attribute of location. This approach has been referred to as 2.5-D, because it's more than 2-D, but less than a fully 3-D representation. Hence the dimensionality of geoscience applications includes 2-D, 2.5-D, 3-D and 4-D representations.

2-D Analysis

Mapping and analysis of 2-D land-surface phenomena are performed by traditional GIS using either vector or raster approaches. Vectors more closely replicate traditional geologic maps and diagrams, and raster systems work well with some of the newer data sources, including a variety of geophysical and satellite remote sensor data.

Several geologic applications can be accomplished by reducing the 3-D subsurface volume to a 2-D representation. For years geologists have used 2-D graphical products to represent 3-D conditions, including geologic maps, cross sections, fence diagrams and specialized geometrical constructions such as stereonets. However, the user must be trained to "read" and understand these products.

2.5-D Analysis

Additional geologic applications can be accomplished by reducing the 3-D subsurface volume to a quasi 3-D representation through the use of surfaces. These surfaces, representing bedding planes, for example, can be contoured, displayed as isometric views or represented as facets in a triangulated irregular network (TIN). However, in all these cases, the surface elevation isn't an independent variable, so these systems are best defined as quasi-3-D or 2.5-D systems, which can accept only a single elevation (z) value for any surface at any given location. Accordingly, several important geologic structures, such as folded or faulted conditions, which cause repetition of a single horizon at a given location, can't be represented by these systems. In contrast, true 3-D systems, containing three independent coordinate axes, can accept repeated occurrences of the same surface at any given location.

3-D Analysis

In the last two decades, computer advances have made it possible to develop applications that create, display and operate on data to fully describe the 3-D geometry and attributes of geological objects. These 3-D techniques include relatively simple polygon meshes and piecewise linear interpolations of surfaces, complex 3-D gridding and isosurface techniques, volumetric element (voxel) techniques, and curved surface and solid modeling based on advanced mathematical spline functions. Such methods may be categorized as either surface or volumetric representations.

Surface representations readily provide accurate spatial definition of stratigraphic and structural components, especially where structures are complex and the rocks are faulted. However, the surfaces merely subdivide the subsurface into zones, and conditions that vary within zones can't be defined easily.

Volumetric representations subdivide the total volume being modeled into a large number of volume elements, called voxels. A chief advantage of voxels and their variations is that they allow easy distribution of heterogeneous attributes throughout the 3-D volume. A huge number of voxels may be required to define a large model. Accordingly, much research has been undertaken to develop data compression and indexing methods. "Octree" methods have been successful for medical imaging, but their applications to geoscience data have been limited, mainly because geoscientists need to iteratively revise their spatial models and they want to incorporate heterogeneities within their geologic units. Octree data structures don't handle either of these requirements efficiently.

Many commercial 3-D systems use some variation of voxels for volumetric rendering. Several incorporate "deformable voxels," allowing variations in shape, size or orientation of the cells, especially in the vertical (z) direction. Such techniques are called geocellular. In geocellular modeling, geological complexity and discontinuities are defined by gridded surfaces that control voxel cell geometry and distribution.

4-D Analysis

Temporal query capabilities within GIS are uncommon. Suppose the geoscientist wants an estimate of all conditions at a single moment, or the average during a certain time period. Can a request be made easily for the "values at time a," or for the values "from time b to time c"?

To fully satisfy geoscientists' needs, such temporal data capabilities should be combined with 3-D modeling capabilities. Although many consider geologic features unchangeable, in fact most geologic features and conditions are dynamic. Not all geologic conditions change slowly—floods, earthquakes, storms and landslides often provide rapid and substantial changes to local geology. Geologists are interested in spatial-temporal models that involve four dimensions—the 3-D volumetric dimensions plus the fourth dimension of time.

Are such 4-D capabilities being developed? I'm sure they are, although I haven't seen any in detail. When will commercial systems offer 4-D capability? Soon, I hope.

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