KNOWLEDGE-BASED GEOLOGICAL VISUALISATION USING AVS

Iain M. Brown
GIS Research Centre
Dept. of Computer Studies,
University of Glamorgan,
Pontypridd
Wales CF37 1DL

Malcolm J. Herbert
NCET
Millburn Hill Road,
Science Park
Coventry
CV4 7JJ

Abstract

The use of computer-based visualisation as a technique for enhanced 3D geological interpretation is assessed by using a general-purpose scientific visualisation system: AVS. Geological data-sets are analysed according to the whether they can be classified as surface data, volume data or discrete shapes known as unstructured cell data. A variety of techniques are available to explore the characteristics of these different data categories and these are reviewed by considering the new insights they provide into the 3-D geometry of structures. Use of a generic visualisation system allows us to identify unique characteristics of geoscientific data which differ from other sciences. In particular, the role of pre-existing knowledge in producing meaningful models is emphasised, which is a reflection on the generally sparse sampling of geoscientific data.

Introduction

The nature of geoscientific work means that the sub-surface environment is observed indirectly via sampling or sensing devices, which provide data from which models are developed. As a consequence, visualisation is a very important technique for evaluating the “mental model” of the geologist against the model derived from the instrumental data. A powerful visual display will stimulate further hypotheses and assist in a clearer understanding of the problem, and a demand for further images. Computer graphics together with recent advances in scientific visualisation (eg. Brodlie et al, 1992; Wolff and Yaegar, 1993; Gallop, 1994) now provide a means by which automated techniques can provide new insights into complex geological data, which should potentially improve interpretation. However, our research suggests that the sparse sampling common in the geosciences means that expert knowledge has a greater significance during visualisation and interpretation than most other disciplines.

This paper demonstrates work carried out with a variety of geoscientific data which has utilised the software of AVS (Application Visualisation System) during the visualisation stage. The advantages and disadvantages of AVS as a tool for analysis of different problem domains is considered, and we consider recent developments in computer graphics which may improve visualisation in the future. Two case studies are included in which AVS (version 5) has been used to assist in modelling coal seams and paleontological specimens.

Application Visualisation System (AVS)

AVS has been developed as a general purpose visualisation system for analysis of complex 3D data-sets, including both scalar and vector data (Advanced Visual Systems, 1992). Unlike specialised geoscientific systems such as VULCAN and GOCAD, it is not designed for use in a particular application area, although the needs of medical informatics have been a significant driving force. This has created a broader user base and has resulted in an open system which the user can extend and customise. Another benefit is that the system can be run on a wide variety of different platforms; for instance, we have used it both on UNIX workstations and on personal computers running LINUX. On workstations, AVS operates under X-Windows and the user interface has been optimised for this. In the UK academic community, the use of AVS has been promoted by a favourable site licence deal (via the CHEST agreement) and by its installation on the CRAY superserver at Manchester Computer Centre which provides remote access free-of-charge (with limitations due to network traffic and support only for software graphics rendering).

AVS fully embodies the paradigm of visual programming in its design. This permits control of computer functions by direct manipulation of visual components (eg. widgets) relevant to the current problem domain. The concept refers not only to the pictures produced by the system, but also to the tools and programming environment in which these pictures are produced. The basic principle of the system is that, by linking together a series of modules in a network, the desired visual output will be produced.

The main components of AVS are outlined in Fig. 1. For a new user to AVS, who initially wishes to get a quick visual impression of their data-set, a Data Viewer exists which contains standard networks for common techniques, such as rendering and slicing of simple objects. However, the full functionality of AVS is achieved through interactive use of the Network Editor (Fig. 2), as this allows modules to be linked in whichever order the user requires, providing that the data types between linked modules match up (they are colour-coded to facilitate this). The Network Editor has a data-flow architecture meaning there are no sequencing constraints other than those produced by data dependencies before a module is initiated. Data can be seen to flow through the network and in combination with error messages, problem areas with incompatible data or slow execution time can be identified.

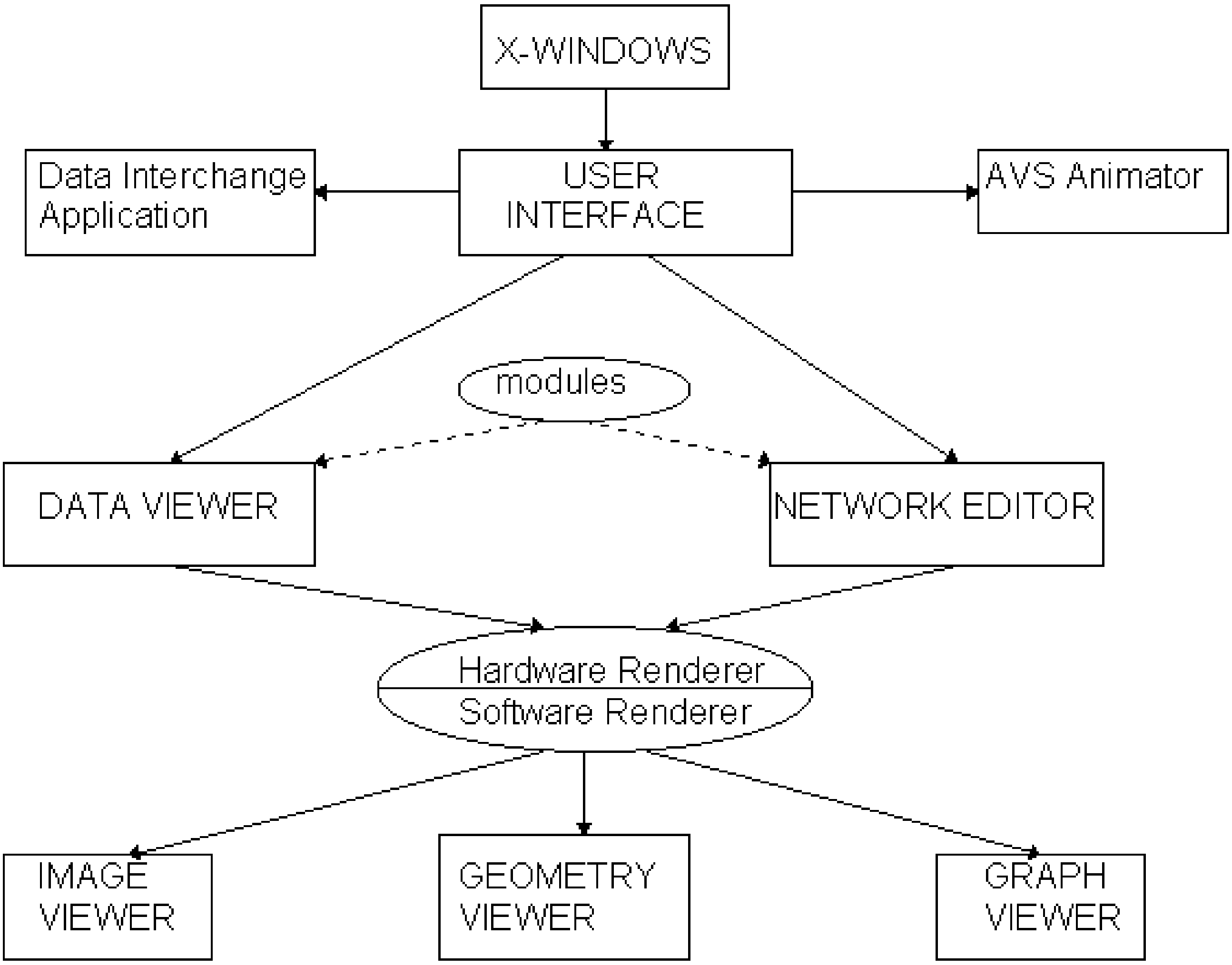

Fig 1: The key components of AVS and its working environment.

Most networks consist of a sequence of modules from four distinct categories: input modules, filter modules (which convert between data types); mapper modules (which transform data types into an image or geometry format for viewing), and output modules. Modules also usually have a control panel and a series of parameters (controlled via widgets) which can be fine-tuned to produce the required effect. If a module to perform the required function does not exist in the standard system, the International AVS Centre has many other, more specialised, modules contributed by users; these are public domain and can be retrieved via the file transfer protocol *(ftp)*. If a suitable module still cannot be found, then tools exist for the user to develop their own using C or FORTRAN programming languages, aided by the Module Generator.

A variety of data types are available in AVS. For geology, the main data types utilised are field data, unstructured cell data (ucd) and geometry data. Data are generally input either as a field, in which the data structure is organised as a regular or irregular grid, or in ucd format, which allows discrete structures composed of nodes and cells to be built from the original data (in triangular, hexagonal, tetrahedral forms etc.). Vectors can be attached to each node in the grid or ucd structure, allowing analysis of multi-attribute data. For use within the Geometry Viewer, primitive structures such as field meshes, polygons and polyhedra are built up into a 3D geometry data type. The geometric object created can then

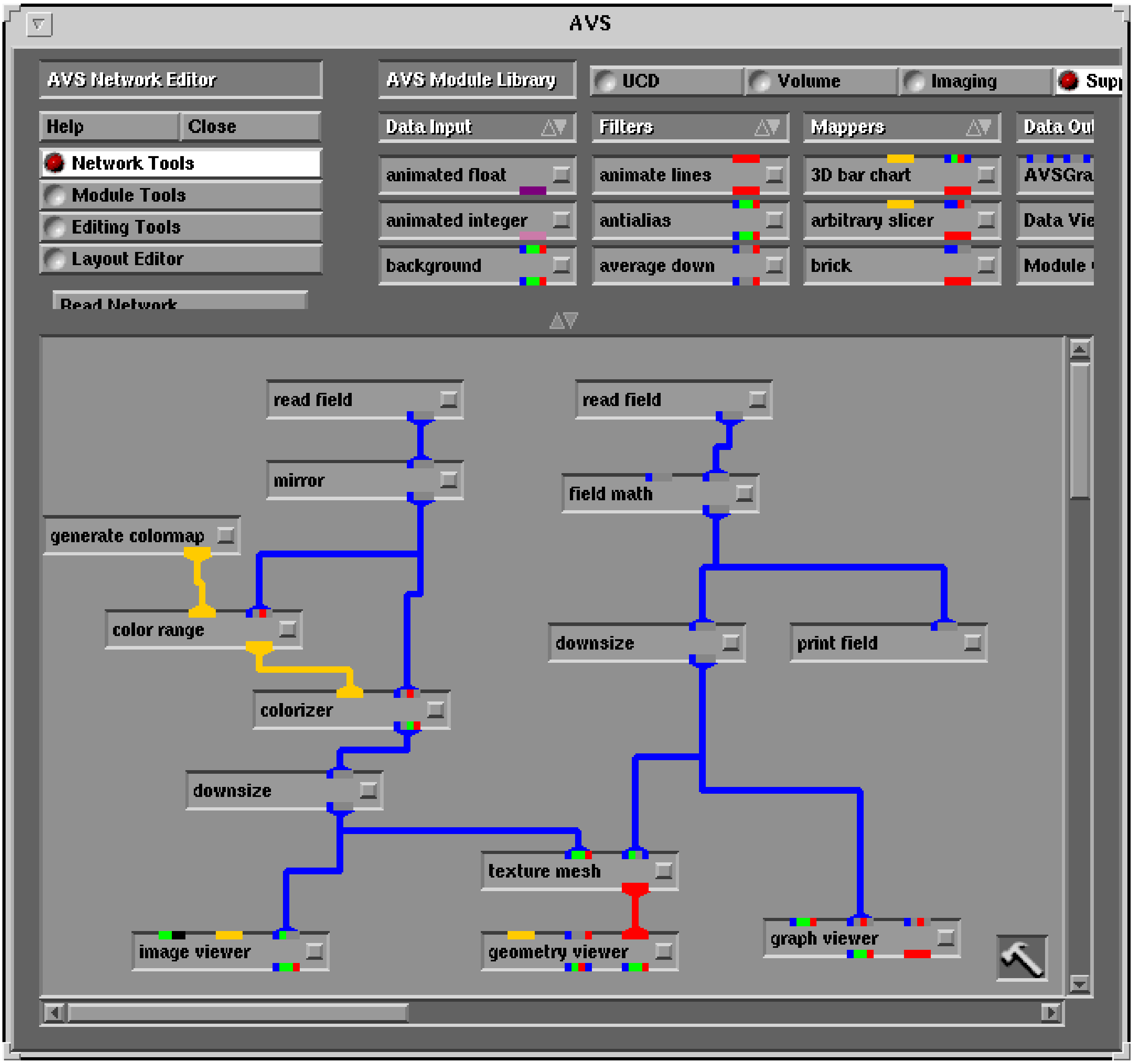

Fig. 2: The Network Editor in AVS showing a typical network using the Geometry Viewer, Image Viewer and Graph Viewer.

be rotated, translated or scaled within the Geometry Viewer. Tools also exist to alter lighting conditions and object properties such as transparency or reflectance, and to apply texture mapping of an image onto the geometry.

Although 3-D visualisation is especially useful, the importance of 2D and even 1D displays (eg. X-Y profiles) in conjunction with the 3D view should not be forgotten, as they can provide important visual cues for complex objects. In AVS, the Image Viewer displays 2D field data as pixels which, together with its image processing tools, means it is very suitable for manipulating remotely-sensed images. The Graph Viewer, allows 1D and 2D data to be portrayed, for example as contour maps. This information can be combined alongside 3D rendered objects portrayed in the Geometry Viewer to assist in visualisation (Fig. 3). Vector values attached to the pixel-based images and at the vertices of the geometry objects allow colour-mapping to be applied to enhance the visual effect.

Import / Export of Data

A critical aspect of all systems used to visualise geoscientific data is the ease of data import and export, because each software package stores data internally in its own proprietary format. AVS provides reasonable support for this problem due to its broad user base, although problems are still often experienced. Generally some form of pre-processing of geological data is required to transform it into field or ucd format ready for input, such as producing a grid. Data can be converted (via modules) from a variety of other software such as ARC/INFO, Mathematica, AUTOCAD (.dxf), GOCAD, GRASS, SEG-Y seismic format, NTF (Ordnance Survey) or Stratamodel. In addition, a form-based tool known as the

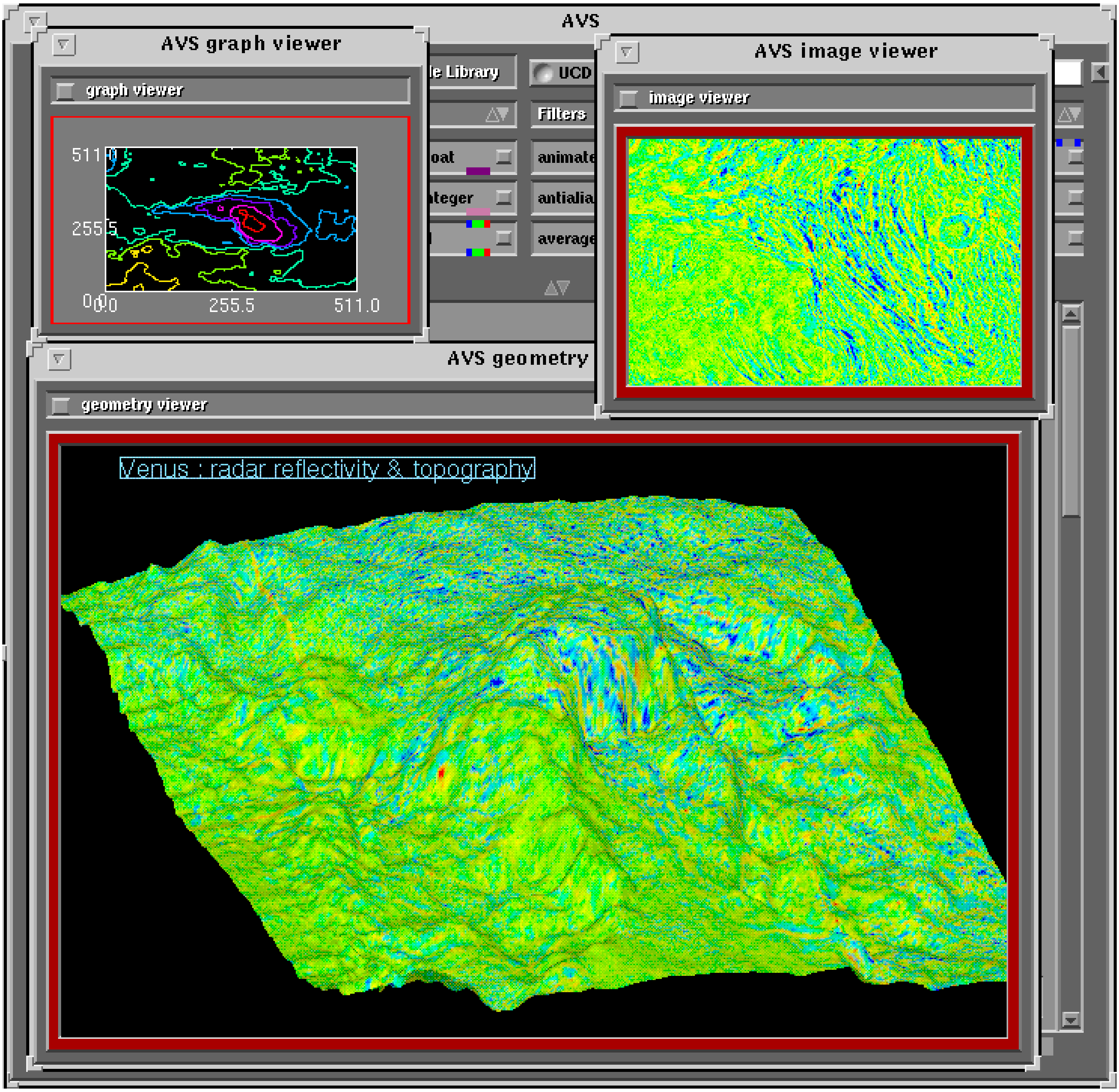

Fig. 3: The display obtained from the network in Fig. 2. The Image Viewer shows radar reflectivity values for the Maxwell Mountains area of Venus (indicating surface roughness) which have been texture mapped onto topography data obtained from altimetry in the Geometry Viewer. The Graph Viewer shows a contour map of the topography.

AVS Data Interchange Application (ADIA) facilitates data import but the diversity of geoscience data-sets means that this remains a time-consuming task. With regard to data output, the standard AVS .x image file can be converted to common image formats such as .gif, .tiff, .jpeg, .mpeg, postscript and also to an EXCEL spreadsheet, via public-domain modules and software.

Surface Data

Geologists often work with horizons or layers, particularly in sedimentary environments, and by using surfaces these may be visualised in 3D space in an informative and uncomplicated manner. Sometimes, as with conventional geographical information systems (GIS), the underlying data structure can only accommodate single z-values for each x,y co-ordinate, producing so-called 2.5D surfaces, which creates problems for features such as reverse faults and overfolds. This problem is resolved in visualisation and CAD-based packages which enable multi-valued surfaces, although querying a spatial database is now much more difficult. As surfaces are simple to produce and manipulate, they can provide a good 3D impression of the geometry of structure boundaries without the interior detail. In the following case study, AVS surfaces have been used to visualise the results from a project developing new methods for automated correlation and interpolation of borehole data.

Case Study I: Correlation Of Coal Seams

The experimental techniques have been applied to a trial area in the Northumberland coalfield where it is difficult to correlate coal seams from one log to another because the sequences consist of variable and often incomplete cyclothems which often exhibit great lateral variation (cf. Lawrence and Jackson, 1990). No geophysical data was available and biostratigraphical evidence was restricted to fossiliferous marine beds which act as markers. In this particular case, it was most suitable to use surfaces to visualise the geometry of the coal seams because of their negligible thickness in a volumetric context and because the intervening material between the seams was of lesser interest.

Lithological logs were automatically correlated using a modified version of the dynamic programming algorithm of Smith and Waterman (1980) which has the major advantage that it can handle gaps in sequences (from non-deposition or unconformities). Detailed description is beyond the scope of this paper, but basically the technique performs pattern matching between two strings (eg. ABACDACBF and BADACBEF) by determining the minimum number of operations (insertion, deletion, matching) required to transform one of the strings into the other, allowing for the possibilty of gaps. Lithological units in logs can easily be treated as string patterns; the algorithm also requires weights related to the environment of deposition and costs for each operation to determine an optimal match between a pair of boreholes.

To develop this methodology for multiple logs requires significantly more computation and is currently the subject of further research (Brown, 1996), but in the area of study it was possible to build up a series of pairwise correlations by matching them all with a central borehole which had the most complete sequence. Eventually a file of xyz co-ordinates for each horizon was produced. As coal seams are the major feature of interest, only these horizons were pre-processed for visualisation in AVS field format. Pre-processing involved interpolating the xyz scatter data into a grid which can then be imported as a 2D scalar field. As error and uncertainty were also important considerations in this project, the geostatistical technique of kriging (cf. Isaaks and Srivastava, 1990) was used to produce the grid (using the geographic information system ARC/INFO).

Once imported into AVS, a surface mesh could be produced from the grid and by applying colour and rendering in the Geometry Viewer, the 3D geometry could be analysed for structural anomalies. Assuming that the method of interpolation has been successfully applied, such anomalies would imply further fine-tuning of the automated correlation weights may be required. The geometry can be expressed in a variety of formats, depending on which modules were used in the network (Fig. 4). An important consideration during visualisation is that the data needs to retain some form of geo-referencing so that potential anomalies can be located. A simple way to do this is to overlay the mesh interpolated from the original data, and use it as a scale; alternatively, a base map could be imported from a GIS such as ARC/INFO.

A second vector value can also be colour-mapped onto the surface for further information. Hence, we can show the relationship between seam thickness and 3D geometry or, by mapping the error variance values obtained by kriging, a quantitative estimate can be obtained of those areas where the interpolated surface is most uncertain and may require further sampling (Fig. 4).

Results show that AVS displays surface information very clearly and the ability to interactively apply transformations, such as scaling, rotation and colour-mapping quickly and intuitively, means it out-performs most other surface-based visualisation packages. However, a serious omission for the geologist is a simple method to combine several surfaces into a block diagram (as in ISM software). The problem relates to the development of AVS for mainly continuous field data, whereas geological data-sets and structures tend to be discrete and heterogeneous.

In this example, geological knowledge is critical to resolve ambiguities resulting from the numerous ways in which sparse data can be correlated, interpolated and visualised. This is manifest in the choice of weights for automated correlation and the parameters for kriging, and also with the control of the visualisation environment to produce the most “realistic” image.

Volume Data

Whereas surface data can be expressed as $f(x,y)$ and mapped as 2D scalar or vector data, some data-sets can only be considered realistically as volume data of the form $f(x,y,z)$. With volume data, some data is hidden from the viewer behind other data and we therefore require techniques to look into the interior and produce a realistic rather than an arbitrary display.

Two alternative methods for visualising volume data exist. Either surfaces can be extracted by techniques such as slicing and isosurfaces or, alternatively, a volume rendering technique based on individual elements (voxels) can be applied. Direct volume rendering techniques assign a colour and opacity to each voxel, based on values such as density. In AVS, volume rendering involves either defining material properties or produce ray cast images. To produce an accurate volume visualisation requires that the user understands both the techniques being used and the integrity of the data. These issues are further addressed in the following case study.

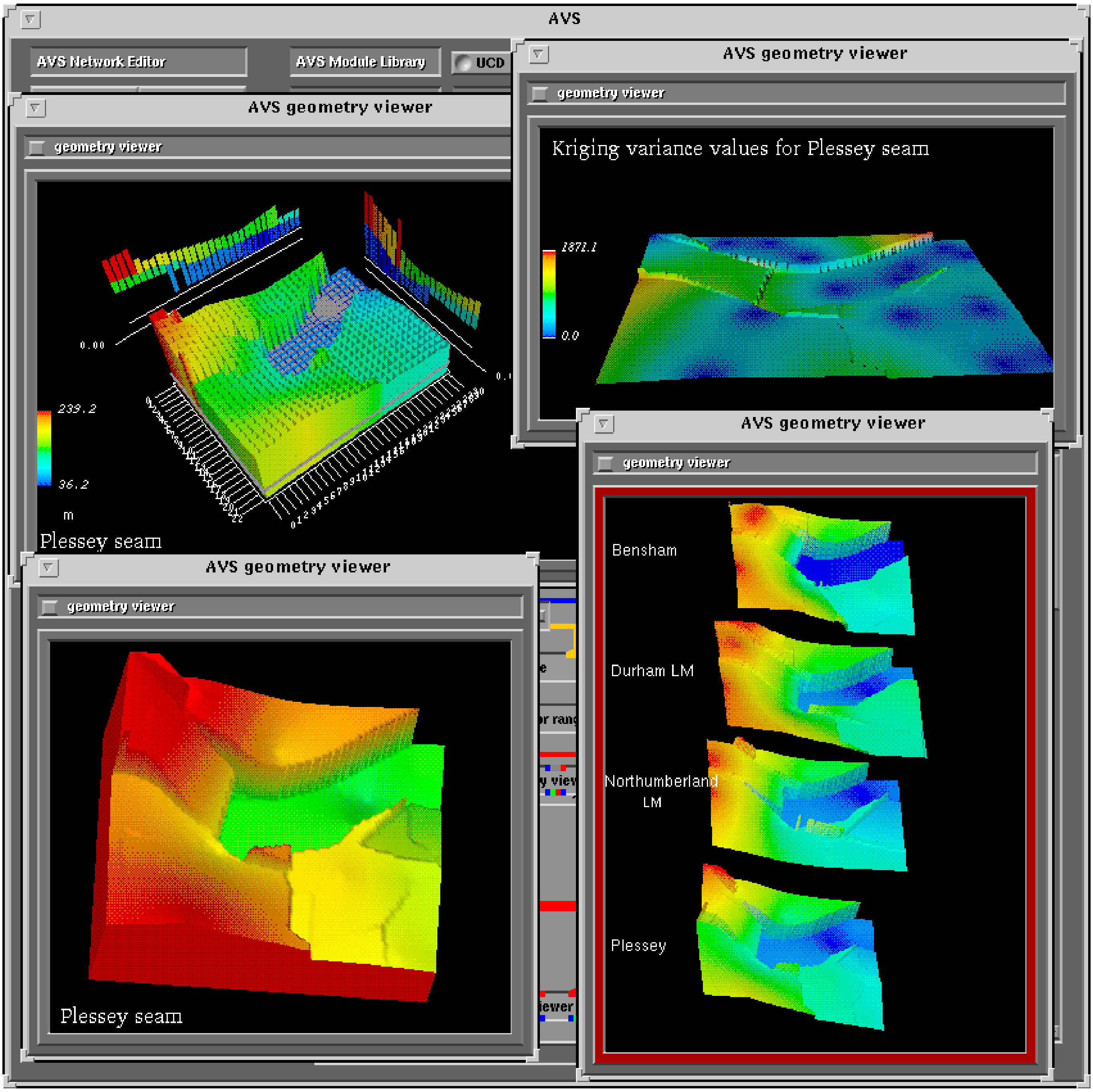

Fig. 4: Visualisation of coal seams in the Pegswood area, Northumberland. Surfaces show the geometry of the coal seams where they are cut by faults with particular emphasis on the Plessey seam. The Geometry Viewer (top right) shows how it is possible to indicate uncertainty by combining the kriging variance values.

Reconstruction of Paleontological Specimens

There are two main approaches to constructing models of paleontological specimens from serial sections:

(i) *Surfaces*: the exterior of the specimen can be viewed in this form by digitising the serial sections as contours and then construction of a 3D surface (Geiger, 1993; Herbert et al, 1995).

(ii) *Volumes*: this involves scanning the sections as raster information, storing information about each element, and interpolating from these to produce a 3D volume made up of voxels.

This discussion will concentrate on volumes, although it should be noted that AVS will render excellent models of shaded surfaces using the Geometry Viewer. The volume data is of graptolite specimens which, after scanning, are relatively easy to input into AVS as field data in the form of density values. Data can be imported as either greyscale (one byte per voxel) or as colour models (three bytes per voxel for red, green, blue model).

Once imported, a number of AVS mapper modules can be used to view the data, either via surface extraction or direct volume rendering. Possibly the best technique for gaining an overall impression of the data, is to construct an isosurface from the voxel data, interpolating the original surface. This method provides a useable solid 3D image (Fig. 5), that can be used to investigate structures not parallel to the original line of sectioning. Other means of display include colour isosurfaces, 3D contour lines and volume rendering but it was found that none of these provided the same quality of image. In particular, the results from volume rendering were too “fuzzy” due to the low resolution of sampling, both between and across sections.

Using AVS, it is possible to re-slice the volume in any direction using either the orthogonal or arbitrary slicers; these are very useful for showing fine detail. The orthogonal slicer cuts the volume perpendicular to one of the three main axis of the values, one of which will reproduce the original set of digitised sections. The other axes show 2D images of the cuts of the volume, where the density of each pixel is shown either by colour or by a height factor (Fig. 6) The arbitrary slice is able to cut the volume in any place, not just those perpendicular to the three main axes, providing a more flexible tool. There also exists a thresholded slicer which functions similar to the arbitrary slicer but values outside the set range are mapped to zero.

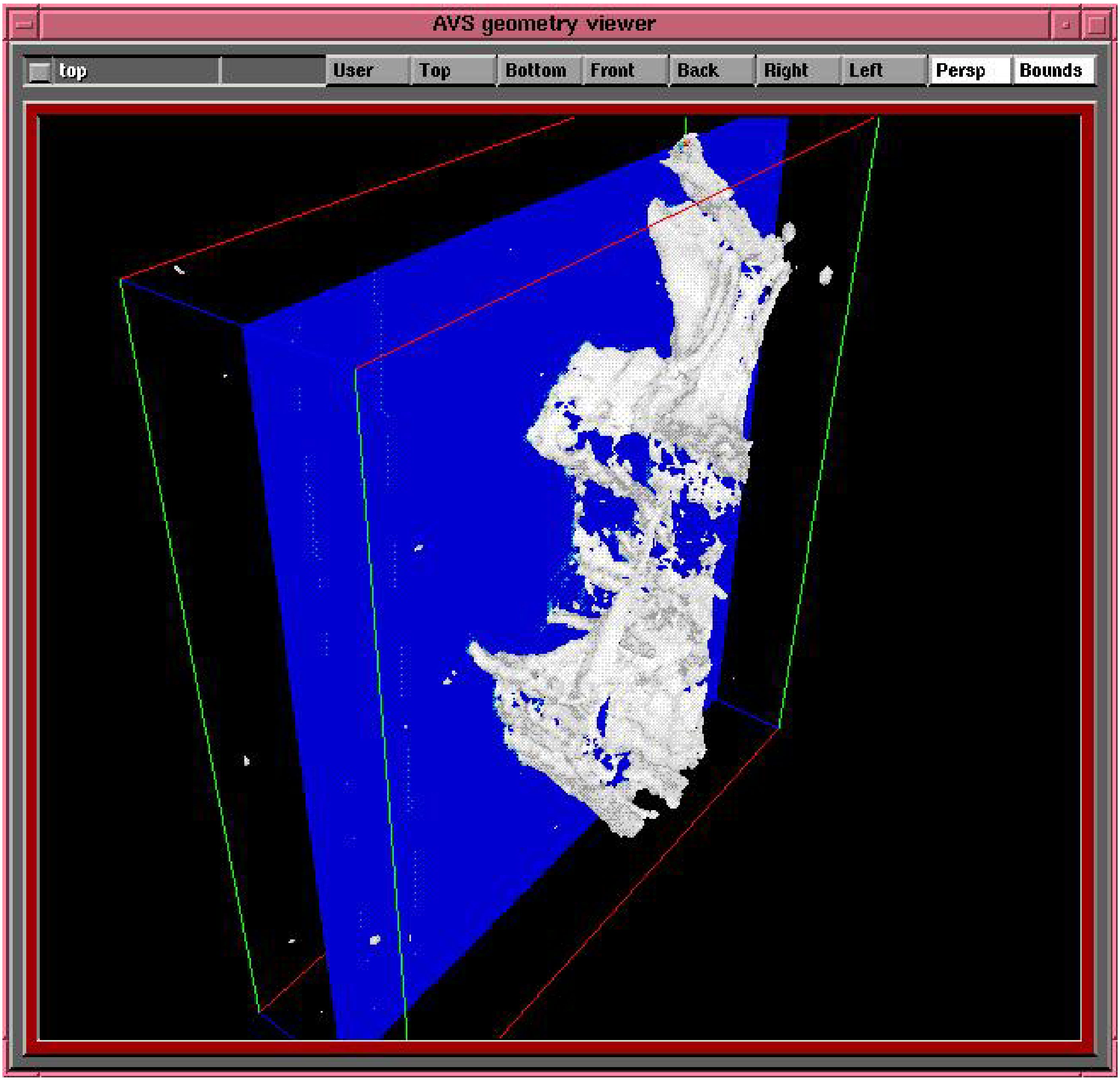

Fig. 5: Isosurface reconstruction of a Graptolite specimen. An orthogonal slice has been included in one of the planes for reference.

Although the results of the reconstructions are currently still at an early stage, it is hoped that future images can be improved. Both surface and volume models suffer mainly from a poor rate of sampling, with the latter being scanned only at a low rate of resolution. Increasing the resolution should significantly increase the quality of the results but this will also dramatically increase the amount of data handled by AVS. Higher resolution data should also make use of direct volume rendering techniques more viable.

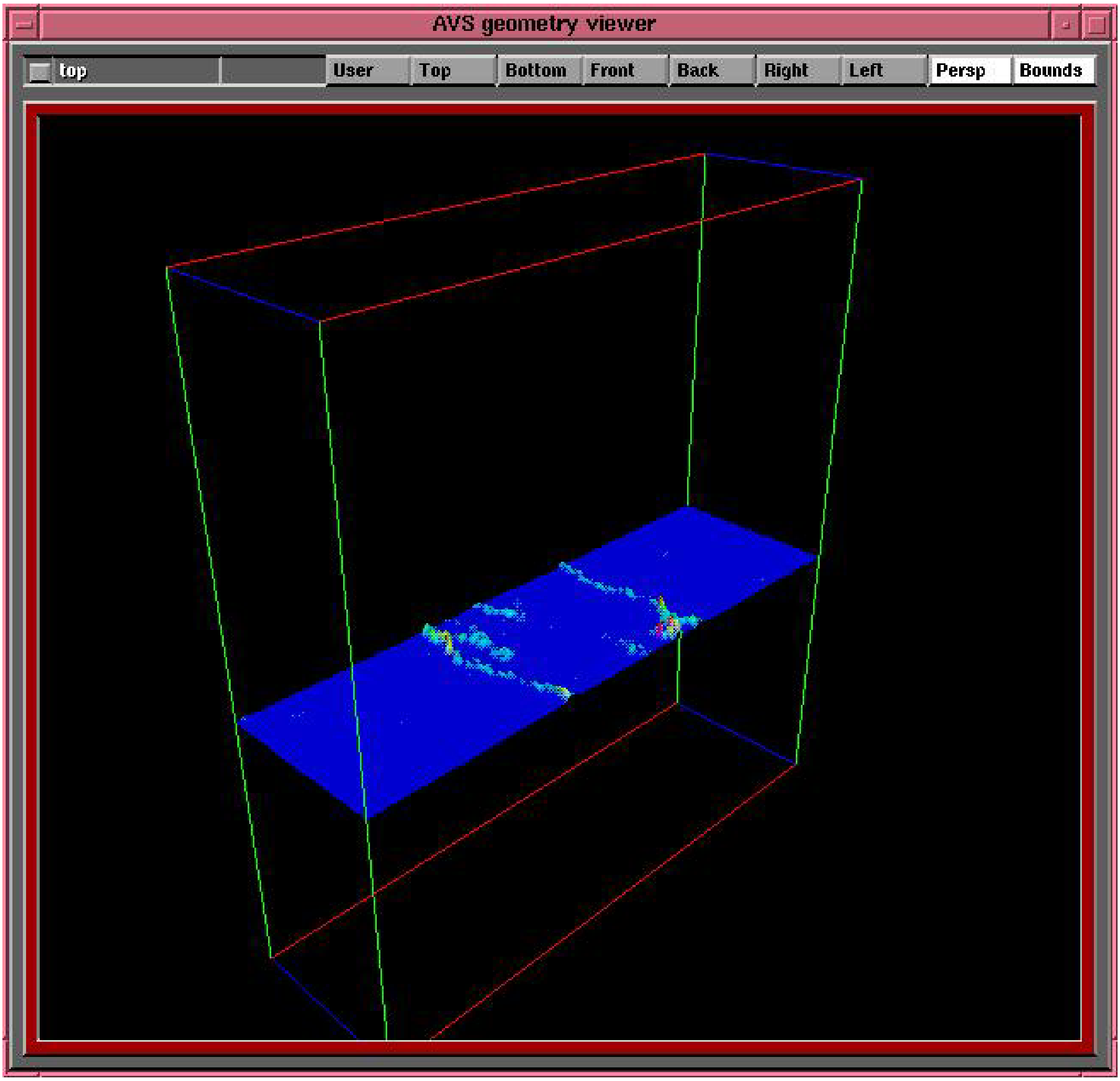

Fig. 6: Orthogonal slice of a graptolite specimen

Currently, surface extraction methods have proved more successful than volume rendering due to the sparse sampling involved; volume rendering techniques also generally require uniform data which is relatively uncommon in the geosciences. Most importantly, volume rendering requires knowledge of the relationship between density values and material properties, with regard to their perceived opacity to light, and this is an area of some uncertainty at present.

Unstructured Cell Data (UCD)

The underlying regular grid structure prevalent in current visualisation systems is often not the ideal format to analyse geological data, because this data is often only available as a series of irregularly-scattered sample points. The ability of the ucd format to define discrete shapes and use tesselations based on triangles or tetrahedrons, which are generally considered more suitable for sparse and irregular data (De Floriani, 1987), suggests that this format may become more popular in future, but at present the functionality is more limited than with field data, although this is expected to change in the future (Brodlie et al, 1995). At present, scatter data can be converted directly into ucd format via an AVS module which uses the Delaunay triangulation method. This produces a cohesive structure and defines the connectivity between the cells but the computation time is high. The results can be compared with those obtained via the volume visualisation approach in Fig. 7. The ucd format is particularly suitable for finite element analysis, for example for modelling fluid flow.

Discussion

Visualisation of Geological Data

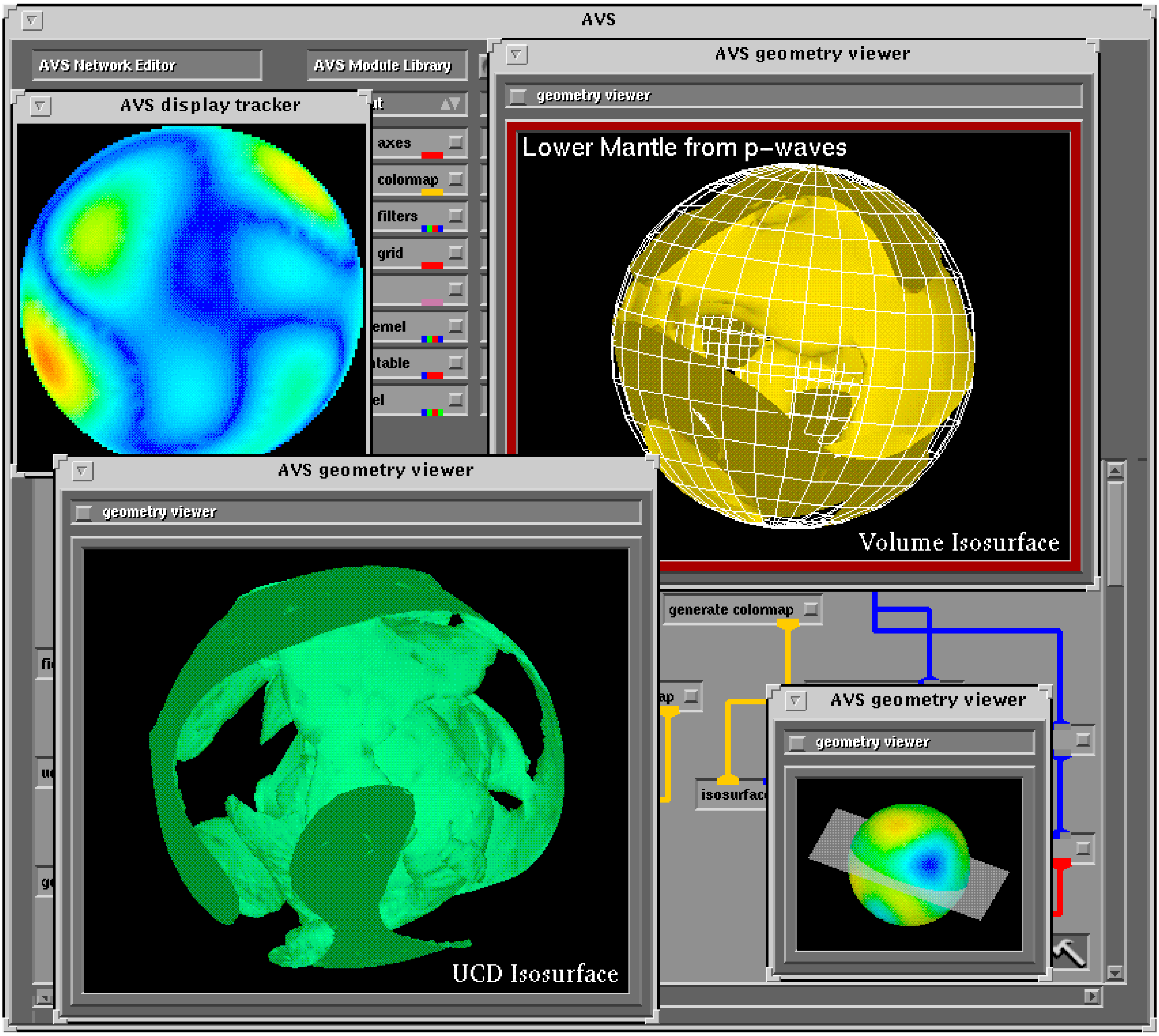

Fig. 7: Structure of the lower mantle (3440 to 5700 km from the centre), as revealed by seismic P-wave velocity. One viewer (top right) shows an isosurface (with upper and lower bounds shown) derived from volume data The other structures use ucd format and feature a ray-traced ucd image (top left), a ucd isosurface derived from scatter data (bottom left) and a ucd contour map (bottom right).

Geological data-sets are so diverse that it is highly unlikely that a single system will be designed that can provide all of the visualisation techniques required. In our opinion, one of the most favourable aspects of general-purpose software, such as AVS, is they provide more flexibility and adaptability than specialised systems allowing further refinements to be made by the user. Functionality is also more varied and data transfer often easier. However, the user must expect less direct support for certain geoscientific functions relevant to particular data-sets (eg. borehole correlation) and, at present, the visualisation of discrete data remains a problem.

A common concern with most visualisation systems, including AVS, is that there is no explicit support for geo-referencing data. This is an important issue because it is very ease to distort the data to produce aesthetic images; however, if some form of reference is provided (eg. latitude and longitude on a global projection of the Earth) then this distortion can be rationalised. Many workers (eg. Rhind, 1992; Sides and Hack, 1995) have considered that the ideal solution would be a combination of 3D visualisation system and geographical information system (GIS), but, as yet, a fully-flexible system which permits both modelling and mapping of the wide variety of geoscientific data remains a problem for future research.

Another related issue is that data reliability is not usually defined on 3D images. Considering the sparse and irregular nature of geological sampling, and the interpolation required to produce a surface or volume model, this needs to be addressed in future. As an example we have included kriging in one of our case studies, as it can provide an unbiased estimate of the interpolation error (Heuvelink and Burrough, 1993) and is being increasingly used in analysis of 2D data in GIS (eg. Oliver and Webster, 1990). The ability of software such as AVS to display multivariate data means that it is possible to combine error estimates together with the geometric data in the final image, yet this is infrequently done at present.

Our work has also suggested that, with sparse data-sets, surface modelling is probably more appropriate than volume modelling. For example, isosurfaces can be used to build up an excellent 3D view of the object being modelled. Direct volume rendering requires data sampled in a detailed and regular format, otherwise a disproportionate amount of interpolation is required to fill the voids between surfaces. Interpolation from sparse data-sets also requires appropriate knowledge to avoid potentially erroneous results which, nevertheless, may look visually attractive.

Future Directions In Visualisation Systems

State-of-the-art visualisation systems, such as AVS, now include 3D/4D functionality through animation, making it possible to view the evolution of structures or run detailed simulations through time. However, one of the major problems we face when communicating 3D information to others is that we are often restricted to a 2D format and static images, as software permitting 3D data exploration (such as interactive slicing and rotation) remains expensive. Even when software is available, the lack of a standard format for data transfer means import / export of data remains a serious problem. A promising solution to this dilemma is provided by the recent explosion in the Internet and multimedia software, with the development of the object-oriented programming language JAVA and the 3D scene-description language VRML of particular relevance. These have become *de facto* standards for cross-platform modelling and the development of the World Wide Web means that it is becoming possible for full interactive 3D models to be explored by the end user at a remote site without using the original software used to create the model.

Another current problem is computer performance: better quality images require denser data-sets but these inevitably take considerable time to process even on specialised graphics hardware. One possible solution is to develop networks enabling parallel module execution, and visualisation systems such as AVS or Iris Explorer already enable this. With the probability of more readily available parallel processors in future, distinct improvements in computer-intensive processes such as interpolation and rendering can therefore be expected.

Conclusion

Currently, general-purpose visualisation systems (eg. AVS) are best suited to property modelling, involving attributed data in the form of continuous fields, which can then be structured in grid format. By contrast, analysis of discrete structures, based on irregular points, are more difficult to visualise. The latter form of modelling will require more development of structures, such as the unstructured cell data type in AVS, for further progress.

In our view, “intelligent” geological visualisation only exists at present with an experienced user, who has both detailed knowledge of the relevant environment and data-set (including factors such as sampling and interpolation strategy), together with appropriate knowledge of the software tools available to produce accurate and realistic images. This produces a rather subjective form of display and analysis, and only by incorporating knowledge directly within future visualisation systems can more objective interpretation result.

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