AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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3D and 4D GIS for Space-Time Modelling of Geoscience Data

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AGSO

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3D and 4D GIS for Space-Time Modelling of Geoscience Data

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Abstract

The state of the art in 3D & 4D GIS was the subject of a recent European Science Foundation research conference which brought together geoscientists and computer scientists from a number of countries. The results of this conference are presented here along with discussions of the principal issues in 3D & 4D GIS and the major impediments to its adoption by the wider geoscience community.

Current GIS technology is fundamentally based on a 2D data model which is generally adequate for geographic applications such as land-use studies and cadastral mapping. The current technology is also capable of some limited manipulation of data in the third dimension through the use of surface modelling techniques such as triangular irregular networks (TINs). This partial extension into the third dimension allows, for example, surfaces to be draped over digital elevation models.

Geology is, by its nature, however a four dimensional science in which the three spatial dimensions and time must be routinely considered. Thus for comprehensive geological studies, a true 4D information system is needed. Such a system has been called a GSIS (i.e. a geoscience information system).

There are a number of currently available software systems which address some of the needs of a GSIS. These are briefly described, and some possible avenues for AGSO's future involvement with GSIS technology are discussed.

Introduction

This Record contains a report on a European Science Foundation research conference held in Castellvechio Pascoli, northern Italy from 30 May to 4 June 1992. The title of this conference was "Space-Time Modelling of Bounded Natural Domains - Tools for 3D Representations" and it was attended by 56 scientists from 15 countries.

This conference followed 2 previous conferences on 3D and 4D modelling. The first had been held in Santa Barbara, USA in 1989 under the auspices of NATO, and the second was held in Freiburg, Germany in 1990. As with its forerunners, the 1992 conference brought together scientists with expertise in computer science and a wide range of the geosciences (see the list of attendees in Appendix A). The talks presented research from a wide range of subjects and were accompanied in many cases by computer demonstrations run on a Silicon Graphics high performance 3D workstation. The program of the conference is included here as Appendix B and notes that I took during each paper are listed in Appendix C.

Conference Themes

Impediments to the Spread of the Technology

A Definition

It was generally accepted by the conference's participants that what was being discussed when we spoke about space-time modelling and about 3D and 4D GIS was really a geoscience information system (i.e. a GSIS) not a GIS which was fundamentally a 2D technology.

GSIS is a rapidly emerging technology but it is one which is little understood outside a select band of practitioners. There are a number of impediments to the spread of GSIS within the wider geoscience community. These include:

System Impediments

There is a computer phobia amongst many geologists which makes it very difficult for new computer technologies to capture their hearts and minds. In the case of GSIS, this is compounded by the undoubted complexity of the subject and by the complexity of the interfaces used in many of the current systems.

The cost of computer hardware and software for GSIS is still relatively high. For example, all of the software packages displayed at the conference could only be run on Silicon Graphics high performance workstations. Even entry level machines of this type cost upwards of A$18000 (Robertson, 1992). Similarly, the software systems cost substantial sums (e.g. GOCAD costs US$20000 and GMS from Lynx Systems costs US$25000).

Data Standards

For GSIS to be effective, a very wide range of different types of data must be imported. This is a very difficult undertaking because of the lack of agreed data standards and because of the widely differing data models used by the various GSIS packages that are available today. This issue of data standards and data models took up an appreciable amount of discussion time during the conference and was returned to by many of the speakers (Appendix C).

No single 3D system on the market today can do all of the things that users need. Thus, data interchange standards between different GSIS implementations and between these and other mainstream spatial information systems (e.g. GIS and digital cartography) are extremely important.

Data interchange is really only going to be easy however if there is data model compatibility between systems. In this context, a data model is defined as a set of concepts which describe data and its structure (in this respect data models are meta-data, i.e. data about data). Data can only be readily moved from system to system if each has the same data model. Andrew Frank in his paper at this conference asserted that the current 3D and 4D GSISs are difficult to use in part because the space-time models they use are poorly suited to their task (i.e. modelling space-time). Jonathon Raper pointed out that if space and time are measured in light seconds then all 4 dimensions have the same units. This observation didn't illicit much excitement from the audience however.

One recent event which may have an impact on the issue of data model compatibility is the development in the computer-aided design/computer-aided manufacturing (CAD/CAM) field of a data model called ACIS. ACIS is beginning to be touted as a possible standard data model (e.g. Potter, 1992) which, if implemented by different CAD/CAM software packages, would make the transfer of 3D data and models between packages very straightforward.

ACIS is a set of object-oriented routines written in the C++ language which can store wireframes, surfaces and solid volumes in a single data structure by using non-rational B-splines (NURBS). For a discussion of NURBS refer to Fisher and Wales (1992). ACIS promises dramatic improvements in performance for CAD/CAM applications and high resolution spatial integrity rules (Potter, 1992). It has already been adopted by Autodesk (and is expected to be released with version 12 of Autocad), Aries Technology, Cadam, Hewlett-Packard and Schlumberger (ibid).

The Uniqueness of Geoscience Data

The very nature of geoscience data makes the use of 3D and 4D modelling techniques difficult. The subsurface of the earth is characterised by enormous variability both in the form of structural complexity and in the form of dramatic differences in material properties (e.g. permeability can vary over more than 10 orders of magnitude over a distance of only centimetres). Furthermore, the knowledge base of the subsurface is always going to be deficient because of the limited opportunities for 3D data collection and the high cost of data gathering. To make matters worse, the data that are available often seem to conflict. These factors inevitably lead to ambiguities in geoscience interpretation and thus at any one time, several models may be equally plausible for the same data set. With the passing of time and the emergence of new concepts come new models and these must also be managed in a GSIS.

Thus the effective management of uncertainty is a crucial issue in any GSIS. This uncertainty must be handled by the the data model and must be presented to the user through some visualisation technique. For example, knowledge of the sub-surface generally becomes more uncertain with increasing depth. One way to depict this in a 3D model might be to draw lithological boundary surfaces which become increasingly transparent or diffuse with depth. Alternatively, sound cueing could be used so that when the on-screen cursor is on a unit which is reliably known, a low frequency sound is emitted by the workstation. As the degree of uncertainty increases, so too does the frequency of the emitted sound.

The difficulties of adequately managing uncertainties are probably the main impediments to the more widespread use of 3D and 4D systems in geoscience. This is the main difference between geoscience applications of the technology and those used in medicine where the technology has been whole-heartedly embraced.

In medical applications of 3D and 4D modelling and visualisation, uncertainty is not a serious issue. Sampling frequencies in medical imaging are very high (e.g. CAT scanning) and the features being imaged/modelled/visualised are well understood (i.e each body is expected to have a liver in more or less the same place, a heart, a spine,

etc.). Similarly, in medical applications, multi-temporal datasets are often available whereas in geoscience modelling of the sub-surface, we only have the here and now to work with.
For these reasons, 3D and 4D modelling and visualisation techniques have gained very wide spread acceptance in the medical profession, in stark contrast to the situation prevailing in the geoscience community.

Modelling in 3D

In an analogous fashion to the way in which GIS developed, two different approaches are being developed to describe and manipulate 3D data.

Voxels

The GIS raster approach is mirrored in 3D by the voxel concept. Voxels are volume elements in a regular 3D grid. Voxels share the advantages and disadvantages of rasters in GIS in that they are computationally easy to handle and are very good for most modelling operations including Boolean 3D-spatial operations (e.g. AND, OR, XOR, NOT), and distance, surface area, volume, centre of mass and adjacency operations. Furthermore, spatial integrity rules are relatively simple to implement in a voxel-based data model. Such rules are required for example to make sure that juxtaposed 3D objects do not intersect and do not have void-space between them. Voxel-based data models are not so well suited however to 3D-spatial operations such as translate, rotate and scale.

A more sophisticated form of voxel approach is the octree which is a 3D equivalent of the 2D quadtree which is used for example by the SPANS GIS. In the octree representation, 3D space is recursively divided into 8 smaller sub-spaces until each sub-space is either entirely inside or entirely outside the 3D-objects being modelled. The result is a 3D space comprised of voxels of a number of different sizes. The octree approach is very well suited to Boolean 3D-spatial operations (Raper, 1989).

Surfaces and Volumes

The GIS vector approach with its arcs, nodes and vertices, has parallels in the 3D domain in several forms of surface modelling. The most common approaches use topological constructs to define boundaries in 3D (e.g. Carlson; 1987 and Burns; 1988). This approach is suited to modelling geo-objects of the sampling limited type as defined by Raper (1989). Such geo-objects have discrete spatial identities and include virtually all the sub-surface bodies with which geologists work such as granite batholiths, fault blocks, salt domes, shear zones and stratigraphic units.

An alternative approach using iso-surfaces can also be used for sampling limited geo-objects. This approach really comes into its own however for definition limited geo-objects (ibid). These geo-objects, rather than being discrete, form part of a continuum such as an ore body which is delineated by the volume of ore with a grade of greater than 3%. Changing the threshold economic ore grade to 2% (e.g. following the introduction of better extraction methods) changes the shape of the ore body that needs to be defined in 3D space.

Iso-surfaces are essentially the 3D equivalent of contours in 2D. An iso-surface can be constructed by interpolating a regular grid of points from a dataset and then triangulating between them (e.g. Smith and Paradis, 1989) or alternatively, the grid can be used to constrain NURBS which define the iso-surfaces and enclosed volumes (e.g. Fisher and Wales, 1992) .

3D Interpolation

The goal of any geoscience investigation of the subsurface is to build a coherent and complete 3D model. This model whether it resides in a geologist's head or in a computer, is fundamentally based on limited data. These data are often sparsely distributed in 3D space and there is often a general dearth of data in the third dimension (i.e. depth). Yet the 3D model must be continuous (i.e. it must describe all of the 3D space being studied) and it must have spatial integrity (e.g. there must be no voids between sampling limited geo-objects and no overlaps).

In order to produce a continuous 3D model, all of the 3D space must be described. In the case of a voxel-based model, all of the space must be sub-divided into voxels and each voxel must be assigned a value. For example, in a stratigraphic model of a sedimentary basin, each voxel in the basin must be assigned to one or other of the stratigraphic units. This might have to be be done for example for 10,000 voxels on the basis of only, say, 2000 observations (e.g. from surface observations, seismic sections and borehole logs). Thus in this example, voxel values must be interpolated for those voxels for which there are no data.

Interpolation of additional points is essential when working with 3D geoscience data because of its sparse distribution. The manner of this interpolation and the artifacts that can result are very important issues and determine to a very large degree the usefulness or otherwise of the 3D model that is produced.

The effectiveness of interpolation depends on the complexity of the real situation and on the sampling density and distribution of the observations. In general, the simpler the real variation and the greater the amount of data, the simpler the interpolation technique that can be used. The converse is also true; with fewer data and greater complexity in the real variation, more sophisticated interpolation techniques must be used. The distribution of the observations is also very important, particularly when the complexity is high &/or the amount of data is small, as it often is in the geosciences.

The most common interpolation techniques used in 2D applications in the geosciences are interpolation using minimum-curvature spline methods and kriging. Both have problems when applied to 3D geoscience data. In particular, both tend to produce crude representational artifacts as a result of the generally poor distribution of data in the Z dimension (i.e. depth) and neither gives reliable results at the boundaries of the data. With kriging, there is no automated means of variogram modelling in three dimensions and it is therefore very difficult to define blocks in the data. Advanced kriging methods (e.g. universal kriging and deterministic kriging) are not generally useful with 3D geoscience data because they require spatial data which are well distributed.

Commercial packages generally do not provide a wide range of interpolation options for the user and it is therefore very important that users know which procedure each package uses so that they can choose an appropriate one for their data. For example, the IVM package (Interactive Volume Modelling by Dynamic Graphics) uses an exact fitting spline interpolation procedure which does not cope well with poorly distributed data.

3D Visualisation

The 3D systems that currently exist are severely compromised by the visualisation and display technologies that are presently available because these are fundamentally two dimensional. Thus while systems like IVM, GOCAD and GMS all have true three dimensional data models, each must resort to displaying its data using two dimensional media (i.e. paper or a computer display screen). In doing so, many of the advantages of the 3D data model are abrogated.

It is for example very difficult to effectively edit 2D visualisations of 3D data since the third dimension (i.e. the direction into and out of the screen or paper) is reliant upon visual cues such as forced perspectives rather than a proper cartesian coordinate system. It is also extremely difficult to make real measurements on 2D visualisations for the same reason.

Some 3D display hardware is now available for specialist applications. For example, Tektronix sell a 3D display terminal which can alternately display two stereo images. The images must either be constructed by user software or be remotely sensed (e.g. SPOT stereo pairs). The two images are interlaced line by line in an analogous fashion to that used by some cheaper PC monitors at high screen resolutions. The result is a flickering colour composite image which when viewed through a polarising screen attachment, or polarising glasses, appears in 3D.

At the moment, there is no simple means of building the stereo pairs in any of the current crop of GSIS contenders. This is a serious problem which greatly restricts the usefulness of the display hardware.

The existing problems with 3D display hardware are likely to have been solved however by the end of this decade (Coleman, 1992). By then, "heads up 3D display systems" such as those now being used in virtual reality technologies are likely to be commonplace. These systems are already making inroads into the computer leisure market (e.g. Waldern, 1992) and are likely soon to be making significant contributions to serious 3D visualisation applications.

Time

The fourth dimension, time, is very poorly handled by all of the current software packages available for GSIS. Basically, all of these software packages treat time as a series of snapshots (i.e. timeslices) rather than as a continuous variable.

It is useful to treat time as a continuous variable, in the same way that the three spatial dimensions are handled, for several reasons. Firstly, by handling the time dimension in this way, it is possible to rapidly interpolate 3D data at times that are intermediate to the snapshots because the data in the snapshots must be linked when they are input.

Secondly, data which have a known temporal dimension can be subjected to integrity checking to make sure that they are consistent with data relating to other times. This is analogous to the kind of integrity checking that can be applied to 2D cross-sections when they are combined in three dimensions.

Thirdly, data relating to different times can only be effectively integrated if time is handled as a continuously varying quantity. Thus for example, the progress of a marine transgression which is recorded at successively later points over a sedimentary basin margin, can only be properly integrated if time is handled as a smoothly varying quantity in the data model.

Lastly, the accurate modelling of geological processes (e.g. faulting, folding, magma emplacement, erosion, etc.) requires that time be handled as a state variable. Otherwise, all that is produced is a series of static images, the elements of which are poorly connected in time.

The State of the GSIS Art

Current 3D Systems

Most of the current 3D and 4D geological information systems were discussed in talks presented at the ESF conference and quite a few were demonstrated on a Silicon Graphics workstation. It is well beyond the scope of this Record to provide detailed comparative reviews of the different systems, but I can at least list a few of the features and some of the weaknesses (where I know them) of the various packages.

IREX

This petroleum reservoir engineering package won general acclaim at the conference as being probably the best of the systems currently available. For example, see the notes on the paper given by Pflug in Appendix C. IREX uses an isosurface approach to describe three dimensional objects.

I saw a looping animated sequence of images from an IREX session running on a Silicon Graphics workstation at the conference. From what I could see, IREX has a good user interface which uses pull-down menus and a mouse. It can also work with lots of different data types (e.g. seismic, well logs, lithology) and users have full access to zoom, pan, truncate and slice functionality. IREX is described at length by Lasseter (1992).

On the negative side, IREX needs an expensive Silicon Graphics workstation to run on. It also apparently needs large amounts of 3D data to be really useful. For this reason, IREX is mainly used in reservoir engineering applications where detailed sub-surface data are available. Like the other GSIS contenders discussed here, IREX does not handle geological uncertainty very well. Also like the other packages, it can be very difficult to get data in and out of IREX because of the lack of agreed standards for 3D spatial data interchange.

GOCAD

This software is a produced by the Fondation de la Geologie et de ses Applications in Nancy, France. GOCAD was demonstrated on a Silicon Graphics workstation by Fabrice Deverley of the BRGM who is a user of the system. As a user, he was able to field questions about the practical applications of GOCAD, but he was unable to provide technical information.

The GOCAD package is a vector-based system which works with triangulated surfaces that can be used to define 3D volumes. The user interface that I saw seemed fairly easy to use, though all the items on the pull-down menus were in French. Apparently, an English language version is available.

The software can be purchased for approximately US$20000 for a single user licence on a Silicon Graphics workstation. I am not clear whether GOCAD can run on other hardware platforms.

IVM

Interactive Volume Modelling (IVM) is a product of Dynamic Graphics Ltd of Wokingham, Great Britain. IVM displays, interactively manipulates, analyses and models 3D data (Paradis, 1990). The IVM package is an extension into three dimensions of Dynamic Graphics' successful ISM (Interactive Surface Modelling) package.

IVM can calculate a 3D grid of points from scattered observations to build up a solid voxel model. Volumes can be defined by bounding surfaces and gridding can be constrained to apply only within these volumes. Thus a series of 3D grids can be constructed and then juxtaposed into a "layer-cake" representation of 3D geology.

At present, IVM uses an exact fitting spline interpolation procedure to interpolate the 3D grids and this tends to produce spurious gridding artifacts at and near boundaries. Apparently future releases of IVM will offer alternative interpolation procedures including minimum curvature methods. The user will then be able to try different methods and choose the one which best handles the distribution of his or her data.

I saw a demonstration of IVM on a Silicon Graphics workstation at the conference. The user interface seemed fairly straightforward and the software provided a good level of 3D functionality including rotations, slices and layer removal operations. Thus for example, a small sedimentary basin was progressively stripped of its sediment fill, layer by layer and the exposed surface could be visualised in 3D with shading effects and forced perspectives.

GMS
The Geoscience Modelling System (GMS) is a product of Lynx Systems of Vancouver, Canada. The chairman of Lynx Systems, Simon Houlding, gave two talks at the conference (see Appendix C) and is something of a luminary in the field. GMS is marketed in Australia by Barrett, Fuller and Partners in Melbourne and by Tennant-Isokangas in Brisbane. CRA Minenco in Melbourne and CSIRO Geomechanics in Brisbane are using the software. USA users include: the USGS, US Sandia National Laboratory, Colorado School of Mines and the Lawrence Berkeley Laboratory.

GMS provides qualitative and quantitative modelling capabilities in three dimensions and interactive 3D visualisation. It does this by using a data model based on isosurfaces which allows volume elements of any shape to be defined. Thus, geological complexities such as discontinuities, fault bifurcations, layer pinch-outs, and facies changes can be modelled. The system is able to compute volumes and surface areas of geo-objects and stores their physical attributes (e.g. unit name, density, geochemical data, porosity, etc.) in a proprietary database.

Data are generally input to GMS either as drill-hole strings or as map layers. The latter type of input is generally how data from other systems (e.g. GIS and CAD) are imported into GMS.

GMS provides geological modelling facilities such as triangulation of and between surfaces, surface intersections and truncation and geostatistical interpolations of surfaces from random observations (i.e. geostatistical kriging).

GMS runs on SUN SPARCstations, Hewlett-Packard series 9000 workstations and IBM RS/6000 workstations and costs US$25000 for a single-user licence. Lynx systems also offer a software rental option for US$2500 per month with rental credits towards later purchase.

Spyglass Dicer
This software package was discussed by David Johnson in his talk at the conference (see Appendix C). Spyglass Dicer is predominantly a 3D visualisation tool which runs on Macintosh, SUN, DEC (Ultrix), Silicon Graphics, Hewlett Packard and IBM computers. Spyglass Dicer works with 3D voxel grids produced by other software. A companion product, Spyglass Transform, allows some analysis of the 3D data including the use of mathematical functions, the generation of contour and surface plots and line graphs.

As a visualisation tool, the Spyglass products serve a useful purpose.

Trip and Geo3View
These software packages have been developed in the Geologische Institut der Albert-Ludwigs-Universitat Freiburg, Germany. Both run only on Silicon Graphics workstations. The Trip package is used to triangulate surfaces from 2D profiles (e.g. parallel geological cross-sections) or from contour maps. Geo3View is then used to visualise the constructed surfaces in 3D.

Cockpit
Cockpit which is a dynamic 3D visualisation package, was developed by John Tipper (Tipper, 1991) at the Australian National University before his move to Freiburg. Cockpit is again written around the Silicon Graphics GL toolkit and therefore will only run on Silicon Graphics workstations at present. The GL toolkit has become something of a *de facto* standard (Flynn, 1990) which makes up in performance for what it loses in portability (Tipper, 1991).

Cockpit is a family of FORTRAN subroutines which can be interfaced to other application program code. In this way, models developed by geoscience applications can be visualised and manipulated in 3D. Cockpit can be used to visualise any combination of points, lines, polygons and triangular meshes and it does so through an easy to use user interface.

Other Software
There are numerous mine planning software packages on the market including Vulcan, Minemap, Minex-3D, Easimine, Mincom and Datamine. Some of these packages are also potential GSIS products. None however were discussed or displayed at the ESF conference.

The Khoros public domain software is another application which provides advanced 3D visualisation capabilities. This software can be downloaded for free by anonymous ftp from pprg.eece.unm.edu (129.24.24.10) at the University of New Mexico, USA. To do this, you must use a computer which is connected to the Internet (usually through AARNet in Australia) and use the TCP/IP ftp functionality. Use the logon name "anonymous" and give your full userid as the password, e.g.:

```
ftp 129.24.24.10
username: anonymous
password: pchopra@bmr.gov.au
```

Khoros requires an X11R3, X11R4 or OpenWindows UNIX server and at least 120 Mbytes of disc space. At AGSO, we could run it on our SUN and VAX fileservers and workstations and on the Convex computer.

Opportunities for AGSO

If the adage about GIS is true, i.e. that it stands for Get Involved Slowly, then this is even more true for GSIS. Without a doubt, the technology for GSIS is much more complex and the problems of quality control are far more severe than is the case for GIS.

Start-up costs for GSIS are also quite high since the software is relatively expensive and high performance hardware is required if performance times are to be acceptable.

Some opportunities have flowed from the ESF conference with regard to software. It is likely for example that a free copy of the Cockpit 3D visualisation software could be obtained from John Tipper. It is also possible that the Geologische Institut at Freiburg might be prepared to exchange a copy of their Trip/Geo3View software for some AGSO data. It may also be worthwhile to explore the lease option with the GMS software.

Possible Implementation Plans

There would seem to be two options which AGSO could follow if we are to begin to investigate the capabilities and future potential of GSIS.

1) Use existing hardware

a) GSIS

With our existing hardware, AGSO could run the GMS package from Lynx Systems (on SUN equiment). The cost of GMS is US$25,000 or US$2,500 per month for rental.

Some of the mine planning software might also run on our existing hardware (see the list above).

b) 3D Visualisation

For 3D visualisation applications, the Spyglass products for Macintosh, VAX, and SUN equipment are cost effective. Spyglass Transform costs around US$500 for the Macintosh version and US$900 for the UNIX version.

The khoros package is an even better solution because it is free.

2) Purchase dedicated hardware for general use

a) GSIS

Most of the GSIS systems discussed above require the functionality of a Silicon Graphics workstation. AGSO could acquire this functionality either by purchasing a Silicon Graphics Indigo workstation for US$13,500 - 27,000 (depending on the options selected) or by buying an add-in-board for one of its existing SUN workstations. The latter boards have recently been released and presumably would be a cheaper alternative, though their comparative performance would need to be assessed.

A Silicon Graphics workstation and the SUN add-in-board would support the IVM, GOCAD, IREX and Vulcan packages which I have seen demonstrated.

b) 3D Visualisation

High performance 3D visualisation work could be carried out on a Silicon Graphics workstation or on a SUN workstation with the add-in-board. The Khoros public domain software and the Cockpit software could be obtained at no cost for such machines. Access to the Trip/Geo3View software might also be possible in exchange for some AGSO data.

Summary

3D visualisation work can commence now, at no cost, using Khoros on the SUN, and CONVEX systems. Alternatively, for a very modest investment, the Spyglass products could be used on Macintosh and SUN computers. Other 3D visualisation software would require the purchase of either a Silicon Graphics workstation, or of an add-in-board for one of AGSO's existing SUN workstations.

Significant GSIS work will require the purchase of expensive software and, for most of the products, a Silicon Graphics workstation or the add-in-board.

Conclusions

The ESF conference provided an excellent opportunity for AGSO to determine the state of the art in GSIS. Future developments in GSIS are likely to have an important bearing on how AGSO assembles and markets its geoscience data and models. The subject is not one in which an organisation should get involved lightly however, nor is it one in which complete off-the-shelf solutions are likely to be available for some years.

AGSO should continue to monitor developments in GSIS and should get its metaphorical feet wet slowly by looking for cost effective ways to explore the technology.

3D visualisation which is a necessary part of GSIS, can be investigated at minimal cost using existing hardware and software that is free (Khoros) or inexpensive (Spyglass). Opportunities may also exist for collaborative projects with ANU which has Silicon Graphics workstations, by acquiring software cheaply (Trip/Geo3View) or at no cost (Cockpit). Site visits to Minenco and CSIRO Geomechanics both of whom use GMS would also be useful, as would contacts with Australian vendors in the mining software market (e.g. KRJA Systems [Vulcan] and ECS [Minex-3D]).

With the continually falling prices of Silicon Graphics workstations, it may soon be practical to purchase a machine for general use within AGSO if, as expected, GSIS functionality proves important.

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APPENDIX A

EUROPEAN SCIENCE FOUNDATION
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APPENDIX B

EUROPEAN RESEARCH CONFERENCES

Co-sponsored by the European Science Foundation and the Commission of the European Communities

RESEARCH CONFERENCE ON

SPACE-TIME MODELLING OF BOUNDED NATURAL DOMAINS:

Tools for 3D Representations

Il Ciocco, Castelvecchio Pascoli, Lucca, Italy
31 May - 4 June 1992

Co-Chairmen: **Brian Kelk (British Geological Survey)**
Jonathan Raper (Birkbeck College, London)
Vice Chairman: **Renier Vinken (Niedersachsisches Landesamt für Bodenforschung, Hannover)**

PRELIMINARY PROGRAMME

Saturday May 30th

ARRIVAL OF PARTICIPANTS

19.30 WELCOMING DINNER
Introductions
Address by Conference Chairman (Dr. B. Kelk, British Geological Survey)
Representatives of the European Science Foundation and the Commission of the European Communities

Sunday May 31st

09.00 EXPLORATION OF THE STATE-OF-THE ART
R. Pflug (Univ. of Freiburg)

User Viewpoint: C.J. Evans (British Geological Survey)
Vendor Viewpoint: S. Houlding (Lynx Systems, Vancouver)
Researcher Viewpoint: J. Raper (Birkbeck College, London)

10.30 Coffee

11.00 DEFINING TERMINOLOGY USED IN DIFFERENT USER COMMUNITIES
A. Frank (Technical Univ. of Vienna)

12.00 Lunch

Informal discussions

16.00 Coffee

16.30 EXPLORATION OF THE MODELLING PROCESS
A.K. Turner (Colorado School of Mines)

17.30	Invited speakers (tentative) P. Brunet (Univ. Politècnica de Catalunya, Barcelona) A. Siehl (Univ. of Bonn)
19.00	Dinner
20.30	COMPUTER SYSTEMS DEMONSTRATIONS

Monday June 1st

09.00	3D & 4D DATABASE DESIGN J.F. Raper (Birkbeck College, London), Convener
10.30	Coffee
11.00	Invited speakers (tentative) H. Schek (ETH, Zürich) G. Gambosi (IASI, Rome)
12.00	Lunch
	Informal discussions
16.00	Coffee
16.30	INTERPOLATION/EXTRAPOLATION IN THE MODELLING PROCESS P. Burrough (Univ. of Utrecht), Convener
17.30	Invited speakers W. Skala (Univ. of Berlin) (tentative) M. Kraak (Tech. Univ. of Delft)
19.00	Dinner
20.30	COMPUTER SYSTEMS DEMONSTRATIONS

Tuesday June 2nd

09.00	TEMPORAL FUNCTIONS AND EXPERT SYSTEMS D. Lyklema (TNO, Delft), Convener
10.30	Coffee
11.00	Invited speakers A. Câmara (New Univ. of Lisbon) J. Harbaugh (Stanford Univ., San Francisco) (tentative)
12.30	Lunch
	Informal discussions
16.00	Coffee

16.30	ENABLING TECHNOLOGIES (INCLUDING GIS & VISUALISATIONS) M. Kavouras (National Technical Univ. of Greece), Convener
17.30	Invited speakers A. Fabbri (ITC, Enschede) H. Preuss/H.-H. Voss (NfLB, Hannover)
19.00	<u>Dinner</u>
20.30	DISCUSSION

<u>Wednesday June 3rd</u>

09.00	APPLICATIONS FOR DATA PRODUCED BY MODELS R. Vinken (NfLB, Hannover), Convener
10.30	<u>Coffee</u>
11.00	Invited speakers (tentative) J. Tipper (Australian National Univ.) K. Felder (IIASA, Laxenburg)
12.30	<u>Lunch</u>
15.00	WORKSHOPS (to report by 10.30 am Thursday)
16.30	<u>Coffee</u>
17.00	WORKSHOPS
19.00	<u>Conference Dinner</u>

<u>Thursday June 4th</u>

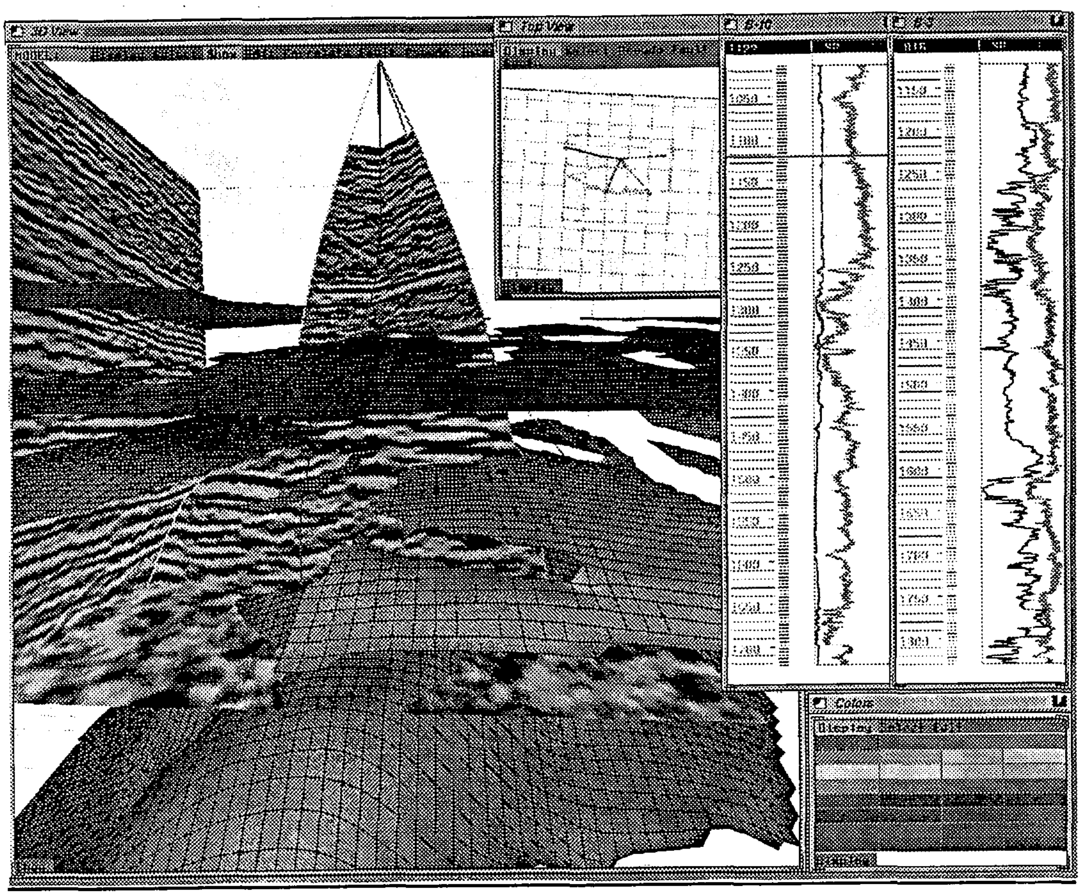
09.00	HOW TO ACHIEVE FUTURE REQUIREMENTS A. Câmara (New Univ. of Lisbon), Convener User Viewpoint: C.J. Evans (British Geological Survey) Vendor Viewpoint: S. Houlding (Lynx Systems, Vancouver) Researcher Viewpoint: J. Raper (Birkbeck College, London)
10.00	<u>Coffee</u>
10.30	HOW TO ACHIEVE FUTURE REQUIREMENTS Workshop Views (Workshop Leaders)
11.30	OVERVIEW OF CONFERENCE AIMS: SUMMARY & CONCLUSIONS Conference Chairman (B. Kelk, British Geological Survey)
12.00	<u>Lunch</u>
13.30	DEPARTURE OF PARTICIPANTS

Appendix C
Notes Taken During the Conference

Exploration of the State of the Art (Reinhard Pflug, University of Freiburg, Germany)

There are now many 3D modelling and analysis packages available (both vector and raster voxel based) but their use is still restricted to only a few disciplines.

One of the better systems is IREX [Interactive Reservoir EXploration] by John Lassiter. A demonstration version was running on a Silicon Graphics workstation at the conference. IREX was presented to the previous space-time modelling conference at Frieburg in 1990 where it received the greatest aclaim of those systems shown. The following figure is an example of output from IREX. It is taken from Lasseter (1992).



IREX's strengths include:

- the user interface is very good. It uses a main title bar with pull-down menus accessed by a mouse.
- IREX can work with lots of different data types (e.g. seismic, well logs, lithology)
- users have full access to zoom, pan, truncate and slice functionality

IREX's weaknesses are:

- it needs expensive graphics workstations
- it needs large amounts of 3D data to be useful. IREX is mainly used in reservoir engineering applications where there are lots of data.
- because there are no standards for 3D spatial data it can be very difficult to get data in and out of IREX

The major constraints on 3D modelling systems in general are:

- the cost of hardware and software
- fear by geologists of Unix and workstations
- lack of data standards for 3D data
- lack of access to useful 3D datasets (most are commercial in confidence)
- the difficulty of incorporating the products of 3D systems (i.e. colour images) in publications
- difficulty of 3D editing
- data displays are shown in 2D through data visualisation techniques (e.g. perspectives) which do not allow users to make real measurements
- the difficulty of meaningfully modelling complex geologic objects which are only imprecisely known
- the sorts of examples of 3D models that are usually seen are just pretty pictures. Rarely are the details of the processing steps that were followed to produce the completed models made known.

The best vector based 3D system is probably GOCAD which is produced by the Fondation de la Geologie et de ses Applications in Nancy, France.

The User Viewpoint (Geoff Wade, University College London, UK)

The 1989 NATO conference at Santa Barbara, USA which was the first of these conferences (Freiburg was the second and this the third) came up with a comprehensive set of geoscientists' priorities for the 3D systems of the future. These were:

1. Easy to use (even for sporadic users)
2. Multi-media, distributed and host independent
3. Must allow geo-knowledge to be incorporated as well as data
4. Process simulation modelling must be available
5. Conceptual modelling mustt also be supported
6. Data input/output should be easy
7. Surfaces and volumes must be co-operatively handled
8. Interactions between geo-objects must be possible
9. ?
10. ?
11. ?
12. Temporal aspects must be handled
13. Interchange of units must be supported (preferably on the fly). For example, time to depth conversions for seismic data.
14. ?

15. Geometric manipulations should obey real-world rules (e.g. mass balance must be preserved)
16. ?
17. 3D spatial functions should be developed (e.g. Raper's paper at Freiburg)
18. Visualisation and hardcopy facilities should be improved
19. Flexible scaling and changes in resolution should be allowed.

This list still remains the best available prescription for useful space-time modelling software systems. The proceedings of the NATO conference in which they are documented have been completed but have yet to be published by NATO.

Vendor Viewpoint (Simon Houlding, Lynx Systems, Vancouver, Canada)

3D modelling and analysis systems are very much an emerging technology at present and quite a lot of work needs to be done before such systems live up to their potential. The potential users of such systems come from many disciplines and as a result they have different objectives and they require different levels of detail.

The intent of 3D systems in geoscience is to develop means to interpret and predict subsurface features. In order to develop such systems:

We need:
- geometric modelling
- attribute modelling
- management of uncertainties
- temporal modelling
- volumetrics

3D systems must be able to handle:
- many different data sources and types
- different data formats
- interchange formats

3D systems need:
- interpretative interaction capabilities
- improved data visualisation

Modelling complications that must be handled include:
- structural complexity of geology
- a wide variety of attributes
- the temporal dimension (the best we can do at the moment is to assemble a series of time snapshots)
- management of uncertainties including:
  - emerging concepts
  - observational uncertainties (sampling limited *a' la* Raper, 1989)
  - definition limited uncertainties (" " " " " " ")
  - lack of unique models for the same data (i.e. several models may be equally plausible)

The pretty pictures of the 3D models that people produce look precise but there are in fact great uncertainties in them and these need to be visualised also.

There are interaction complications for 3D systems:

- interactions with complex processes are difficult
- the sheer volume of interactive input is problematic
- maintaining flexibility in the system is very important given the very wide discipline base using/ going to be using 3D systems

Available functionality for existing 3D systems:

- recognise many data types
- can use a variety of modelling techniques (minimum curvature, distance weighted, etc)
- different modelling approaches from system to system reflect their origins (mining, petroleum reservoir engineering, cartography, etc)
- most users can only interact effectively with 3D data by working with 2D intersects
- advanced visualisations are supported to different degrees by different systems

Current limitations of all 3D systems include:

- all systems are difficult to use (super-users are needed to help those less trained)
- there are serious problems with modelling attributes which fluctuate rapidly in space, or which vary very widely in value (e.g. permeability can vary by 8 orders of magnitude over distances of only centimetres)
- limited handling of uncertainties
- limited provisions for handling the temporal domain
- limited data interchange capabilities with other software systems (e.g. mine planning software, reservoir engineering software)

Development priorities for 3D systems should include:

- improved data interchange capabilities
- improved attribute modelling techniques (e.g. indicator kriging)
- using probability statistics to produce maps of 3D data which include uncertainty (e.g. a 3D model of the probability that coal with an unacceptably high ash content will be encountered)
- conditional simulation (allowing for discontinuities as compared to normal kriging)
- ultimately we want to be able to provide true interpolation in the time domain rather than just the snapshots at selected times that we can produce now.

The researcher's viewpoint (A. Keith Turner, Colorado School of Mines, USA)

No single commercial software system for 3D modelling and analysis can do all the things that are needed to handle a large regional dataset. It is therefore necessary to use several different systems to get a particular job done. This makes data import./export a very important issue.

There is also a real problem with training especially when more than one (complex) system must be used. Casual and sporadic users need very easy to use interfaces because otherwise the training overheads are unacceptably high. Atificial intelligence systems and expert systems may be useful in the future (i.e. "artificial intelligence" compared to "real stupidity")

Defining the terminology used in different user communities (Andrew Frank, Technical University of Vienna, Austria)

A data model is a set of concepts which describe data and its structure (i.e. in one sense a data model is meta-data [data about data]).

Semantic data models are built up in three steps:

1) conceptualisation	concepts
2) formalisation	data models
3) implementation	data structures (e.g. database schemas)

Moving data betwen different semantic data models can only be done successfullyi if both semantic models share a common formalisation. So you can't move data from an Arc/Info coverage to Intergaph unless both systems have the same basic formalisation (i.e. data models).

3D space can be conceptualised in many ways (e.g. as a raster domain, as a Euclidean domain)

The current 3D and 4D systems can be very difficult to use because the space-time models that they use are very poorly suited to modelling space and time. Jonathan Raper pointed out however that space-time can be measured in units of light seconds and in this way, all 4 dimensions have the same units.

In working with space, people tend to work at 2 different scales. At one end of the spectrum, we have small spaces e.g. a book or some other small object which you can put on a table. Such things can be seen at a single glance and comprehended.
At the other end of the spectrum, we have large objects like a city. In this case, it is impossible to take all of the city in from one vantage point. We experience the city by accumulating lots of experiences at different vantage points as we move through it. If we try to combine both types of space in a single data model and manipulate it, we can get into trouble.

Several GISs can currently work with what is called 2.5D data. This really means a 2D plane embedded in 3D space. Time adds further complications. In the time domain we can have time points (i.e. discrete events). Alternatively we can consider the time intervals between events (these are continuous).

Any system that works with time must be able to cope not only with changes in data with time, but also with changes in knowledge/understanding with time (e.g. a new theoretical understanding can completely alter the way in which a dataset is interpreted).

Exploration of the modelling process (A. Keith Turner, Colorado School of Mines,USA)

A geological modelling system should:
- provide a means of freely interpreting the sub-surface
- allow the combination of disparate data types
  e.g. sub-surface, outcrop, satellite
- be able to experiment with multiple working hypotheses

A successful 3D modelling system will provide a computer graphics system which allows the creation of models which incorporate:
- geometry of rock and statigraphic units
- spatial relationships between units
- variations in the internal composition of units (e.g. changes in porosity in a shale)
- displacement and deformation of units by faulting and folding,etc
- flow of fluids through rock units

What is special about geoscience models?
- there is incomplete and often conflicting information about the sub-surface
- it is never possible to drill enough holes to be absolutely certain of all the details in the sub-surface
- the sub-surface is typically heterogeneous and complex
- scaling of observations can be difficult (e.g. porosity measurements made at the microscale cannot be directly scaled up to infer macroscale porosities)

Raper (1989) has defined geo-objects. These can be:
- sampling limited (more samples lead to better understanding. For example the location of a particular marker unit in the sub-surface is better defined the more observatons there are)
- definition limited (as the definition of what constitutes the object changes, so to does its shape. For example, revising the economically viable cut-off grade for an ore deposit will change the shape of the ore body defined by this parameter).

Geo-objects are:
- multi-dimensional
- heterogeneous
- may be dynamic
- may be hierarchical (e.g. objects within objects)
- are scale dependent

There are many approaches that can be taken to geological process modelling:

- process simulation
    - . deterministic models
    - . stochastic models
    - . combined methods
- inverse solutions
- Markov process models in 2D and 3D
- geostatistical models
- fractal models

Volumes can be represented using:

- raster voxels (including octrees)
- 3D grids and isosurfaces

Surfaces can be represented using:

- constructive solid geometry (CSG)
- non-uniform rational B splines (NURBS)

Medical 3D and 4D modelling techniques cannot be applied to geoscience problems because:

- sampling frequencies are very different (in scans of the human body, samples are often taken at less than a 1 mm interval)
- geological features are variable and unfamiliar (cf. models of data for the human body which is well known [e.g. each has a spine, liver, leg, etc])
- geological models are based usually on a single dataset wheras in medicine, models are often concerned with changes in the data with time (e.g. tumor growth)

Problems with geological models:

- database integration is often necessary
- complexity of data structures
- inadequacies in relational retrieval logic for spatial data
- difficult ad hoc query language
- difficulty in the past with transportability of RDBMSs
- lack of agreed geologic unit code standards (DLG/E is not yet released)
- lack of data and format standards
- maintenance costs increase with time
- quality control
    - . multiple sources for some data
    - . nomenclature an change with time
- interface with computer graphics provides one set of requirements while the requirements for map outputs are different. You shouldn't necessarily require the computer graphics system to produce map-like products. New products which are more suited to the graphics environment need to be developed.
- interface to applications software
- raster/vector conversion methods (though these are becoming available in some GIS systems now)
- visualisation of data quality is difficult. Some suggestions include vibrating models, sound queued to mouse pointer position and (facetiously) smell (e.g. "this model really stinks"!)

Exploration of the modelling process (Agemar Siehl, University of Bonn)

Numerical models are not yet widely used in geology because:

- models are still too simple
- exceptional local results are often the most important and these are very difficult to incorporate into a general model. For example, very special local circumstances may create a groundwater spring.
- data availability
- integration of heterogeneous datasets is difficult
- cost of hardware and software systems neeed to support the modelling
- too few geoscientists are either writing computer programs or are engaged in teams developing them.

What is needed if numerical models are to gain greater acceptance:

- user friendly systems
- object oriented 3D graphics programming systems
- object oriented 3D GIS to handle large datasets
- links to expert systems
- better input and output links to other systems
- improved rendering and visualisation tools
- better handling of geological uncertainties

3D and 4D database design (J. Raper, University of London)

3D and 4D databases are needed because:

- geoscientists work with objects
- many data representations are just created and then destroyed. We need to be able to save them for re-access.
- 'spatial' integrity constraints are needed analagous to the integrity controls in a RDBMS (e.g. procedures to prevent duplicate records and missing records). One case in point would be controls to make sure that 2 adjoining objects don't both occupy the same space at their common boundary.
- models come and go but little meta-data on them is preserved (e.g. what were the parameters used to generate them, what was their quality, what were their failings).

At the moment virtually all the above tasks are being managed in people's heads. There is currently no database management system for 3D and 4D datasets.

There are 3 alternative approaches to designing 3D and 4D databases:

- a standard geometry/ attributes hybrid approach using current RDBMS technology. To do this, 3D object types must be created (in an analogous way to what SIRO-DBMS does in 2D). However, such an approach would not provide 3D integrity rules and it would not support complex 3D operations.
- extended geometry/attributes hybrid approach using revised RDBMS technology. This will be possible with the SQL3 query language standard when it is released. However, spatial operations will not be optimised so system performance may not be very good.

- object oriented approach. This would allow 3D objects to be created and these would have interaction rules defined. Such systems offer the maximum flexibility with 3D operations built in but this technology is still some way off in the future. Existing object oriented database products (e.g. Empress) are not good enough at this stage.

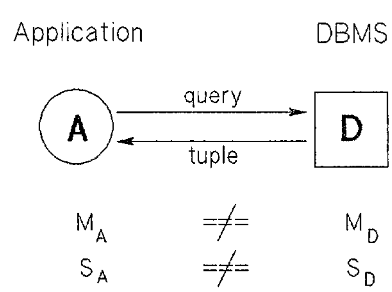
3D and 4D database design (H Schek, Information Systems - Databases, ETH, Zurich)

The issue discussed was co-operative processing schemes between DBMSs and Applications software. Schek used the following definitions:

APPLICATION		DBMS	
role: Data Manipulation & Evaluation		**role:** Data Storage	
Data Structures	} M_a	M_d	{Data Structures
Algorithms	}		{Generic operations
System Platform	} S_a	S_d	{System Platform

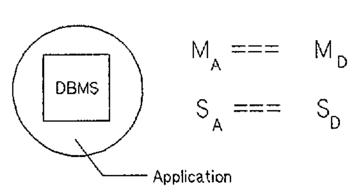
Four schemes were discussed:

- Strict separation between DBMS and Applications software

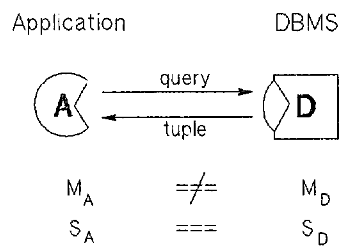


In this scheme, the communications between the DBMS and the Application are restricted to the transfer of primitive objects only.

2) Object oriented DBMS (OODBMS)
In this scheme, the application and the DBMS are coded together from the outset. Thus the two functions are essentially handled by a single entity - the OODBMS.



3) Improved cooperation through externally defined types (EDTs)

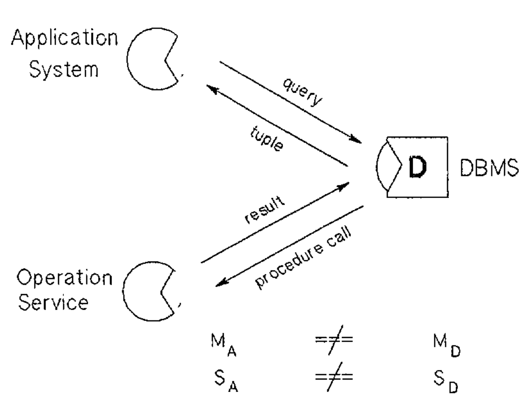


Here the DBMS knows more about what the application is doing so that it can do a better job. Essentially for this to work, part of the object code of the application is taken out and linked to the DBMS object code. Note: only those parts of the application which are needed by the DBMS are linked in this way.

The advantages of an EDT approach are:
- user defined data structures
  . efficient exchange of data between application and DBMS
  . less explicit data conversions are required
- user defined predicates and operations
  . more sophisticated queries are possible
  . less data transfer is required
- user defined indices and storage structures
  . precomputed query results can be defined and stored in the DBMS

The disadvantages of EDT are:
- technical problems
  . complex calling sequences
- protection
  . linking the application code into the DBMS could cause data corruption to occur

4) Operation service



In this scheme, the functions of the application which were wedded to the DBMS in the EDT model are here handled by a separate system operation service. The advantages of this over the EDT scheme are:

- all the advantages of the EDT model
- no technical difficulties
- no protection problems causing data corruption because the systems are separate

The disadvantage of the operation service model is that it generates additional network traffic. This additional traffic makes it arguable as to whether the operation service model represents any advance over the simple strictly separated model. It depends on the specifics of each case.

ETH have gone further than the operation service model with a system called XYZgeobench which is linked to a DBMS. The former is on a Macintosh, the latter on a SUN 3. ETH's conclusion is that for for simple query operations, the comms overheads are very significant. But as the query complexity increases, the comms overheads become fairly unimportant. However if cpu performance continues to increase as it has over recent years, and Ethernet comms speeds remain static at 10 Mbits/second then ultimately the ETH system may become redundant.

Interactive grade-control imaging (David Johnson, Etheridge & Henley Geoscience, Canberra)

For as typical gold ore body of 10-25 million cubic metres, there is usually drill hole information on a 2-3 metre spacing. Something like 1 million data points at a typical cost (including assay costs) of around $20 million. This represents a huge and very expensive 3D dataset.

The samples are 2.5 metre long volumes of chips from the boreholes and grade control assaying done during the mining operations. In addition there are boreholes sunk on a 20-30 metre grid into the deeper sub-surface and off to the sides. These boreholes are used to find continuations of the orebody.

For his study he used Spyglass running on a Macintosh quadra computer. It takes approximately 2 seconds to render each 3D image with this system. Therefore the best way to develop an animated sequence of views is to use the automated capture facilities in Spyglass and go home for the day.

The human brain is very good at building 3D models from such animations. This is really the same process that we use when we see a speeding car approach. We can estimate the speed of the car in 3D space in a micro-second or so and take evasive action as necessary.

Interpolation and Extrapolation in the Modelling Process (Peter Burrough, Utrecht University, the Netherlands)

The advantages of interpolation are:

- you can map attributes that can otherwise only be done mapped with very dense sampling.
- you can create surfaces from point data

The disadvantages of interpolation are:

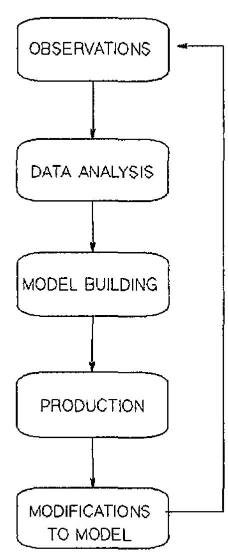
- the results depend on the complexity of the real variation
- the results depend upon the sampling density and distribution. The more data, the simpler the interpolation techniques you can use. Conversely, the fewer the data, the more sophisticated the interpolation techniques that must be used.

For qualitative data (e.g. data expressed as classes such as clear, salty and silty groundwater) maps can be usefully produced by interpolating the probabilities of occurrence of each class. For example, you can produce maps of the probability (expressed as 0-100%) of finding clear water.

Geostatistical Interpolation: Application in 3D modelling (Heinz Burger, Free University of Berlin)

A 3D geological model is a spatial realisation of a genetic hypothesis (e.g. a model of ore genesis at a particular location such as a stratabound hypothesis).

Spatial modelling is an abductive process:



Consequences of 3D computer realisation:

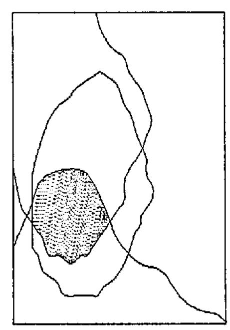
- we need a dynamic environment (requires fast computers and responsive software)

- the inclusion of new objects in models should be easy
- there must be acceptance and quantification of geologic uncertainties
- models must be easy to reject

The geostatistics techniques that are available for 3D interpretation include:

- disjunctive kriging
- indicator kriging
- conditional simulation

Conditional simulation is a powerful tool for producing maps of probability (e.g. that coal grade is > 30%). The way that Burger does this is to compute 100-300 different conditional simulations. He then overlays all these simulations and counts the intersections.



The approach is reasonable since all the conditional simulations are equally valid.

The problems with kriging in 3D include:

- there isn't any automated means of variogram modelling for 3D problems. Thus it is difficult to do the necessary picking of the blocks from the data.

- significant trends and data holes must be tackled separately (the latter requires extrapolation).

- kriging doesn't give reliable results at the boundaries of the data.

- more advanced kriging procedures (e.g. universal kriging, deterministic kriging) require well distributed spatial data.

- extrapolation at angles <120 degrees is not recommended because this is outside the convex hull of the data.

- support of data is not clear (e.g. permeability values from pumping tests and sieve analyses, etc).

- qualitative data are better handled by Markov analysis.

- multivariate problems are still far from practical solutions (including space-time problems).

Temporal functions and expert systems (Dick Lyklema, Delft)

Expert systems are virtually unused in science. There are a handful of developers and researchers and essentially no users.

To set up an expert system you have to ask and answer a lot of basic questions (many of which are very hard to answer). For very complex systems like geology, there are an enormous range of interpretations for any given problem. So setting up an expert system which will have any value will require a great deal of work. The only really successful expert systems seem to have been in subjects which have a very narrow knowledge domain (geology is definitely not one of these).

There might perhaps be a role for expert systems in assisting scientists to use statistical models because here the knowledge domain is narrow and the goals are well defined.

There was an expert system called PROSPECTOR developed by SRI. This system was intended to help select exploration targets for mineral deposits. There is some uncertainty about whether it really was useful. The consensus at this meeting is that it was not.

Dick seemed to be saying that in his discipline (hydrogeology) there is never much agreement in interpretations between the specialists and that he is hoping that expert systems might lead to a consensus view for many problems. This it seems to me is very unlikely.

Extended cellular automata based rules for space-time modelling (Antonio Camara, New University of Lisbon, Portugal)

The cellular automata is also known as "the game of life". The extension used here is that he has introduced the idea of probability in determining each cellular outcome wheras in the normal case, there are fixed rules (e.g. when there are 3 or more cells in contact, they die from overcrowding). A comment was made by Christoph Lindenbeck that by making the extension, many of the nice features of the cellular automata (e.g. memory) are lost. This may not be a good thing.

The basic rules of a cellular automata are:

- only local effects determine local outcomes
- the same rules apply everywhere within the system
- each cell's outcome is determined separately at the same time (i.e. parallel processing)

The cellular automata can be extended to n dimensions, though numerical processing would have to be implemented in a parallel procesing computer to make this practical. Also, the cellular automata is able to bridge the gap between microscale and macroscale processes (i.e. very large macroscale processes can be modelled by just considering microscale interactions).

Camara gave an example of how he and his group had used the cellular automata to model water quality in a river. They had considered the path of contaminants by modelling behaviour including deflection, decay and dispersion. They used an Intel personal supercomputer to do this modelling. The results are to be published in the Journal of Water Research later in 1992.

The extended cellular automata procedure used has some similarities to finite difference modelling. There are also some similarities with a Markov chain but there the rules don't need to be probabilities.

They confirmed that there is a law of diminishing returns with this type of parallel processing machine as you add more processors. You quickly reach the situation where adding additional processors produces only minimal increases in computer throughput. This happens because parallel processing requires message passing between the processors to coordinate the tasks. As the number of cpus increases, so too does the volume of this message traffic and this slows the computer down. They found that there was no real gain for their work in using more than 30 cpus.

Camara says that the extended cellular automata technique can be used to build very rich models incorporating all sorts of interacting entities. He is exploring the combination of things like photographs, satellite imagery, maps, sounds, expert opinions and video in an extended cellular automata and intends to try using multi-media techniques as a means of combining all these different data types using his interaction rules.

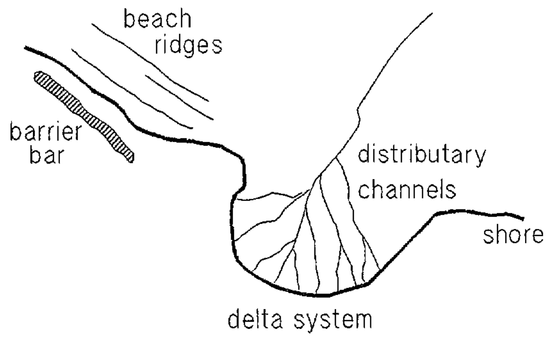
SEDSIM - Stanford's Sedimantary basin simulation project (John Harbaugh, Stanford University, USA)

SEDSIM is a computer model which has been under development since 1983. The intention is to provide a tool for petroleum exploration. SEDSIM models a dynamic system which produces sediments and sedimentary basins. Factors such as waves, wind, deformation, diagenesis, sea level changes, stream flows, clastic grainsizes, etc are modelled dynamically. Thus when one of these parameters is changed, the other processes that interact with it are changed as well.

The goals of SEDSIM are:

- to represent energy, space and time in the development of a sedimentary sequence
- to conserve energy, space and materials
- to represent flow at all scales with equations (e.g. river flows, ocean currents and pore fluid flow)
- to obtain numerical solutions
- to display the results graphically

The SEDSIM project aims to model all the major sediment features and processes of an active depositional basin. Work is concentrating at present on deltaic sequences because these have important economic potential for the oil exploration industry. The deltaic environment is depicted in the following figure:



SEDSIM works with the concept of fluid elements. These can be set at any appropriate size for the modelling (usually on the scale of metres). SEDSIM creates thousands of these elements and it tracks their velocities and locations wih time. The model maintains the status of the mass, momentum and energy of each fluid element. As the fluid elements increase in velocity, they pick up sediment (if it is available). The greater the velocity, the larger the grainsize and the more that can be picked up. Conversely, as the velocity falls, sediment is deposited. The larger grainsize material is deposited first.

As the fluid elements in a stream reach the shoreline of the sea, they slow and begin to deposit sediment. This sediment modifies the topography which in turn influences the way subsequent fluid elements behave. The result is a prograding delta if the sea level is constant or falling. Changes in sea level during the model can be accommodated. The sediment is divided into 4 size classes(called coarse, medium, fine and finest) and the grainsizes of these can be set (e.g. in mm) at the beginning of the model.

The effects of ocean currents including long-shore drift and the effects of wave action have been included through an additional module which can be interfaced with the SEDSIM code.

SEDSIM was run in a number of different starting configurations. The results were visualised on a Silicon Graphics workstation using a program called SEDVIEW. These visualisations included 3D perspectives and fence diagrams of grainsize distributions and age distributions. The resulting images included transgressive and regressive sequences.

Enabling technologies (including GIS and visualisations) (Marinos Kavouras, National Technical University of Greece)

The goal should be the development of spatial information systems for the geosciences. Such a system should provide advanced:

- modelling capabilities
- presentations
- retrieval capabilities (particularly spatial queries)
- analysis
- exchange facilities (of both data and models)

Recent developments in GIS have included:

- movements toward RDBMS approaches
- accuracy issues are starting to be addressed (i.e. variations in data quality)
- spatial indexing is now fairly commonplace
- very large databases
- multiple representations of the data in 2D are now possible (e.g. raster and vector)
- object oriented approaches are beginning to be used
- advanced analysis and modelling
- data integration
- interface developments

Many spatial problems arise in 3D applications and show up the inadequacies of 2D systems for geoscience.

In modelling geo-objects (both sampling limited and definition limited) we must have coexistence of volume representations and surface representations within the 3D GIS. That is, both types of representations must be available for users. There are 3 ways to handle this coexistence:

- single representations. For example, we determine that for most cases a particular object can be represented as a surface. So it is stored in this form in the database. If a particular application needs the alternative form then it must be possible to quickly convert it to that form.

- multiple representations. For the same object the system maintains more than 1 representation in the database. For example, for an orebody volume the system also stores its content, the spatial distribution distribution of its attributes and its surface morphology.

- hybrid representations. In this case the system doesn't save 2 separate representations but instead it stores a very much more complex representation which includes both representations. For example, in 2D the GIROS system of the Lower Saxony Geological Survey which has a hybrid data model combining raster and vector representations.

Marinos doesn't think that the hybrid approach is a practical solution for 3D geo-objects. They are just too complex to manage in a hybrid model. Also such complex models would be difficult to exchange between different 3D systems.

A lot of work is going to be needed to develop a 3D data structure. The US spatial data transfer standard (SDTS) while it does include 3D manifolds, does not address these issues. SDTS is basically just a "parking space" into which some specific 3D data model/s will have to be added in the future, according to Jonathan Raper.

A 3D system needs to be able to tell the user about the limitations of the modelling displayed rather than just leaving representational artifacts in the models which are wide-open for mis-interpretation. Marinos thinks that this information should be included in the data structures themselves.

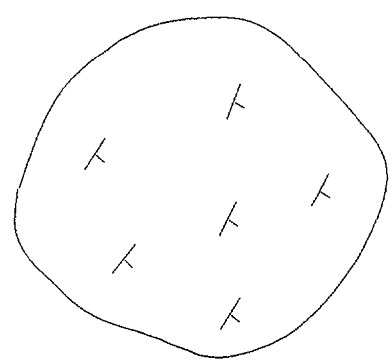
Similarly the assumptions that were used in the production of models should be stored with it (i.e. the lineage of the 3D data must be recorded as it is in the SDTS).

Visualisation.
At the moment one of the greatest shortcomings in visualisation is the visualisation of uncertainties in data. Some ideas which are being discussed include: using vibration &/or transparency &/or sound. The current limitations may not last however because developments in computer science are taking place much more quickly than are developments in 3D geoscience modelling. By the time that 3D geoscience modelling matures, visualisation technologies will have dramatically advanced.

Some field data capture techniques for geologic mapping, production cartography and GIS processing. (Andreas Fabbri, ITC the Netherlands)

Field mapping is usually carried out at a scale finer than the scale that maps are eventually produced at. Therefore in producing the map, the mapping data must be generalised. This generalisation requires subjectivity.

For example a rock outcrop which contains a number of measurements of bedding plane orientation (see Figure xx) may have to be described on a completed geological map by a single "representative" orientation.



Such generalised data are very inferior to the actual measurements and we certainly shouldn't digitise it into a GIS unless no other data are available. If we do have to use such data then we need to know what logic was used in applying the generalisations.

Field data capture
The Geological Survey of Canada have developed a field data capture system using a PC and purpose built software called FIELDLOG. The features of this system include:

- data are entered by geologists at the outcrop and a distinction is made between observed and inferred data
- the geologist can display field data while in the field and can integrate it with raster data
- data are exported from FIELDLOG as dxf files which can be imported into Arc/Info at the end of the field season

3D systems for environmental damage monitoring and remediation (Tom Fisher, Radian Corp, USA)

Radian Corp is both a vendor to the GIS industry (the CPS-3 gridding software) and a user of a very wide range of 3D systems (environmental consultancies such as waste dump clean-up programs).

Why use 3D modelling?

- it allows work to be carried out with a minimum amount of data
- it is cost effective because it provides excellent platforms for 3D analysis

Why not use it?

- the cost of training
- the difficulties of getting data into the packages (lack of data interchange standards)
- US courts insist that some traditional models be used

The things that need to be determined with the 3D systems:

- site characteristics
- accurate volumes and spatial distributions
- predictions of pollutant plume movement
- interactions between processes
- results of remediation

Needs:

- expression of inter-relationships between objects and processes
- data distributions based on physical laws and processes

Requirements of a geoscience information system (GSIS) for environmental engineering:

- geometry representations
- geological framework models
- process models

Primary functionality of a useful GSIS:

- surface modelling
- volume modelling
- manipulative capabilities
- data input/output between the GSIS and other systems

The key components of a GSIS are:

- data management
- graphic utilities/ interactive graphics
- geometric manipulation
- visualisation tools
- modelling functions
- statistics and calculation modules
- graphical 3D querying
- interfaces to 3D query systems (as distinct from just I/O)
- a graphical user interface for geologists rather than computer scientists

Development of a 3D hydrogeologic model simulating groundwater flow in the Yucca Mountain area (A. Keith Turner, Claudia Faunt and Frank D'Agnese, Colorado School of Mines)

A 100,000 km^2 area is being studied to a depth of 10 km. This area is planned as a nuclear waste repository and so its groundwater characteristics need to be understood in 3D and 4D. The model to be developed needs to be able to predict groundwater flow for 10,000 years.

The geology is fairly complex as the area is part of the Basin and Range province. Furthermore, there is a history of seismicity in the area. Site selection has been made largely on political grounds.

There are three steps being followed in the groundwater study:

- evaluation of past groundwater discharge using remote sensing in particular (NOAA, Landsat TM)
- regional 3D hydrology modelling using GIS technology
- simulation of past, present and future groundwater flow

They have a 1:500,000 scale map in Arc/Info (a 3deg x 3 deg latitude/longitude region) and they have 30 cross-sections in predominantly E-W orientations (there are some N-S) which cut across the regional Basin and Range trends. These sections are a based on a combination of surface geology interpretation and seismic sections. They are 100-150 km long and extend to a depth of 3000 km.

The sections have been digitised into 3D space using Intergraph microstation. Any feature on the sections can be selected and a UTM reference and a depth are returned.

The procedure to be used in building the 3D model is:

- input the cross sections into 3D using INTERGRAPH (already done)

- add attributes to all the cross section features

- input the geology (already done)

- add attributes to the features on the geology map
- link the sections with surfaces by picking common features across sections. This is to be done with with the Intergraph EPsect software. The surfaces are going to be built using the other EP modules (EPmap, EPgeo and EPmgin).

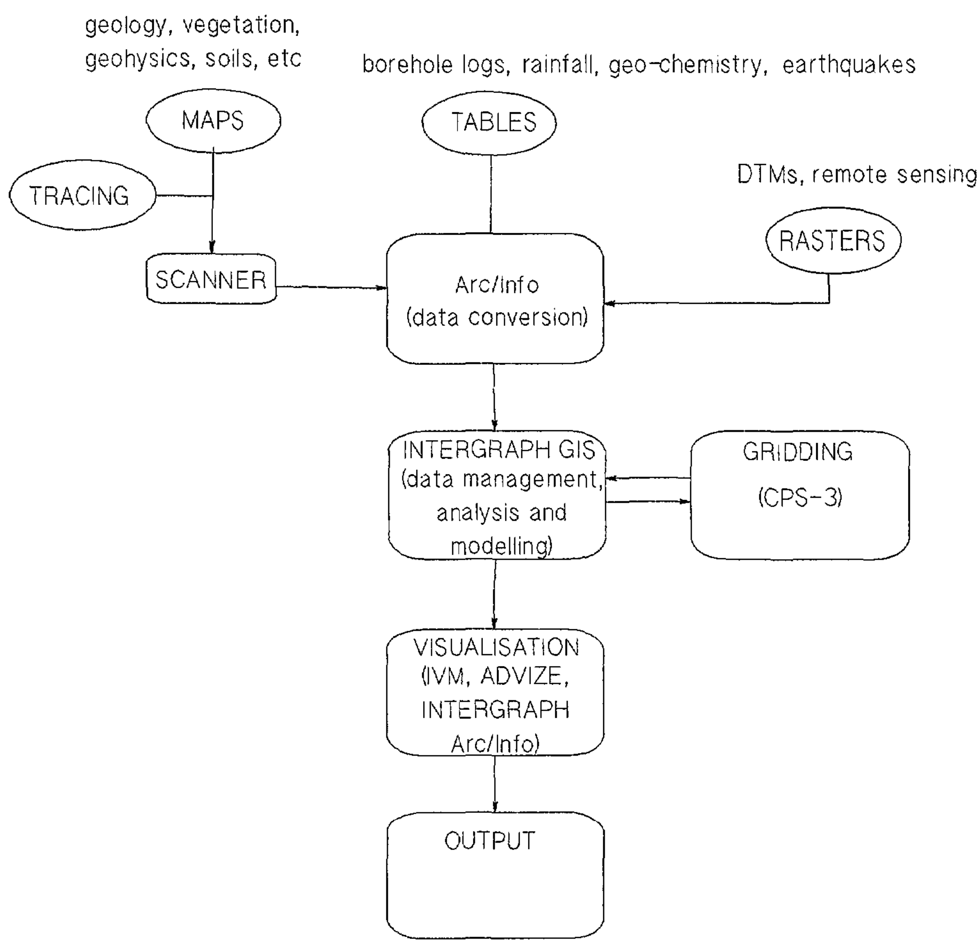
- export the lines and surfaces as X,Y,Z data

- interpolate the 3D volumes between the surfaces. The software to be used for this hasn't been decided yet. IVM by Dynamic Graphics could be used. IVM essentially does the constrained gridding by doing the interpolations and then truncating the resulting grid by applying the surfaces. Note: using IVM and similar products to produce mathematically correct interpolations can produce geological nonsense. The user must be very careful to physically interpret the resulting grid.

IVM uses an exact fitting minimum curvature interpolation technique. This can create horrible artifacts around sparsely distributed data.

- display geologic framework in 3D both as surfaces and volumes

These procedures are illustrated in the following diagram:



Application of new technologies - The DASP/GIROS experience (Horst Preuss,
Lower Saxony Geological Survey (NLfB),
Hannover, Germany)

DASP - an in-house developed DBMS for storage and retrieval of geological data. DASP is used to manage:

- . borehole data
- . strata descriptions
- . surface boundaries of geological units
- . contour lines of depth of geological units (i.e. isopach data)
- . contour lines of topography

DASP is a hierarchical database which was written in-house in 1982. It runs on VAX systems. DASP can produce lithological log diagrams of borehole data.

GIROS - an in-house developed GIS system used for digitisation and evaluation of

- . geoscience thematic maps
- . borehole data
- . profile sections
- . DTMs in raster format
- . geological cross sections
- . overlays of raster and vector data

GIROS is a unique GIS system. It uses a hybrid vector/raster data model in which vector locations are stored with the pixels that they cross. Eight bits are used for each pixel value (i.e. 256 values (or colours) can be represented) and additional bits are used to store the vector data. This model makes it very simple to perform spatial operations which overlay vector and raster data.

GIROS was developed for prototype map production and for the generation of quick thematic maps. It is not particularly suited to producing cartographic quality products although this can be solved to a degree by using a cartographic standard base map as one of the data layers to be printed.

Output plots are produced using standard GKS plotting routines. GIROS is written in FORTRAN77 for VAX computers (i.e. it uses the VAX FORTRAN extensions) and can run on Vaxstation GPX, 2000, 3100, 3200 and 3500 workstations under VMS. A small German company is exploring the technical and economic feasibility of porting GIROS to SUN workstations using Unix. Horst is not very hopeful that this porting will go ahead however.

Other software being used at NLfB includes:

- ISM (Interactive Surface Modelling by Dynamic Graphics Corp.)
  - . used to interpolate 2D grids from scattered sampling points
  - . used to contour data

- ISM2DASP (an in-housed system written in 1990)
  - . converts ISM contour maps to DASP format
  - . creates points in polygons for attribute tagging (e.g. areas, labels)

- MOPS (written in-house in 1985)
  . used for alphanumeric data input to DASP (mainly used for strata descriptions)

- DIGIT (written in-house)
  . used for input of points and lines from scanned maps

A new research project funded by the German Research Foundation is currently underway at NLfB. This project aims to develop an expert system for geological investigations. Specifically, the system is aimed at:

- identification of geological horizons in seismic sections
- interpretation of geological map units
- construction of cross sections
- calculation of unit thicknesses and volumes
- construction of 3D models with IVM (Interactive Volume Modelling by Dynamic Graphics Corp.)

The expert system is based around the NEXPERT expert system engine.

Space-time modelling in hydrocarbon exploration (John Tipper, University of Freiburg, Germany)

The processes that are responsible for petroleum accumulation are many and they interact with one another. For this reason, space-time modelling of such basins must be very complex to be meaningful.

Data visualisation tools however don't need to be difficult to use. If good consistent easy to use visualisation tools can be put into the hands of geologists then even very complex models can be comprehended.

John demonstrated a dynamic visualisation system called Cockpit he has written for Silicon Graphics workstations using the GL graphics library. GL is becoming something of a *de facto* standard in the field of 3D visualisation. His code is in FORTRAN 77 because most geoscience application programs which might be interfaced with Cockpit are still in FORTRAN. He is preparing a C version of Cockpit.

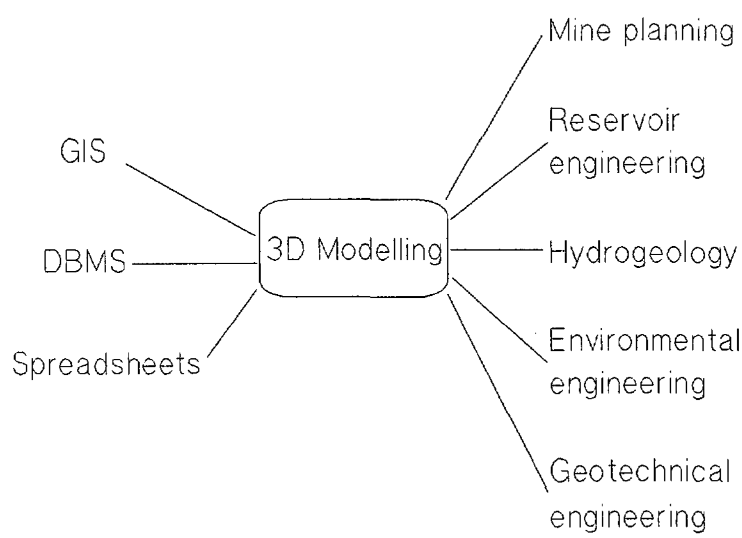
The Cockpit software may be available to AGSO on a nominal-cost as-is basis. The recommended hardware however presents a problem. John recommends a Silicon Graphics or compatible workstation preferably with the TG graphics option or better. A dial-and-button box is also strongly recommended for maximum flexibility. The software requirements are a FORTRAN compiler and access to the GL graphics library.

Summary: the vendors viewpoint (Simon Houlding, Lynx Systems, Vancouver, Canada)

Simon emphasised 3 issues which he sees as crucial to the success of GSIS technology in the geosciences. These issues are:

- the need for data interchange standards
    . essential for anybody who needs to get data from multiple sources
    . a very large part of any 3D project is just converting data
    . affects the viability of the whole 3D discipline
    . both for data and models

  3D geoscience modelling sits between many different fields in geoscience as illustrated in the following diagram. For this reason the transfer of data and models between systems is very important.



- addressing the functionality of the modelling process
    . it is a complex and difficult process to build a 3D model
    . exploring and explaining the tasks in building a model to the wider geoscience community is very important if 3D modelling is to become generally accepted.

- the lack of familiarity with modelling methods
    . a large part of training on any GSIS system is teaching users how to develop and apply modelling techniques
    . much more training in modelling needs to be done at the undergraduate level in universities. At the very least all undergraduates should be exposed to GSIS so that a basic level of awareness of the technology is achieved.

Summary of the Conference (Jonathan Raper, University of London, UK)

What have we achieved in terms of data structures?

- there are some systems which are being used successfully (e.g. GOCAD, IREX, IVM) and these use their own structures
- there still isn't much of a plan as to how to store data

There are a number of problems that are slowing down the spread of 3D technology:

- inherent computer phobia amongst some geoscientists
- problems with data interchange between 3D systems and between these and other spatial IT systems (e.g. GIS, DBMS, digital cartography)
- there has been a lack of applications to big problems which capture the imagination
- there has been a lack of a group approach amongst the practitioners of 3D
- some research groups have been too academic in their orientation
- the high cost of hardware and software

The scientific infrastructure that is needed if the 3D discipline is to gain wider acceptance:

- a generic 3D ideas generator is needed for PCs
- more work is needed in structuring and interpolation of sparse datasets
- perhaps work should concentrate initially on voxel-based systems because these are simpler to deal with than are systems built on vector/surface-based models. This would be an analogous situation to what happened in 2D GIS where raster GISs where the first to be developed.
- data interchange of structured data
- better user interfaces (including the use of 3D cursors)
- voxel-based games to teach 3D concepts painlessly
- further scientific meetings (next ESF conference in 18 months with one more to follow after that).