Three-dimensional visualization of geophysical datasets

Rick Ottolini

ABSTRACT

Recent advances in three-dimensional graphics systems challenge geophysicists how to best display their data. Scientific visualization uses computer graphics to maximize insight into scientific data, both grandeur and blemishes together.

Shape, color, and motion are the visualizer's building blocks. Not all graphics primitives are equally effective—surfaces, solids, and point clouds survive perspective transformations better than lines and polygons. Care must be taken to reduce object and color clutter. Effective labeling prevents orientation confusion.

Many geophysical datasets are characterized by continuous sampling along a warped surface such as a tube or sphere. The utility *SEPsurf* displays such "sepcube"-format datasets. Other geophysical datasets are characterized by objects oriented in a three-dimensional volume and are displayed by *SEPdraw*.

INTRODUCTION

New graphics technology leads to new methods of data presentation and ultimately to new research results. We saw how high speed raster graphics terminals gave us data cube movies several years ago. Now surface graphics terminals have come of age.

The goal of scientific visualization is to provide maximum insight into data and models via graphics—give a concrete presentation of numerical information, show large datasets in a compact way, illustrate spatial and temporal relationship between components, expose weaknesses in the data. My specific interest is the

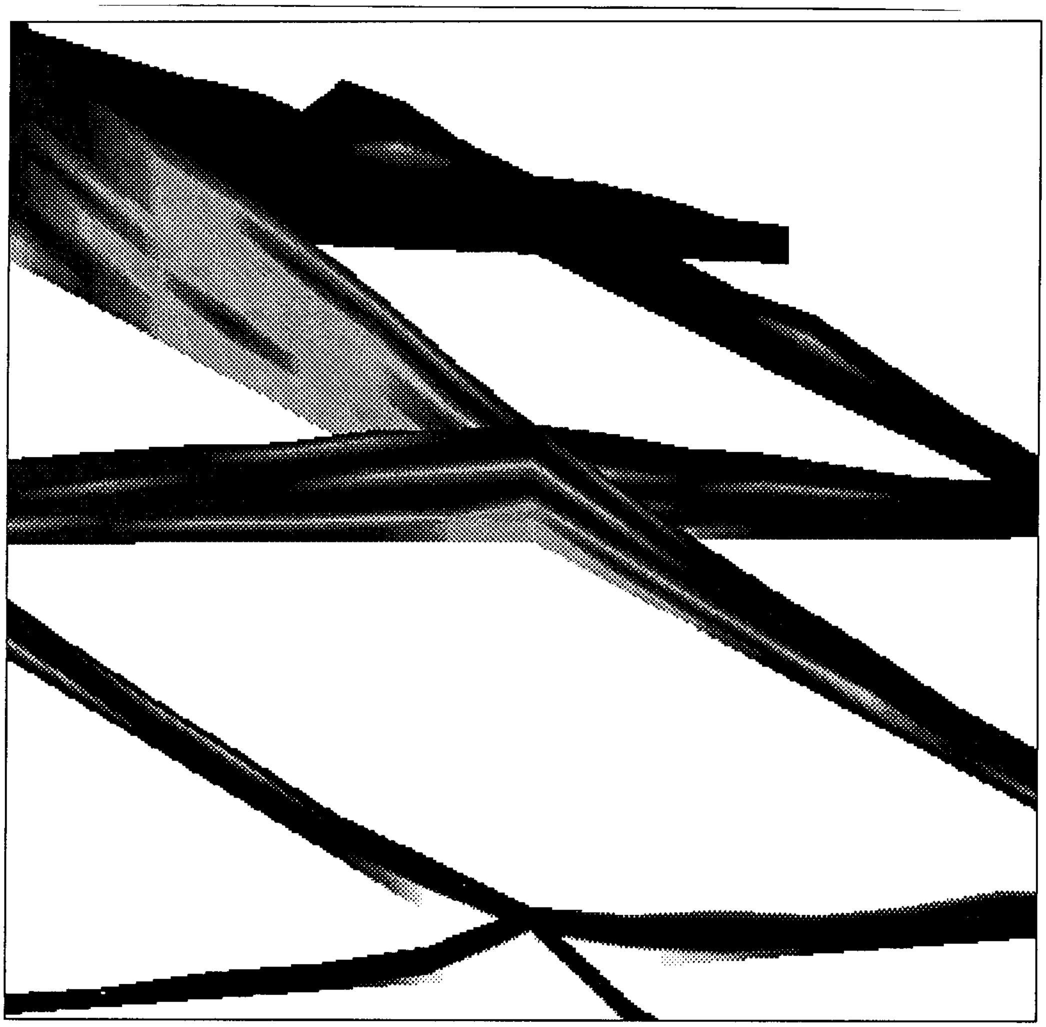

FIG. 1. Sedimentary basin display (John Harbaugh's SEDSIM group). A sedimentary basin is represented as (1) a set of isochron sediment surfaces, (2) a lattice of vertical sediment fences, shown above, and (3) erodable basement topography. The sediments are color-coded to represent sediment age or composition. A transparent blue box outlines the water body, if any. Sediment flow velocity is depicted as cones floating above the sediment. We can interactively evolve the basin through time, show or hide any portion of the basin, highlight a sediment trend, and rotate, resize or vertically exaggerate the basin. The basin description is given by the Stanford SEDSIM sedimentary basin simulation computer program. The lattice fences consume the bulk of the hardware resources and algorithmic complexity. They display a five-dimensional array of volume, time, and sediment type up to a 100 units on side—the triangle memory capacity of the Titan. Interactive visibility controls keep speed and complexity manageable.

presentation of geophysical datasets. My investigations were driven by datasets in the SEP library and from Stanford colleagues.

The research platform used in this study was the Ardent TITAN graphics supercomputer and graphics language called Doré . The software was the more important innovation, although the fast hardware helped a lot. There are two TITANS at Stanford and Doré runs on most computers.

Raster and vector graphics

Graphics hardware and software is generally oriented along one model—raster or vector. This dichotomy affects visualization from both a conceptual and implementation points of view. The goal is to unify these two paradigms, but that is not yet the reality.

Raster graphics is a rectangular or volumetric array of color points. It is useful for seismic data and mathematical matrices. Raster graphics performance is measured in millions of rasters per second. The SEP movie program (Ottolini, et al., 1984) is an example of raster graphics.

Vector graphics is lines, surfaces, and solids. It is useful for maps, geologic surfaces and seismic models. Performance is measured in tens-of-thousands continuously shaded triangles drawn per second. Assuming a datum per triangle, vector display density is about one percent of raster display density. However, vector graphics allows a richer variety of display techniques, such arbitrary 3-D perspective and lighting models. The SEP vplot language (Cole and Dellinger, 1989) is an example of vector graphics. This article focuses on vector graphics.

Visualization resources

The graphics programmer has the techniques of shape, color and motion at their disposal. There are a wide range of shape primitives—points, lines, surfaces, solids and raster volumes. Surfaces are the most effective shape because they encode a lot of information, but don't distort that much when changing three-dimensional perspective.

Color is not only that of the display objects, but modifications induced by illumination, perspective and reflectivity properties. The modifications can be used to encode scientific information too. However, too much color can confuse.

Motion is image change. Interacting with the image can manage the complexity of information—hide and highlight features, change three-dimensional perspective or time stage.

VISUALIZATION OF GEOPHYSICAL DATA

I solicited geophysical datasets that I thought would be interesting display exercises from my colleagues about Stanford. They are described in Figures 1 through 11.

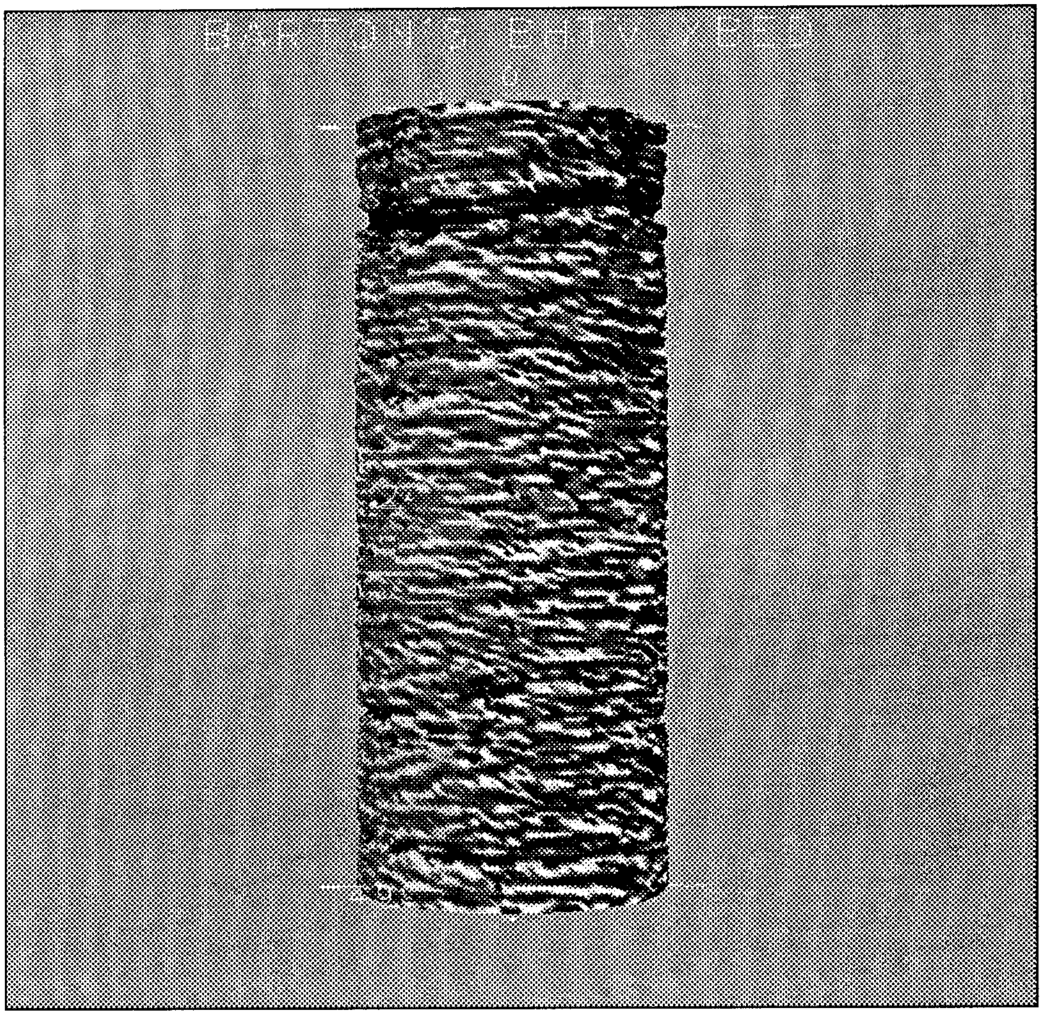

FIG. 2. Borehole televiewer data (Colleen Barton). Televiewer data is an acoustic survey run helically down a borehole. First break travel times and amplitudes are rendered as shape and color. This is one of the stock shapes of the SEPsurf utility. The main implementation problem is obtaining smooth scrolling. Long datasets easily consume hundreds of thousands triangles and require sophisticated visibility control to be interactive.

These figures only hint how images appear. The full 24-bit color dynamic images on the Ardent Titan are much more spectacular.

Survey topologies

Many geophysical datasets are characterized by regularly spaced measurements along some survey topology:

planar— area geophysical surveys: sedimentary basins (Figure 1);

tubular— borehole geophysics: borehole televiewer (Figure 2); well log (Figure 3);

spherical— global geophysics: earth topography (Figure 4); earth tomography (Figure 5);

irregular— rock pore geometry (Figure 6); anisotropic slowness surface (Figure 7).

Data can be encoded as secondary shape such as relief, the primary surface color, or as a color modification such as illumination or transparency. Multiple, coincident datasets can be simultaneously displayed combining these techniques. Alternatively, an attribute derived from the data such as measurement quality can be displayed. The utility *SEPsurf*, described later in this article, displays datasets as various surface topologies.

Discrete data

Some geophysical datasets are characterized by discrete objects oriented in a three-dimensional volume. Examples include earthquake fault plane orientations (Figure 8), migration velocity scan point cloud (Figure 9) and a paleomagnetism stereonet (Figure 10). Another utility *SEPdraw* displays this kind of data.

GRAPHICS SYSTEM

Ardent Titan graphics mini-supercomputer

The Ardent Titan is a combination vectorizing-parallelizing computer and high speed graphics computer. It gets about eight megaflops on my slant-stacking benchmark, a little slower than the Convex. Raster graphics is about two million pixels a second for pixel-replication zoom and several hundred thousand a second for spline-interpolation zoom. Vector graphics includes 24-bit color shading, scaling, positioning, rotation, visibility, transparency and illumination calculations in real time. It draws about 25K shaded triangles per second and can store over a million triangles in a 64 megabyte memory. It animates shaded-triangle images of 5-10,000 data samples assuming an animation rate of three frames per second and two triangles per mesh node. Interactive controls include a three-button mouse, eight-dial box, and spaceball control knob with three dimensions of freedom.

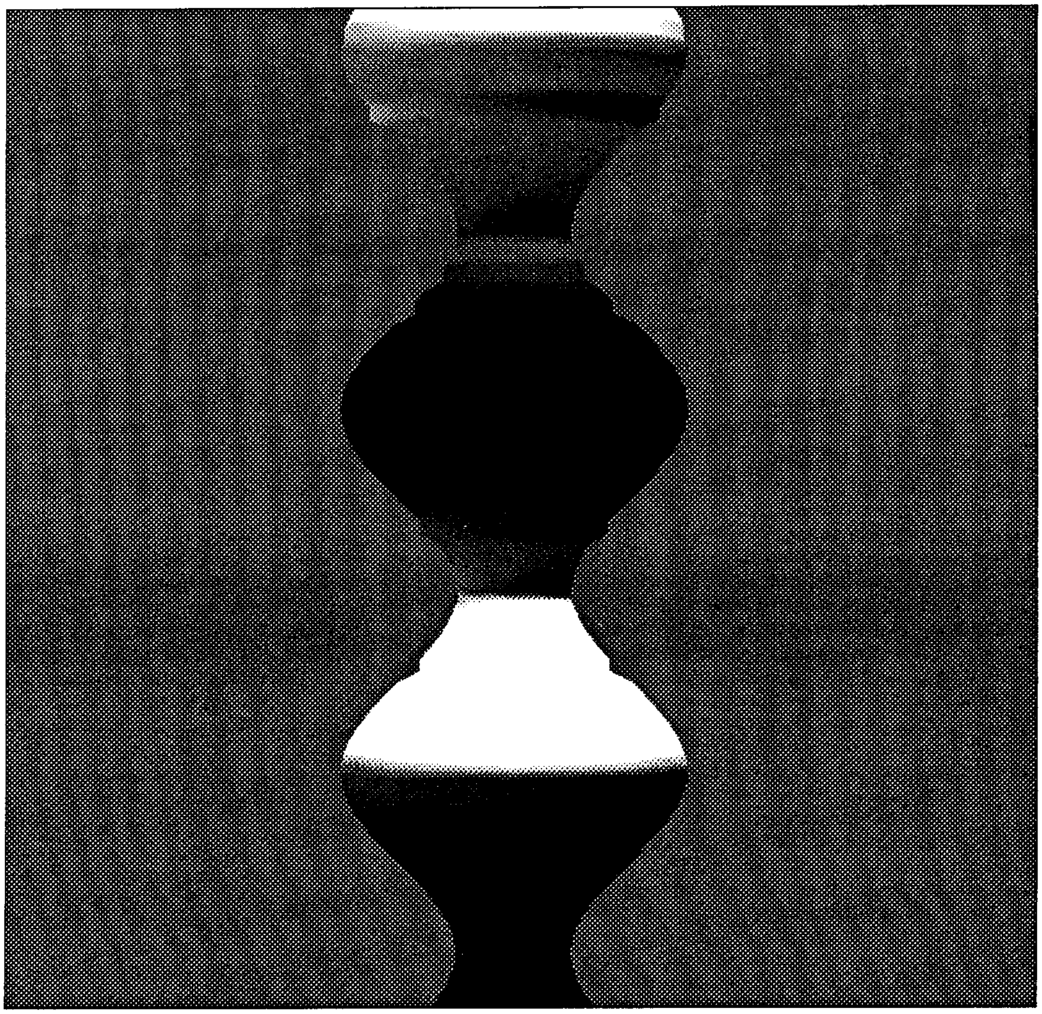

FIG. 3. Synthetic well log data (Richard Ottolini). One type of well log is rendered as shape, another as color. A third may be a transparent sheath of variable radius. Well logs are rendered as surfaces of revolution because lines or variable-area plots are easily distorted by three-dimensional geometric transformations. This image is a part of a developmental-geophysics display. Logs are one of the stock shapes of the SEPsurf utility.

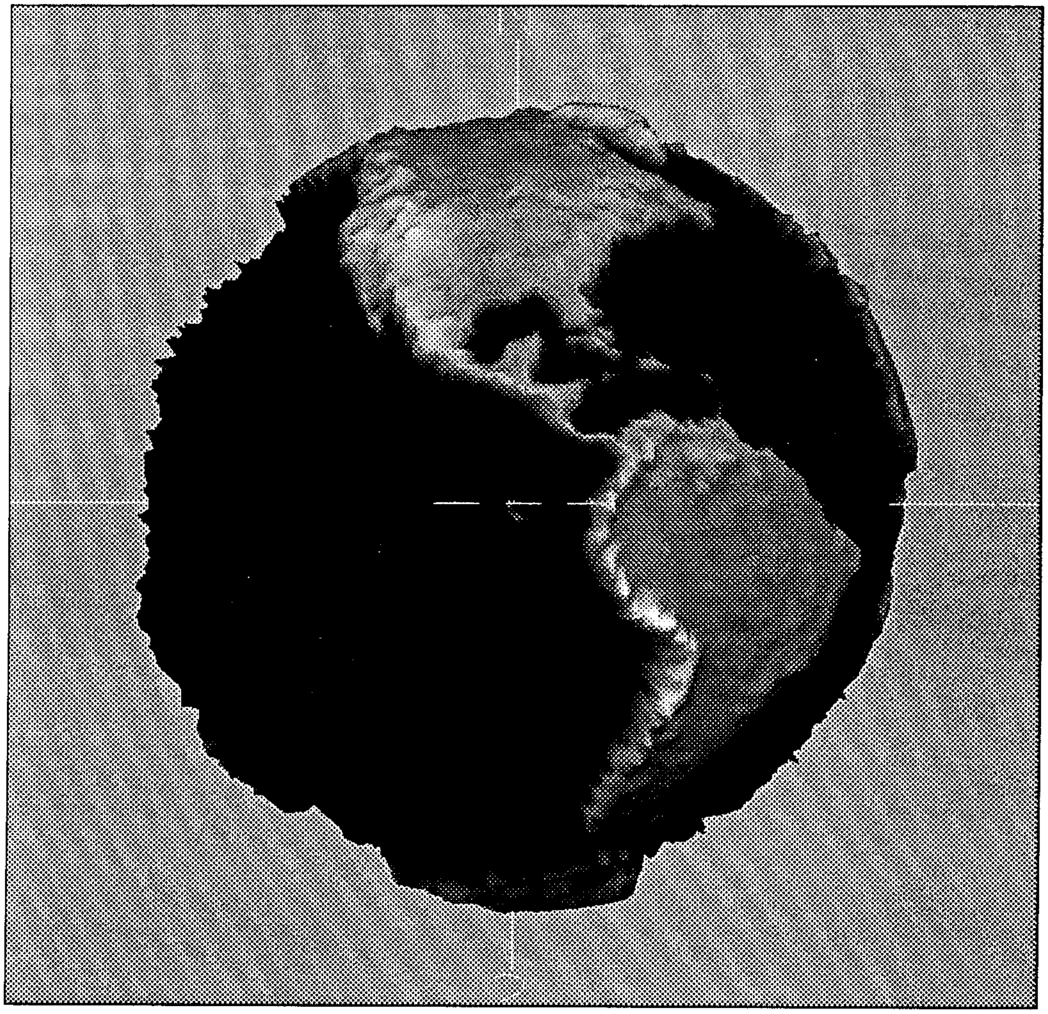

FIG. 4. Earth topography (NOAA via Robert Simpson). Topography is rendered as both relief and color on a sphere. It is very beautiful as a color movie and epitomizes earth science. One implementation issue was the spherical mesh. I tried Sword's icosahedron and then used a bi-pyramid. A sphere is a stock shape of the SEPsurf utility. Another implementation issue is mesh resolution. Mountain chains are not rendered well until one degree sampling. However, this results in 64K triangles, about five times too slow for smooth animation.

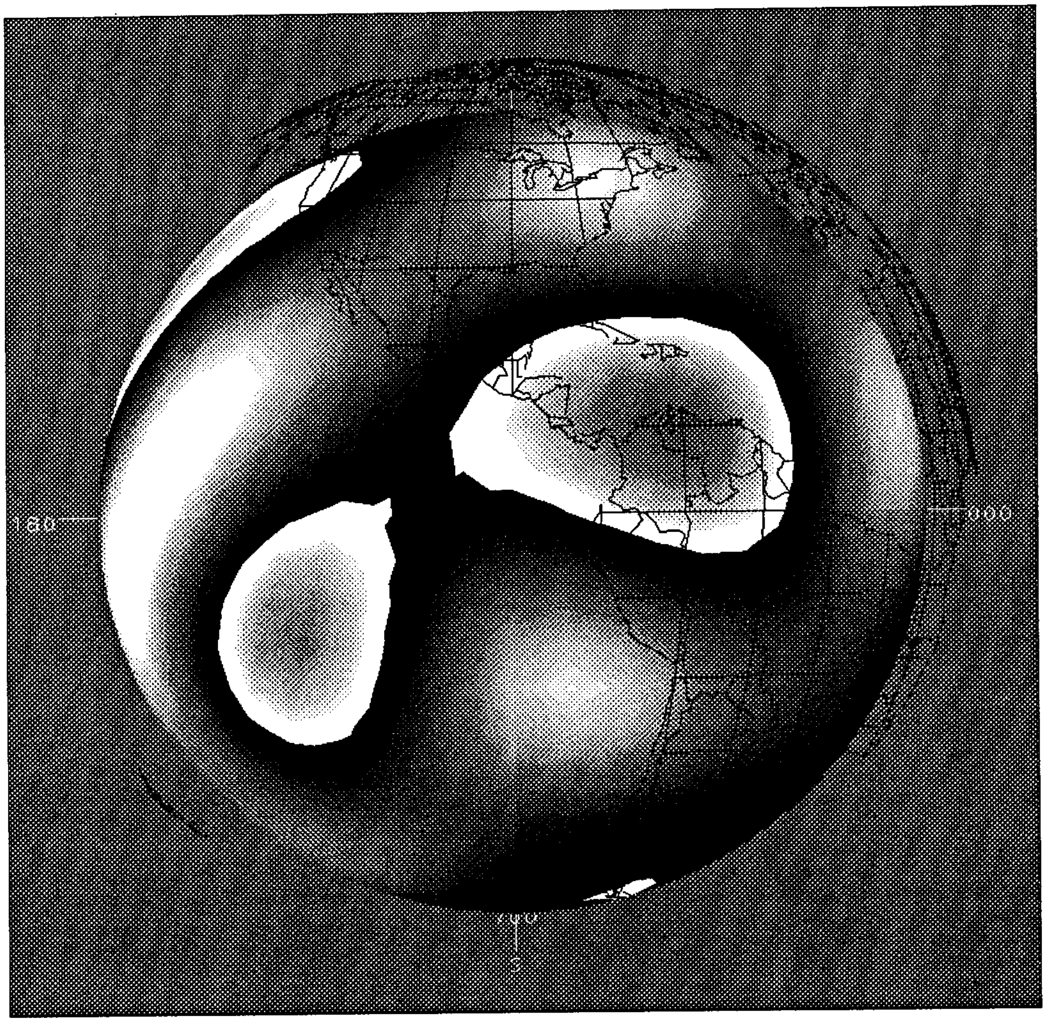

FIG. 5. Earth tomography (Woodhouse and Dziewonski, 1984). As one interactively peels away layers, new pattern patterns of fast (blue) and slow (red) velocity anomalies appear. Input data were velocity variations in spherical harmonics derived from an inversion of surface wave traveltimes at different wavelengths. Continent outlines, axial labels and radial sizes orient the viewer. I experimented with various representations such as octants flying apart, but it it was harder to correlate velocity anomaly patterns of different depths.

System software

The Ardent Titan runs AT&T V.3 UNIX and X-Window V11.3 window system. The difference in the FORTRAN-to-C subroutine calling conventions between AT&T and Berkeley UNIX's caused problems porting the SEPlib subroutine library. Ardent X-Windows is standard, although not particularly fast.

Doré graphics language

Ardent Doré is a full-featured interactive three-dimensional graphics language. It has a rich set of graphics primitives including points, lines, texts, surfaces and basic solids. (It lacks image arrays, however.) Three-dimensional geometric transformations, material and lighting models may be applied. Images are created by grouping these into a graphical database that can be interactively modified.

The most important graphics primitive for geophysical data display is the mesh surface. Surfaces are specified as an arbitrary triangulation of vertices—each a location, color (optional) and reflectivity angle (optional). Doré shades the mesh according color, perspective, and illumination. Figure 12 illustrates sample geophysical meshes.

Color is richly developed in Doré . In fact there was little motivation for SEP to acquire a color printer because pre-Doré SEP software did not use color very much. Doré allows the assignment of arbitrary color to any display object or mesh point. Geometric transformations, illumination and material properties modify coloring. Geophysical information can be encoded in the color modifications, e.g. transparency, as long as it doesn't destroy the original intentions of the color modification. Full resolution 24-bit color displays are generally necessary to fully exploit Doré 's color capabilities.

Doré User Interface

The Doré User Interface (DUI) package supplies a program shell and interactive interface for embedding user's applications. Although originally intended for demonstrations, all of the applications software I've seen use DUI. DUI initializes Doré , supplies generic interactive controls for geometric transformations, animation, lighting and rendering options. The programmer writes one or two subroutines—one to draw the image and an optional one to add new interactive controls. Controls are buttons (discrete states), dials (continuous state) and mouse picks on the image. DUI is written in a combination of Doré and X-Windows (version 11) routines.

Other Ardent graphics languages

Doré and X-Windows use an raster-vector primitive library called *DGL.* It runs very fast and is difficult to program. Because it was not intended for direct user

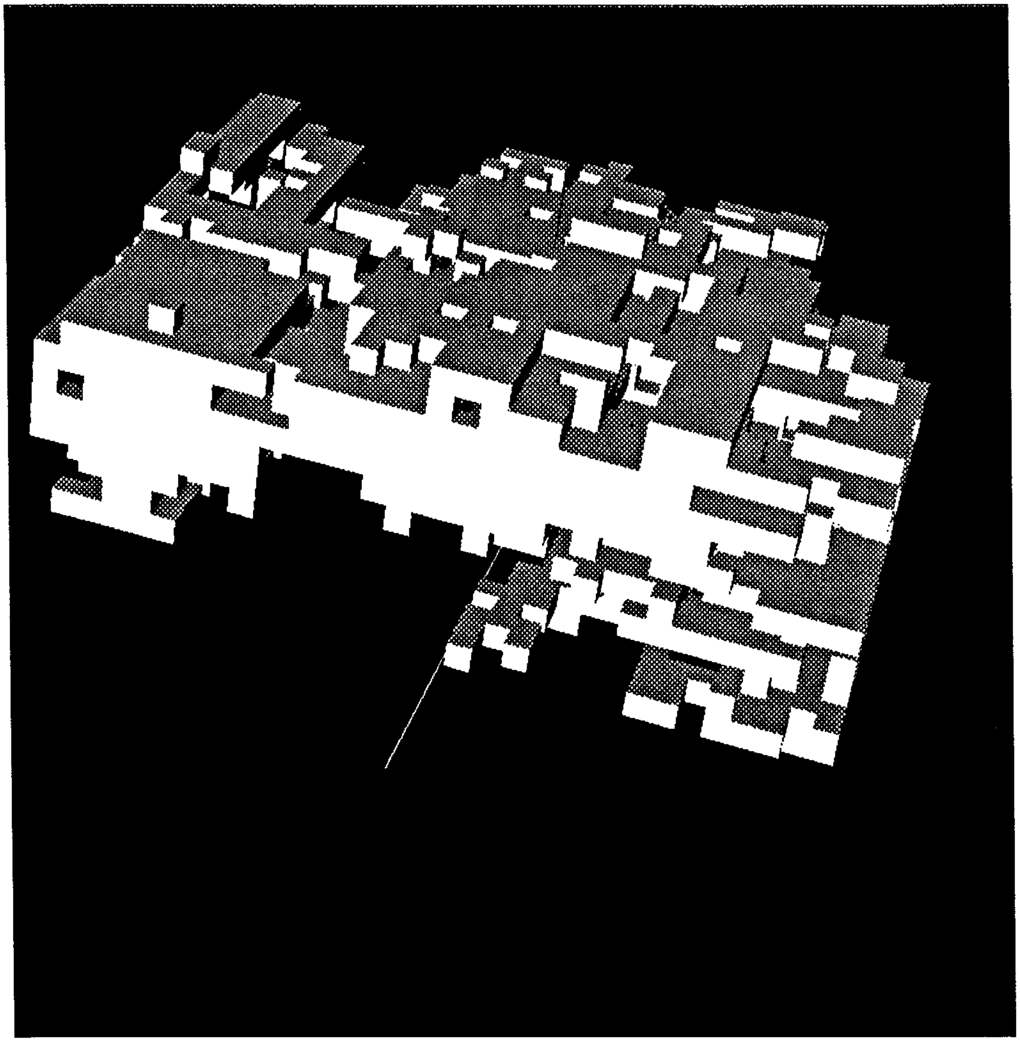

FIG. 6. Rock pore network (Francis Muir). There is much research in simulating or measuring three dimensional pore geometries in rocks or reservoirs. I found movie slices inadequate to understand the third dimension. A empty pore cells or solid rock elements are rendered as boxes. Then the image may be studied under various perspectives. I tried various labeling mechanisms to prevent observer disorientation. Different colors on each of the six sides were not always distinguishable and were distracting. A transparent box and colored axes worked better. Even the smallest simulations (32 x 32 x 32) rapidly became uninterpretable and slow. Highlighting a single pore helps significantly. The pore extraction algorithm exhaustively searches all neighbors of a seed cell.

access, documentation is sparse. I would use this language for the SEP Movie program were I to convert it for the Ardent Titan.

Ardent is preparing a raster manipulation toolkit, yet unnamed, similar to that of a Pixar or Sun-TAAC board. Preliminary demonstrations indicate an order-of-magnitude greater speed and image memory capacity than the Sun product. Ardent's preliminary raster cube manipulation utilities are so good they have intimidated my efforts to develop a seismic movie there.

Hardcopy

Doré can produce images—screen or files—at arbitrary color precision. They look best with 24-bit color resolution. A screen image is captured with the X-Windows screen dump utility *xwd*. This was the method of printing the figures in this article. Color hardcopy images, such as the transparencies used at the SEP meeting talk, are printed on a Tektronix 4396D color plotter. Ardent provides a Tektronix driver. The Tektronix driver, however, alters the Doré output slightly as it dither-zooms from screen raster to page raster size.

There are three options for video output. First, the DUI package can drive a Minivas VHS frame-grabbing video recorder. Second the Ardent Titan can output NTSC-size (quarter screen) images. A separate NTSC encoder converts these onto standard video tape. Third, and lowest resolution, is photographing directly from the screen with aa television camera.

Software portability

There are two portability issues—code and functionality. Ardent has recently released a portable version of Doré written in C. It compiles and runs successfully, although slowly, on the Convex. It creates 24-bit color rasterfiles. Device drivers for graphics-accelerator hardware can be written for portable-Doré , thereby improving performance. Our intention is to make Doré available on most of our computers as a powerful three-dimensional graphics language, even if it has to be run in batch mode.

To run my visualization software on non-Doré systems the hardware must be at least as fast the Ardent Titan and software must emulate important Doré features. Foremost are surface meshes of arbitrary size, color, and illumination; a powerful color model; and flexible display lists. Efforts to translate my code to competing popular three-dimensional software systems have been painful due to a lack of some or all of these features.

STANDARD APPLICATION

The standard applications includes the components of database access, graphical modeling, labeling, and interaction.

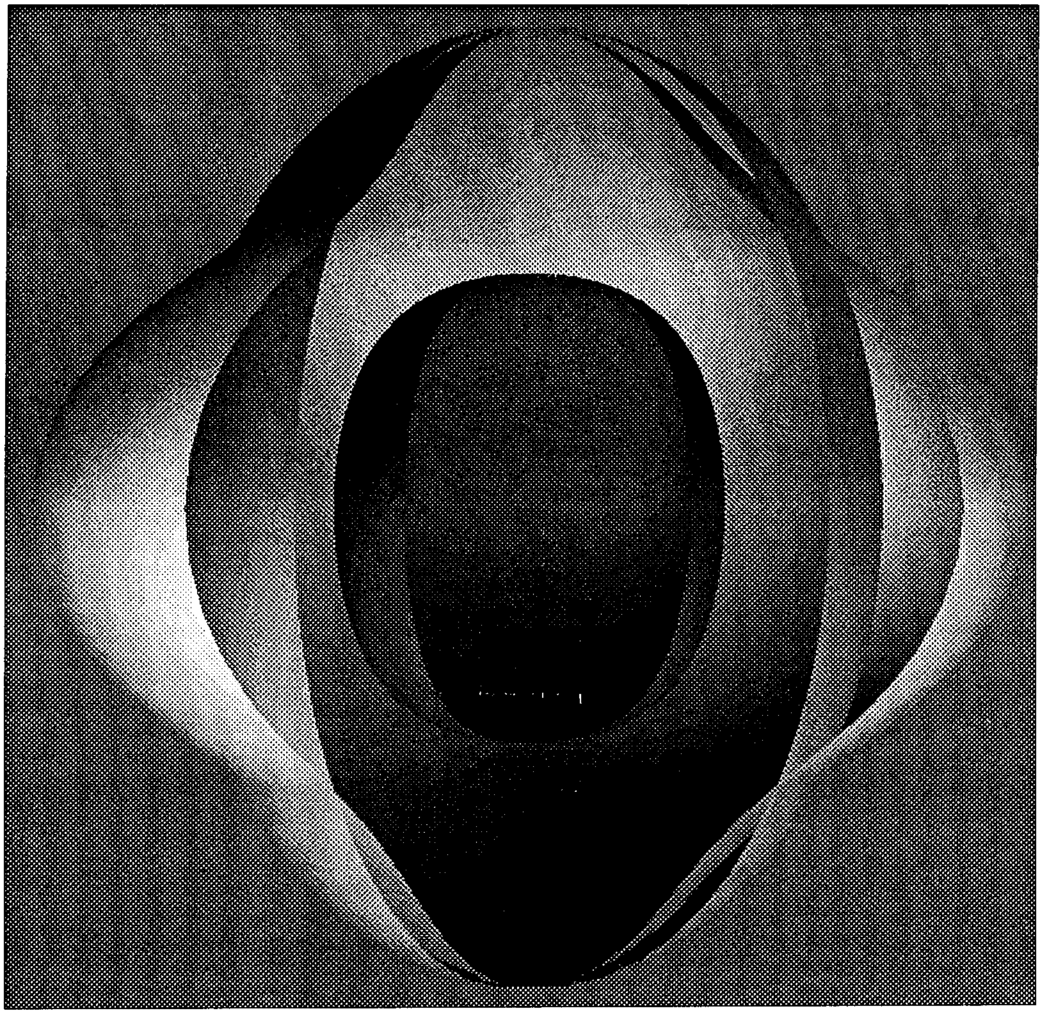

FIG. 7. Transverse anisotropic slowness surface (Joe Dellinger). The blue inner surface is compressional while the red and green outer surfaces are shear. As the anisotropic model becomes more complicated, e.g. orthorhombic, shear surfaces become complicated both kinematically and graphically. Singularities, depicted by gaps, and shear wave type mixing, depicted, by color blending, occur. Slowness surfaces are computed by evaluating the Christoffel equations at regular steradial intervals in three-dimensional Fourier space and refining the sampling in complicated regions. The resulting data structure is not a continuous mesh, but a set of adjacent patches.

Database

All of examples in this article read an external database and made an image out of it. The more standard the database, the more reusable the application program. Standard databases around SEP include sepcube, segy and vplot.

Visualization

The programmer must determine how to most effectively convert the scientific information in the data into an image using shape, color, and motion. This requires understanding the scientific information content of the data and imaginative graphics artistry. The visualization computer code is a two step process of converting the input data into an image data structure and then calling the appropriate Doré subroutines.

Labels

Viewers easily get confused when the image has changed size, perspective or color. Orientation labels are essential. Lines and text are not best because they clutter the image and distort under transformation. Transparent planes, transparent bounding boxes, and 3-D arrows are objects that work better. Doré provides two kinds of text—one that responds to geometric transformations and another that stays parallel to the screen. Each type plays a role in labeling—transforming text for object *parts* and non-transforming text for images in general.

Interaction

The Doré User Interface toolkit has programmable controls for interaction. The programmer may want to overide default control functions and add new ones. Often the default functions have inappropriate degrees of freedom—too much or too little. For example, an earth image only needs to turn about the rotation axis instead of any axis. Useful additional functions include visibility control, constrained motions, re-coloring and save options.

UTILITIES

A utility is a standard application a works on wide variety of datasets. Utilities are motivated by repeated code and functions in specialized applications. Consolidating the code makes it easier to maintain and extend. If an utility is general enough, imaginative users will create new uses. The SEP movie program is an utility for data cubes on raster displays.

Geophysicists frequently want to map data arrays onto regular surfaces such as sphere or cylinder. The *SEPsurf* utility maps sepcube-format datasets onto surfaces. (SEP software users will recognize SEPsurf as the extension of *thplot.*) Other datasets consist of repeated objects oriented in a three-dimensional volume and are

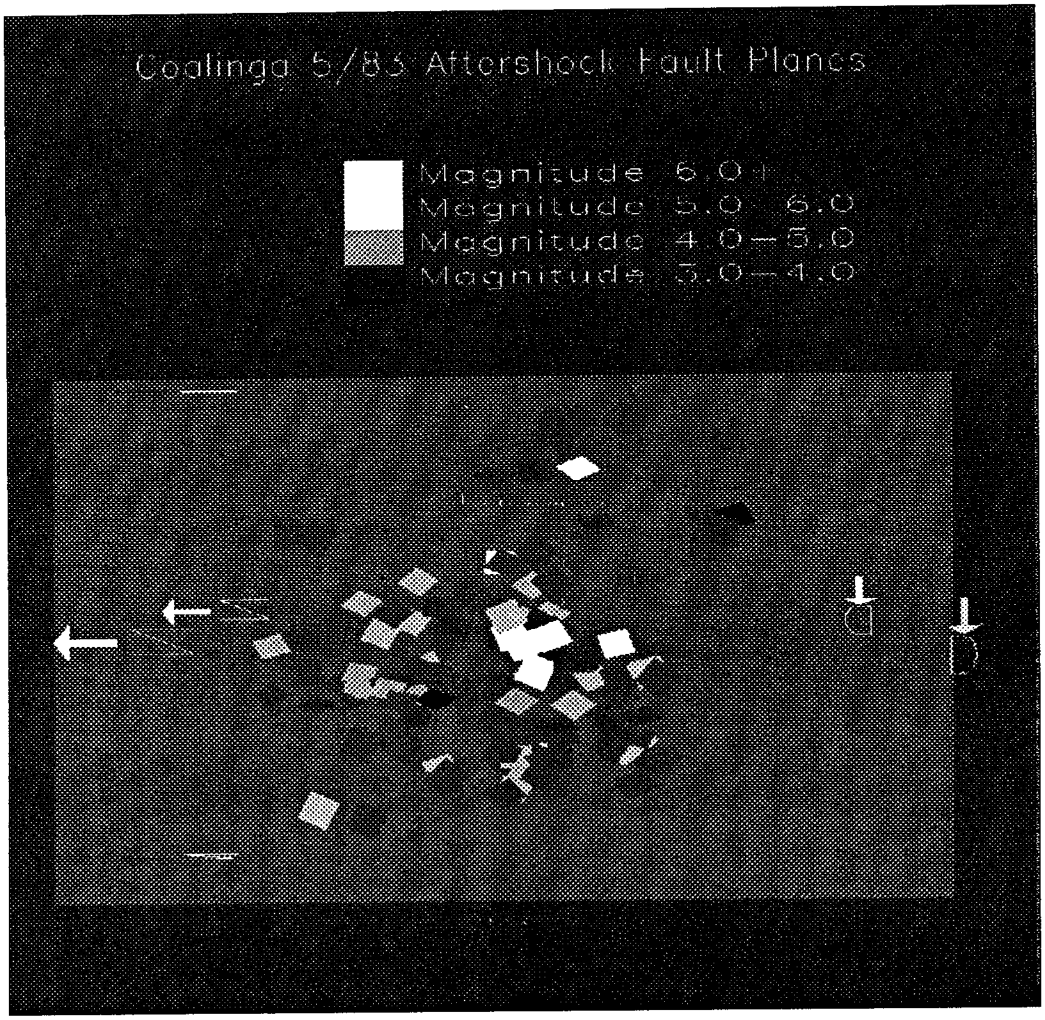

FIG. 8. 1983 Coalinga aftershock source mechanisms (Donna Eberhart-Phillips). Each sheet represents an aftershock of Richter magnitude 3.0 or larger. The sheet is located at the epicenter and brightness shows the magnitude. The sheet is tilted in the direction of the fault plane determined from first motions. It is necessary to study this image at various rotations in order to see the aggregate fault plane orientation. An auxiliary image, not shown here, displays several thousand aftershock hypocenter determinations as a point-cloud. It gives additional insight into the Coalinga earthquake. This image is an exercise in graphics noise. Size and color changes makes information less clear. A transparent box with reference arrows shows orientation. This figure was created with the SEPdraw utility. SEPdraw was invaluable for rapid experiments in display techniques.

displayed with utility *SEPdraw.* (SEP software users will recognize SEPdraw as the extension of vplot-*plotas.*)

SEPsurf

SEPsurf displays one to three sepcube-format datasets as a colored surface. Four stock surfaces are supplied: plane (default), tube, ball and log. Planes are for area geophysical surveys; tubes and logs for borehole measurements; and balls for global geophysics. One dataset may be mapped as relief, another as color, and a third as a transparent overlay on the same surface.

Input datasets are three dimensional arrays of floating point numbers or byte integers. The first two dimensions are mapped onto the surface (first one for well logs) and the third dimension defines an animation sequence or array of surfaces. The first dimension is horizontal or longitudinal; the second is vertical or latitudinal. When the second dimension is very long such as in a borehole, it may be scrolled or subdivided into overlapping parts.

Dataset and display dimensions can be different. In fact, the default display grid size is the largest grid less-or-equal to the data that can be animated satisfactory, or about five thousand points. Data is interpolated nearest neighbor onto the display grid. SEPsurf adds shape-dependent orientation and scale labels to each surface type.

SEPsurf supports three mutually exclusive color schemes—a single color, bipolar seismic colors, or range maps. The default is the red-white-blue seismic color. One can also specify the line, text and overlay colors. Color parameters use common English color names.

The earth topography (Figure 4), borehole televiewer (Figure 2), and well log (Figure 3) were rendered with SEPsurf. SEPsurf does not handle surfaces of multiple shapes (Figures 1, 5, & 7) or irregular shape (Figure 6).

SEPdraw

SEPdraw plots three-dimensional objects from a script file description. Multiple script files are rendered as different frames. SEPdraw permits quick prototyping of images by automating repetitive programming chores.

Each line of the script file describes a plot object. The first word names the object followed by an optional list of attributes on the same line. Text following a # sign is a comment and discarded. Pre-defined object include:

points— point, pointlist*;

lines— line, linelist*, rect, circle, frame, polyline*, "text";

surfaces— background, sheet, disk, arrow, polygon*, trianglelist*;

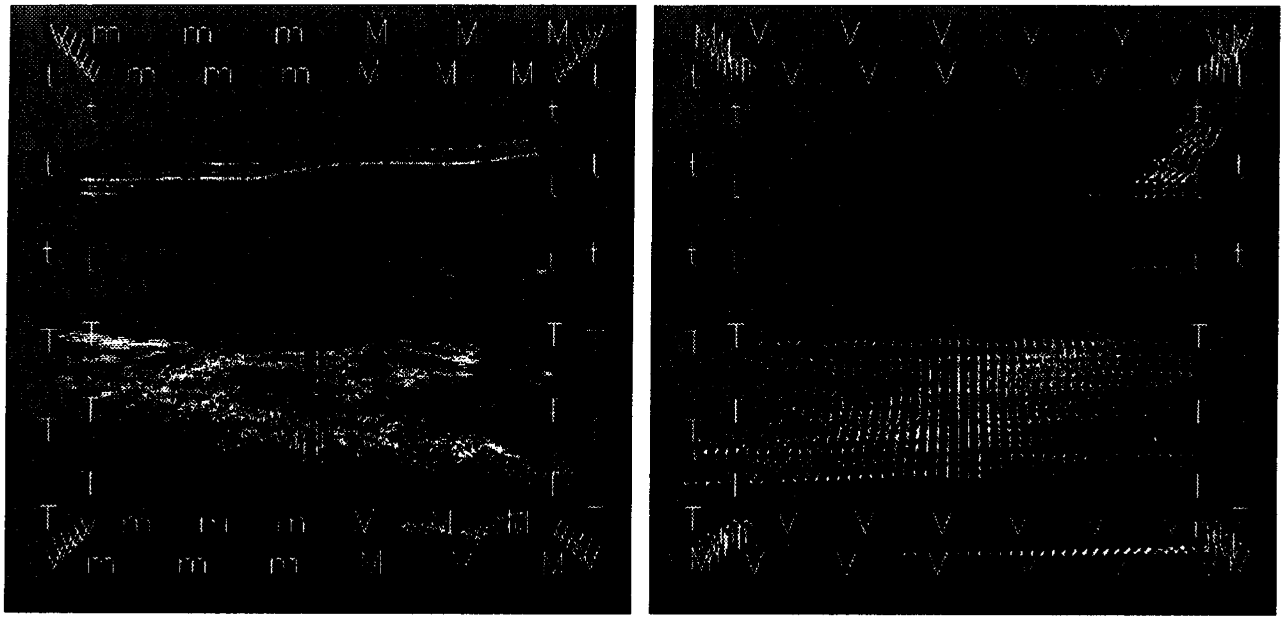

FIG. 9. Migration velocity scan displayed as a point cloud (Paul Fowler). The letters 'M', 'V' and 'T' refer identify the midpoint, velocity and time axes with capitals showing the larger end. On the left is the midpoint-axis projection showing primarily geological structure. On the right is the velocity-axis projection showing the velocity trend. Mixed projections show the effect of geologic structure on velocity migration velocity scans. projection. Only the strongest one percent of the data are plotted. Any more would have made the image too complicated to interpret. Point-clouds are an easy method of visualing *simple* structures inside volumes. In this instance we are seeing approximately a single two-dimensional geo-velocity surface. Any greater complexity, such as multiple surfaces, would be difficult to interpret. The method of depicting axes with single letters is less cluttered than lines and words.

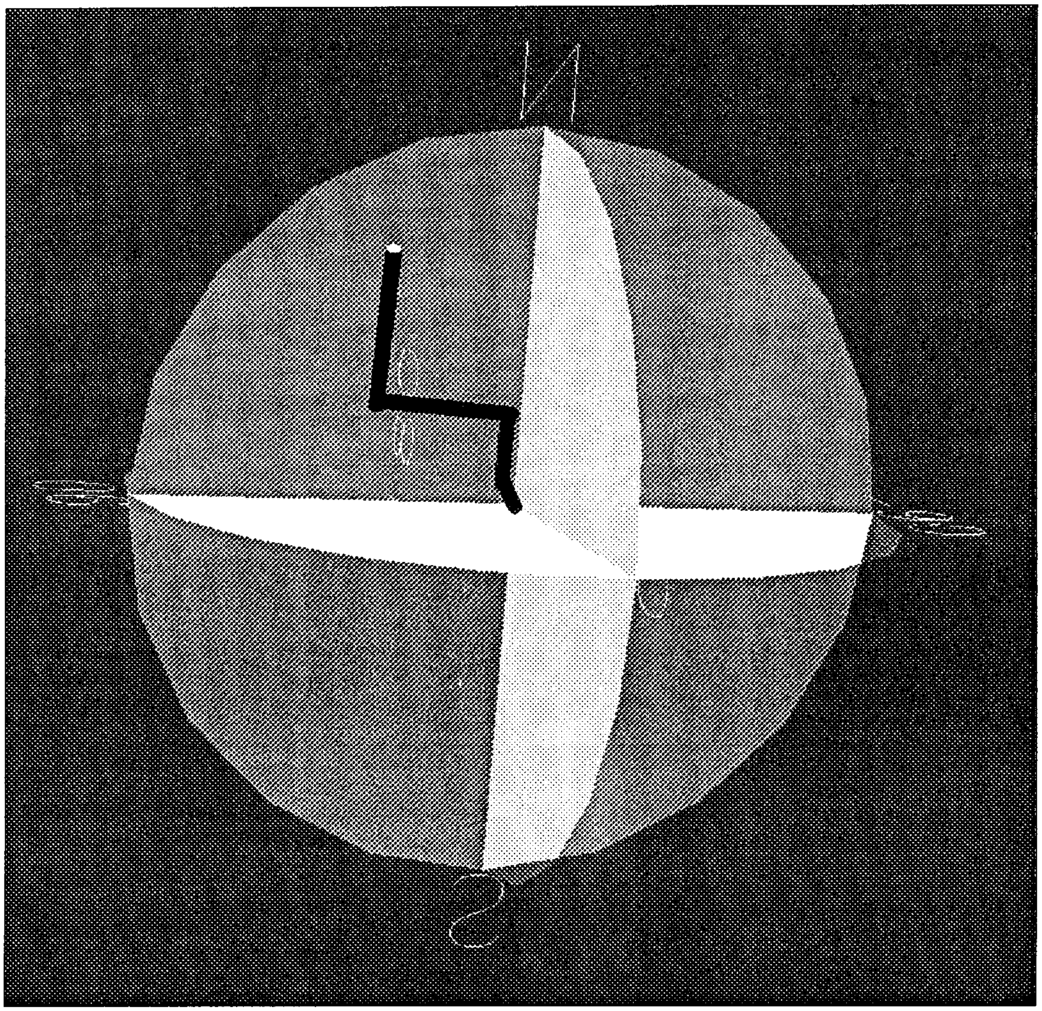

FIG. 10. Three-dimensional demagnetization diagram (Mike McWilliams). The latitude and longitude are the paleo-magnetic pole position and the radius the magnetic field strength at various stages of demagnetizing a rock sample. As the line moves to the center, magnetic overprints are removed, and the original magnetic orientation of the rock can be seen. This image was generated by SEPdraw. Ploytubes and transparent planes survive three-dimensional transformations better than other graphics primitives.

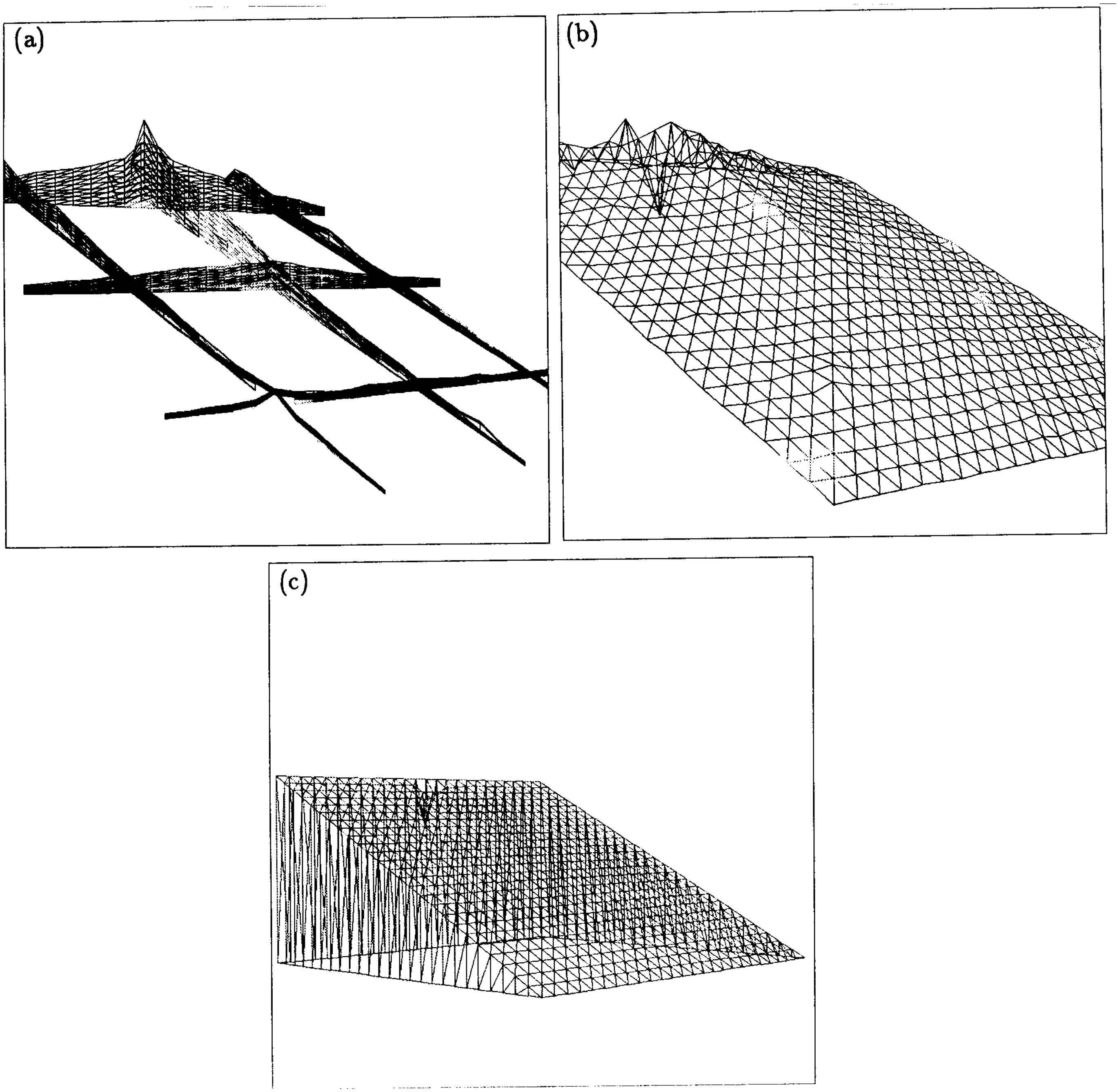

FIG. 11. Sample mesh triangulations for components of the sedimentary basin displayed in Figure 1: (a) fence lattice, (b) sediment surface, and (c) basement topography (erosion near top). Meshes (b) and (c) are regular retangular meshes. The fence diagran (a) is more accomplished to account for discontinuous sediment deposition.

solids— box, sphere, cylinder, cone, wheel, spear, polytube*.

Each primitive object has unit dimensions and defined origin. Origins are at zero for flat edges and the middle for round edges. This convention makes it easy to align objects.

The starred objects require lists of x-y-z numbers. Numbers are in a specified file or on subsequent lines until the word "end".

Attributes modify each object. Attributes names begin with a capital letter, have zero to three arguments, and follow the object name in any order on the same text line. Not all attributes apply to every object. Attributes include:

Align *alignment* (align text);

Color *colorname* (common English names);

File *filename* (list file);

Loc $x\ y\ z$ (location);

Polar (location in polar coordinates);

Rotate $x\ y\ z$ (degrees);

Size $x\ y\ z$;

Transparent ;

Width *thickness.*

The geometric attributes are applied in the order—Rotate, Size, Loc—irrespective of their specified order. Otherwise geometric attributes are order-dependent and confusing to remember in what order to apply.

New objects are defined by grouping together already-defined objects with optional attribute transformations. A definition begins with the line "define new_name" followed by its contents until the next definition or file end. Attributes can be on definition lines. They cascade or override previous attributes. Definitions are not nested, though sequential definition compose hierarchical objects.

Every file must contain definition for "main", usually at the end. This is the only object displayed. Figure 13 is the SEPdraw script for generating the geophysical image of Figure 8. The first line in a file should be a define statement.

A strategy for organizing SEPdraw plots is to define one or more data parts, then labels, and compose these into a main. Various parts can be commented out while debugging the display.

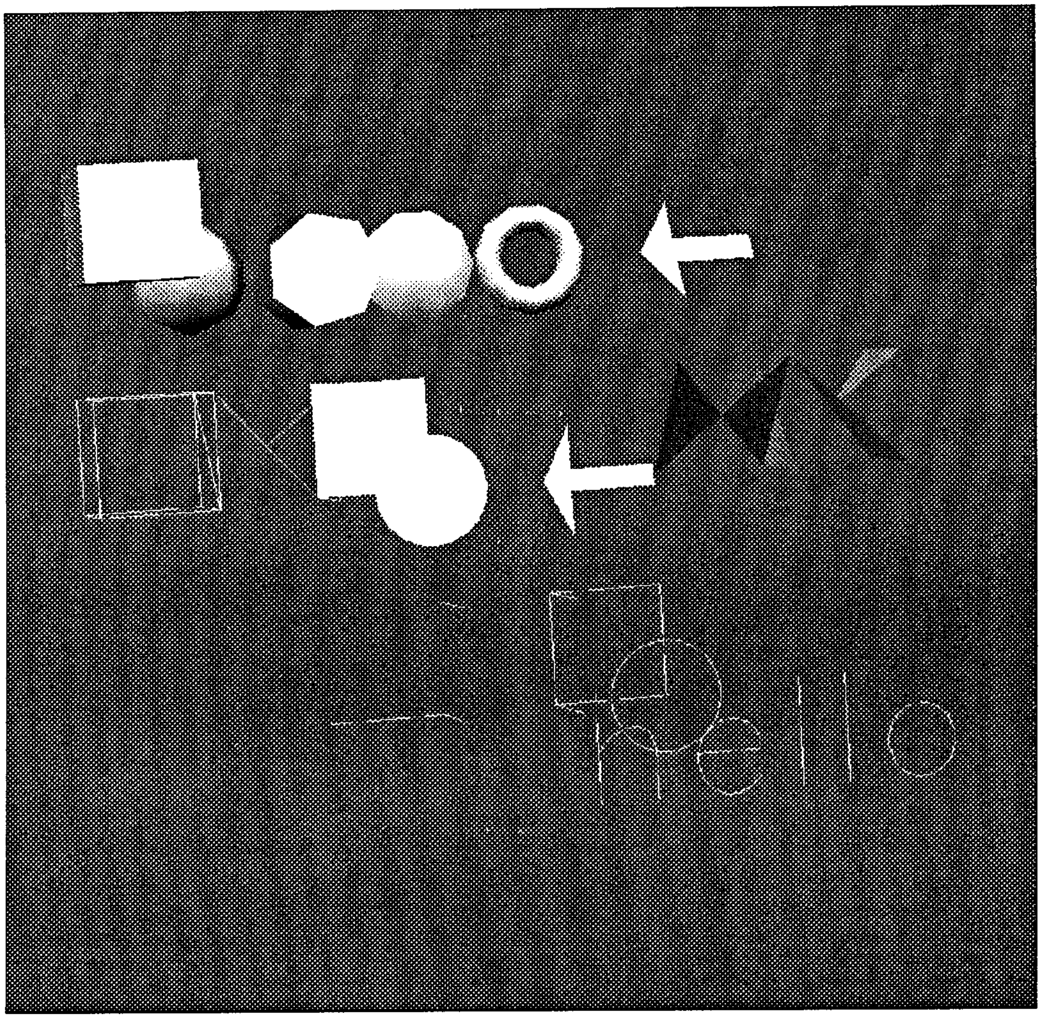

FIG. 12. Shape primitives in SEPdraw. From the bottom up are points, lines, surfaces and solids.

FUTURE DIRECTIONS

I plan imaginative new algorithms to visualize new kinds of datasets. Projects in the progress include reservoir geophysics, tomography, tectonic animations and geochemical crystalline structures. Projects are driven by interesting datasets I find. My motto is: "Find data, will image".

Another direction is increased functionality. Most of my programs only change display parameters of pre-computed objects. I plan dynamic data computations such as interactive simulation and processing.

ACKNOWLEDGMENTS

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```
# Eberhart's Coalinga faultplane solutions

# data rendered as little squares at hypocenter locations
# magnitudes rendered in color
define data
  sheet Loc 13.27 17.52 9.65    Rotate 30 0.0 235      Color white
  sheet Loc 9.22 13.97 9.03     Rotate 85 0.0 330      Color darkred
  sheet Loc 10.11 16.29 7.37    Rotate 45 0.0 120      Color darkred
# 140 additional aftershocks

# magnitude key
define key      Rotate -90 0 0  Scale .25 .25 .25
  box   Loc 0 3 0       Color white
  box   Loc 0 2 0       Color gray
  box   Loc 0 1 0       Color red
  box   Loc 0 0 0       Color blue
  "Magnitude 6.0+"      Loc 1.2 4 0     Size .5 .5 .5 Color white Align left
  "Magnitude 5.0-6.0"   Loc 1.2 3 0     Size .5 .5 .5 Color gray Align left
  "Magnitude 4.0-5.0"   Loc 1.2 2 0     Size .5 .5 .5 Color red Align left
  "Magnitude 3.0-4.0"   Loc 1.2 1 0     Size .5 .5 .5 Color blue Align left

# labels
define north    Color yellow    Size .07 .07 .07
  arrow
  "N"   Loc 1.3 0 0     Rotate 0 0 90
define down     Rotate 0 90 0   Color red       Size .07 .07 .07
  arrow
  "D"   Loc -1. 0 0     Rotate 180 0 90
define  label
  box   Color darkgray  Transp
  north Loc 0 .5 -.01
  north Loc 0 .5 1.01
  north Loc 0 -.01 .5   Rotate 90 0 0
  north Loc 0 1.01 .5   Rotate 90 0 0
  down  Loc 1.01 -.01 .5        Rotate 0 0 -45
  down  Loc 1.01 1.01 .5        Rotate 0 0 45
  key Loc .3 .5 -.2     Scale .3 .3 .3
  "Coalinga 5/83 Aftershock Fault Planes"       Loc .5 .5 -.75  Size .03 .05 .05

# main image
define  main    Rotate 90 0 0
  label Size 25 35 15
  data
```

FIG. 13. SEPdraw script file for generating Figure 8.