A seismic modelling environment as a research and teaching tool for 3-D subsurface modelling

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KEYWORDS: 3-D complex geology modelling, educational tool, forward modelling, finite difference algorithms, generalised cylinders, geological structures, seismic validation, student tests, visualisation

ABSTRACT

Early geological modelling and visualisation techniques were limited to manual cross-sections or isometric perspectives. Computer modelling has automated this task to a certain degree, but traditional approaches do not allow iterative validation during the modelling process. When the structure is complex and data sparse, as is often the case in geology, interactive 3-D modelling techniques should be employed that can interrogate new and existing data, guided by the geological experience of the modeller. Using the Vredefort dome in South Africa as a case study, we describe a Seismic Modelling Environment (SME) to demonstrate the potential of this type of computer-based modelling and geological visualisation. SME offers a novel approach to interactive 3-D modelling of complex geological structures using an extension of sweep representations and user-controlled forward modelling with seismic analysis for validation. Incorporation of validation techniques allows early confirmation or rejection of models. Tested by a group of third-year geology students, SME's iterative construction and exploration of a 3-D model clearly provided users with a superior understanding through visualisation. SME has, therefore, potential both as an educational as well as a research tool.

INTRODUCTION

In the past, hand drawn fence diagrams and isometric perspectives were used for visualising hidden geological structures [McClay, 1987; Sims, 1992]. Drilling commonly exposed the shortcomings of these techniques, which were often related to "out of section" facies changes or relative tectonic displacements. Early geological modelling software tended to mimic the old manual approaches [Sims, 1992] and used traditional CAD techniques. It therefore suffered from many of the same disadvantages: modelling was tedious to perform and did not exploit the 3-D nature of the modelled structure. Moreover, editing was often restricted to a command-line or menu-driven approach that was limiting, as interaction was not intuitively related to the 3-D geometry of the model [Lin *et al*, 1995]. In order to gain a more complete understanding of geological structures, interactive 3-D modelling and visualisation techniques were needed.

Recent developments have overcome many of these shortcomings, but several factors still hinder the creation of accurate and meaningful models. For example, most modern software relies on densely sampled data in order to generate a model. This approach has been criticised for being rigid and inaccurate when unusual formations are encountered, or when the data are sparse or sampled irregularly [Turner, 1992; Jessell & Valenta, 1996; Cox *et al*, 1997]. A more flexible approach to geological data modelling is then required – one that encapsulates the geologist's experience and insight. Various validation methods can be used to test the viability of the model.

We have developed a Seismic Modelling Environment (SME) that adopts this type of approach. SME helps the geologist construct 3-D models that incorporate both geological and seismological constraints. Model validation is achieved through analysis of synthetic seismograms produced from simulations.

RELATED WORK

COMMERCIAL SOFTWARE

Most commercial modelling systems are comprehensive packages aimed mainly at mining and resource management. These systems are devoted to providing specific software solutions for the mining, petroleum and other industries. Because of this, many of these packages emphasise the stratiform modelling that is important to these fields.

Vulcan, *Datamine* and *Lynx* are CAD style systems that have traditionally been used for this type of mine design and management. These legacy systems have extended their functionality to include geological modelling and visualisation. They are often reliant on dense, uniformly sampled data, however, and build models as "wire-frames" or triangulations. Some packages have provided complex modelling tools for geological interpretation and characterisation, for example *Lynx* has tools for interactive geological sectioning. Interpretation can be performed at any orientation and the results are first incorporated into intersecting fence sections and later provide full 3-D interpretations of geological volumes. Similarly, *Datamine* provides features for constructing 3-D strings and polygons by snapping onto sample end-points. String and point manipulation tools allow the user to complete the sectional interpretations. The wire-frame models can be converted to surface and cell models as required.

RESEARCH PROJECTS

gOcad currently sets the standard for 3-D geological modelling and interpretation and is widely used by geo-scientists around the world. The *gOcad* project was initially an academic venture started by the Computer Science group of the National School of Geology (ENSG) in Nancy, France. It has now evolved into a consortium of research institutions and companies that produce a commercial software package as an end product. Academic research continues, however, and the results are incorporated into the software.

The project develops modelling techniques from the perspective of both computer scientists and geologists. Two major aspects of their research are structural modelling and geophysical analysis. The structural modelling includes fault and horizon modelling, fault morphology, and the folding and unfolding of 3-D horizons and layers. It also addresses the construction of surfaces from lines and points and the construction of 3-D geo-cellular models from 2-D cross-sections. The geophysical analysis aspects of the project include 3-D velocity model building with continuous or discrete functions defined in each geological layer; 3-D seismic interpretation for the construction or editing of surfaces; and the display of 3-D seismic and velocity data [gOcad, 1999].

Another centre of innovative geological modelling and visualisation research is the *Australian Geodynamics Cooperative Research Centre* (AGCRC). The general goal of this group is to geometrically model complex geology from sparse data using the user's geological interpretations [Cox *et al*, 1997]. This is achieved through a combination of advanced interpolation techniques and 3-D editing tools that allow the geologist to interactively adjust the model.

A major focus of the research at the AGCRC is surface detection and the construction of non-convex hulls from sparse observational data [Watson, 1997]. Related projects in the CSIRO Exploration and Mining group have attempted to define a standard "Data Model" for the storage and classification of 3-D geological data [Power *et al*, 1995] and build tools – a "GeoEditor" – for the creation and manipulation of models [Cox *et al*, 1997]. An innovative methodology allows the user to "sculpt" a 3-D structure by manipulating point data in 3-D space [Hornby, 1999; Regi, 1999]. This requires a data set to be established before editing can take place, however.

The *Noddy* system [Jessell & Valenta, 1996] takes a different approach to geological modelling. Instead of directly building the geometry, *Noddy* allows the user to apply a sequence of standard geological deformations (faults, folding, etc.) to an initial stratigraphic layering. This method is described as kinematic modelling. Cumulative deformations make up an event history for the structure and result in a voxel model representation.

Noddy integrates structural and geophysical modelling by producing synthetic potential field (gravity and magnetic) responses from the voxel models. The correlation of these results to real potential field surveys of the structure can lead to a refinement of the model. Techniques have been developed to partially automate the refinement process in simple models by using genetic algorithms to find the most suitable parameterisation of the deformations comprising the event history [Farrell *et al*, 1996].

The disadvantage of *Noddy's* approach is its inability to directly incorporate sampled data. Users are also unable to directly manipulate the 3-D model, so that highly irregular forms are difficult to realise. To overcome these shortcomings, *Noddy* allows voxel models to be imported and exported.

OUR APPROACH

We have developed an interactive 3-D modelling and validation tool capable of building realistic models of complex geological structures. Our Seismic Modelling Environment (SME) embraces user-controlled forward modelling in a methodology that is similar to *Noddy*.

We built SME to satisfy the following requirements:

Modelling: enable the user to transfer a conceptual geological model, based on scientific evidence, into a well-defined 3-D computer model.
Visualisation: allow exploration of the 3-D model and provide mechanisms for confirming whether the model represents the user's intended design.
Scientific Validation: guide the user towards a scientifically correct model.

User interaction was considered to be an important design issue affecting all three of these requirements. Much effort was therefore put into making the system intuitive to use whilst scientifically accurate.

Visualisation was also a focus of development since real-time manipulation and 3-D explorative ability aid model comprehension. The construction and interactive exploration of a 3-D model gives users a better understanding, possibly resulting in a re-examination of the prevailing concepts and encouraging the development of new models [Cox *et al*, 1997]. This point is emphasised by Houlding [1994], who believes that an interactive visual representation of the geological entity under consideration is not only beneficial, but also critically important to the modelling process.

Houlding [1994] has also noted that geological interpretation is itself an inherently iterative and interactive process. It is important, therefore, that modelling systems used for 3-D geological interpretation and characterisation share these properties. The methodology we have adopted is based on the need for translating the user's conceptual ideas into a computer model (Figure 1). The realisation and interactive visualisation of the conceptual model may influence the user's understanding of the structure. This interaction continues until the user is satisfied that the computer model accurately represents his/her conception. The model is then subjected to a validation process where model-generated synthetic data are compared to existing empirical data. The validation process leads to further adjustments of the model. This iterative methodology allows a user to create and edit the model directly and refine it as additional data become available.

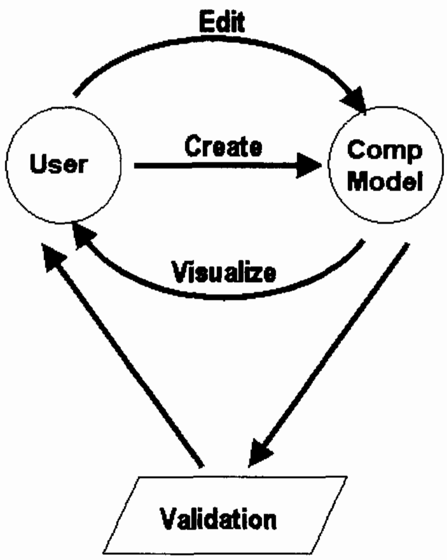

FIGURE 1 Iterative modelling flow-diagram: adjustments to the model are made as a consequence of visualisation and validation.

DEVELOPMENT OF SME

SME was initially developed with the aim of modelling the Vredefort dome, situated in the Witwatersrand basin of South Africa. The Vredefort dome is believed to be the erosional remnant of a 2020 million year old meteorite impact crater [Hart *et al*, 1991]. The rocks of the target area are as old as 3500 million years and experienced a prolonged history of deformation and metamorphism prior to impact. In response to the impact, the rim of the crater has been overturned and the centre of the dome uplifted. The Earth's crust in the area has been turned on edge and now stands sub-vertical instead of horizontal in the centre of the dome (Figure 2). Hart *et al* [1990] propose that the structure is intersected by a NE-SW trending, vertically dipping shear zone termed the south-east boundary fault. In detail, the structure is complex and one that is the subject of sustained debate [Gibson *et al*, 1988; Tredoux *et al*, 1999].

The Vredefort dome represents a good test case to incorporate into a localised geological modelling system because:

- Vredefort is a complex but quasi-symmetrical irregular structure that, because of its postulated origin as the result of meteorite impact [Hart *et al*, 1990, 1991], has analogues in experimentally derived models of impact structures.
- The surface geologic outcrop is fair, but subsurface geological data available for this structure is minimal.
- Potential field data from gravity and magnetic surveys across the structure are available and theoretical models of the structure have been developed. Models of this existing data could be iteratively tested using seis-

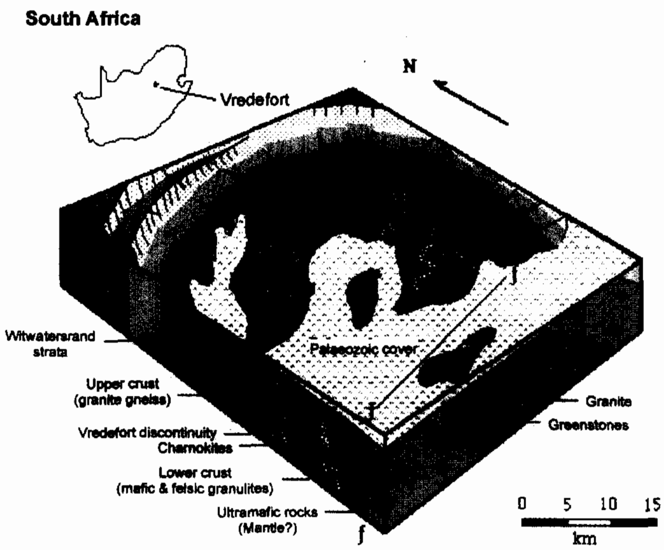

FIGURE 2 Simplified geological cross-section of the Vredefort structure, believed to be the remnant of a 2,020 million-year-old meteorite impact site [Hart et al, 1990, 1991]. The south-east boundary fault is indicated by f-f . The scale applies to the surface of model only.

mic data from vibroseis lines shot across the structure [Durrheim, 1986].

THE MODELLING TOOL: GENERALISED CYLINDERS

The Vredefort dome reveals that localised geological structures may have quasi-symmetrical features in overall shape [Hart *et al*, 1991]. In the case of Vredefort, there is a semi-circular symmetry along a SE-NW axis. A solid modelling technique that easily incorporates such information is the method of sweep representations. This technique defines 3-D objects by sweeping a 2-D cross-section along a 3-D path or trajectory. We chose to use a particular type of sweep representation called generalised cylinders [Bronsvoort, 1990; Foley *et al*, 1990; Bloomenthal, 1990]. Bronsvoort and Foley *et al* clearly define the different types of sweep representations, including generalised cylinders. We chose to further extend generalised cylinders and use them as our fundamental modelling tool. In our implementation, multiple cross-sections may be defined per trajectory. This allows the user to specify numerous layers following the same trend. To account for variations in shape along the path, our tool allows the definition of cross-sections at any position on the trajectory. As these cross-sections are swept along, they change shape into the next user-specified cross-section (Figure 3). In effect, the entire model is an interpolation of the user-defined cross-sections.

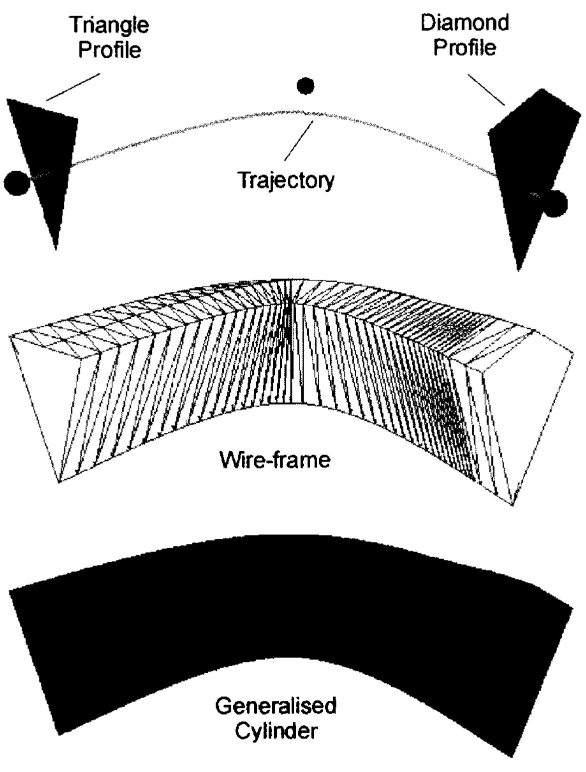

FIGURE 3 A generalised cylinder. The trajectory and profile are shown on top, followed by a wire-frame representation, and finally the 3-D shape. Note that the profile changes shape from a triangle to a diamond at the two endpoints of the trajectory. In the generation of the generalised cylinder, the profile is smoothly interpolated at points in between.

Our tool is similar to the "extrusion" feature of the Virtual Reality Modelling Language (VRML), but there are several important differences. As with our tool, VRML extrusions are constructed by sweeping a cross-section along a trajectory (or spine, in VRML terminology). However, VRML spines are defined by a series of 3-D points that represent line-segments. This leads to 3-D shapes that are composed of distinct segments. Our tool uses NURBS, a special form of B-Splines, to define the trajectory, thereby ensuring C^2 continuity along the length of the shape. VRML extrusions are also limited to only one cross-section for each spine. The cross-section may be scaled or rotated at each control point of the spine but it keeps the same basic shape. We allow the user to *uniquely* define the cross-section shape at *any* point along the trajectory. As mentioned before, we also allow multiple layers to be swept along the same trajectory.

Using our tool, the task of modelling a 3-D structure becomes that of creating a 3-D path and many 2-D cross-sections. Most information for the 3-D shape of geological structures comes from sporadic borehole data or 2-D seismic sections. Our technique provides an effective tool for incorporating such data into a 3-D model.

MODEL VALIDATION

Since a critical part of the modelling process is rigorous scientific validation, the model requires existing data against which it can be tested. Although many data sets (geochemical or geophysical) can be used to test or validate a proposed model, we have chosen to use seismic analysis. Our choice of validation was motivated on the following grounds:

- Exploration data are often collected in the form of seismic sections. For Vredefort, in particular, the best data suited for structural interpretation are available from vibroseis sources [Durrheim, 1986].
- Seismic forward modelling has been well tested and applied to many problems [Reshef & Kosloff, 1985; White & Boland, 1992; van Mount, 1990].
- Finite difference algorithms exist for producing detailed synthetic seismograms that may be used to create seismic sections suitable for comparison and analysis.

SME uses a 2-D finite difference algorithm developed by Vidale & Helmberger [1988]. The algorithm input requires discrete 2-D velocity and density grids and various other parameters describing the source and receiver locations and characteristics. The 2-D algorithm holds an advantage over more rigorous 3-D techniques because of its relative speed and smaller memory requirements. These factors are critical for interactive applications.

It was necessary to integrate the modelling and validation components tightly in order to create an effective system. With SME, the challenge lies in extracting a user-defined 2-D cross-section from the 3-D model for use with the finite difference algorithm. The extraction of the velocity and density grids from the 3-D model is achieved through manipulation of the camera viewpoint, the viewport and the near clipping plane. After pre-processing the scene representing the model, it is possible to produce a discrete 2-D image representing the chosen cross-section. This image is converted to the appropriate velocity and density grids suitable for input to the finite difference algorithm.

IMPLEMENTATION

SME has been implemented on Silicon Graphics (SGI) workstations using C++ and the Open Inventor libraries. For the user interface, we have used OSF Motif, the windowing toolkit adopted by Open Inventor. The implementation, like the modelling process, cycles through three stages: modelling, visualisation and validation. Figure 4 represents these stages.

MODELLING VREDEFORT

The model in Figure 4a represents an early attempt at modelling the Vredefort structure. The colours have been chosen to correspond to those in Figure 2.

Although the layers in the model do lie vertically at the surface, they must return to the horizontal for the model to be physically viable. Consequently, Figure 2 represents only the top (vertically lying) portion of the entire model in Figure 4a. Various properties, including velocity and density information, were assigned to each of the layers. A set of "background" properties was defined for the area surrounding the model. This is required in order for the finite difference algorithm to work. In future versions of the software, we hope to allow the specification of a complex "background" with multiple layers and properties.

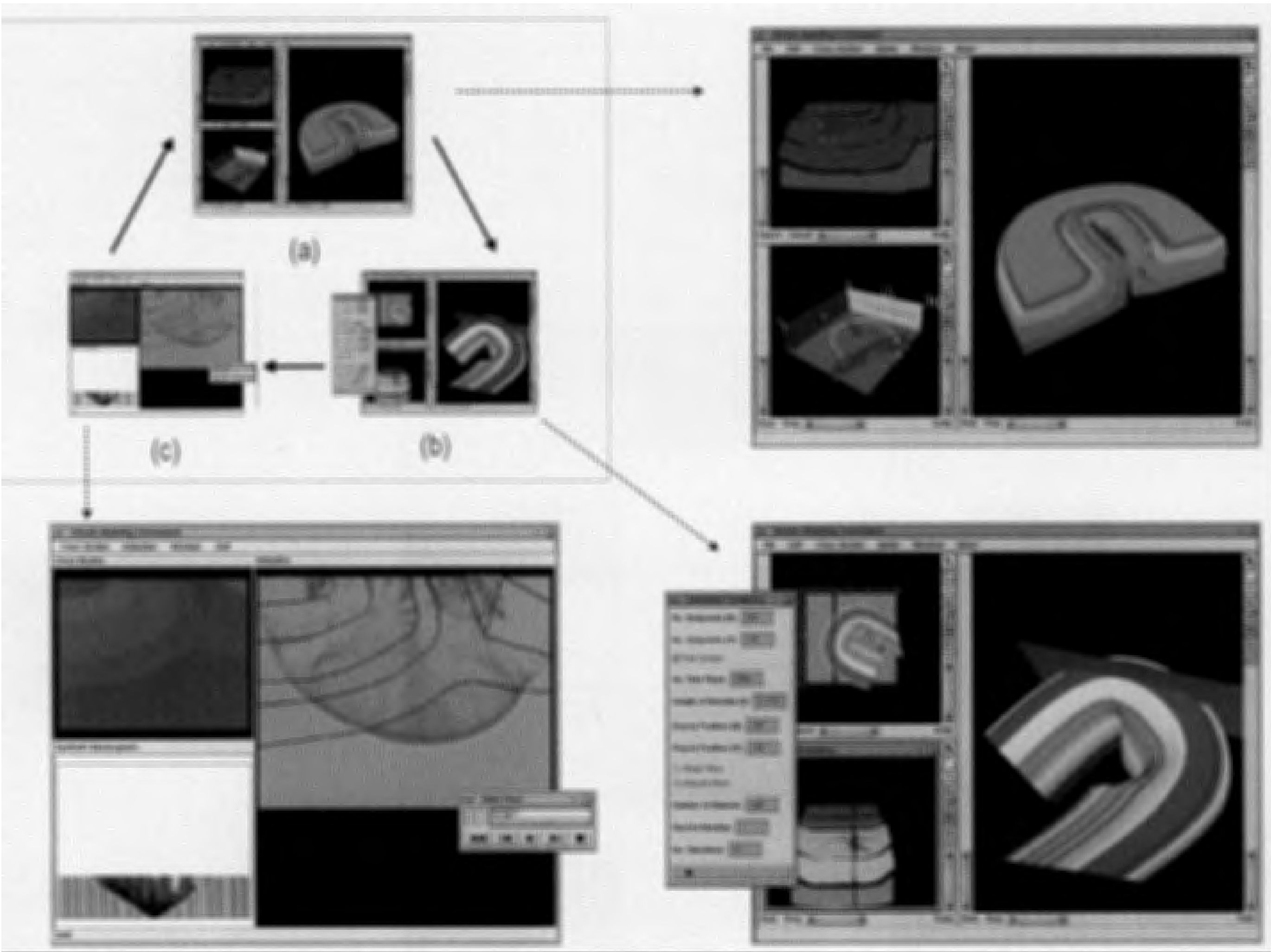

FIGURE 4 Main program window, split into three sub-windows, each presenting a different aspect of the modelling. These windows are re-used for the selection of the simulation cross-section and again for seismic analysis. A menu at the top of the window controls the major program functions. A number of pop-up windows exist to capture additional user input. The Seismic Modelling Environment is used iteratively: (a) model creation and editing, (b) choosing a cross-section and setting the simulation parameters, (c) viewing the seismic simulation results superimposed on the cross-section data. A series of snapshots in Figure 5 shows how the propagation of the simulated seismic wave is animated.

USER TESTING: TEACHING STUDENTS TO USE SME

The two main reasons for conducting user testing were, firstly, to test whether we had met the design goals for SME, and secondly, to determine any educational value or benefit that SME might carry.

The testing concentrated separately on the modelling and seismic analysis features of the software. A modelling test checked SME's ability to create an envisaged geological structure. Development speed, ease of use and flexibility of modelling were evaluated. A seismic analysis test verified SME's ability to convey seismic information to the user. Various tools that aid visualisation of seismic wave propagation were assessed.

The user-base for these tests consisted of a group of fifteen third-year geology students at the University of Cape Town. The students were divided into a modelling group and a seismic analysis group. Within these groups they were split into pairs and each pair provided with a SGI workstation running the SME software.

MODELLING GROUP

Within a 40-minute introductory tutorial, all participants managed to both learn the system and complete an arbitrary model. During a 40-minute practical that followed, the users were required to model a 3-D structure loosely based on Vredefort. The model comprised four layers following a semi-circular path with each layer assigned specific velocity and density information and specifications of cross-sectional shape along the path. Half of the user-base were able to completely model the structure, including varying cross-sections, layer colouring, velocities and densities. The other half of the students constructed a rudimentary model matching the basic specifications, but their shaping of the cross-sections and specifications of layer properties was incomplete.

Our observations suggest that generalised cylinders support interactive modelling and, on the whole, SME allows the user to effectively and efficiently model a conceptual geological structure.

SEISMIC ANALYSIS GROUP

The primary seismic analysis tool in SME is an animation displaying wave propagation, shaded according to wave intensity. The animation and seismographic data are synchronised (Figure 5) and a video panel tool (Figure 6) is provided for controlling the animation. Outlines of the underlying layers can be superimposed on the animation.

The students were shown a simulated seismic wave propagation moving through a cross-section of a Vredefort-like structure. Without any indication of the medium's underlying layering, all students identified the larger scale aspects of propagation, such as refraction. With the model layering superimposed, all of the students could correctly identify the smaller effects such as reflection,

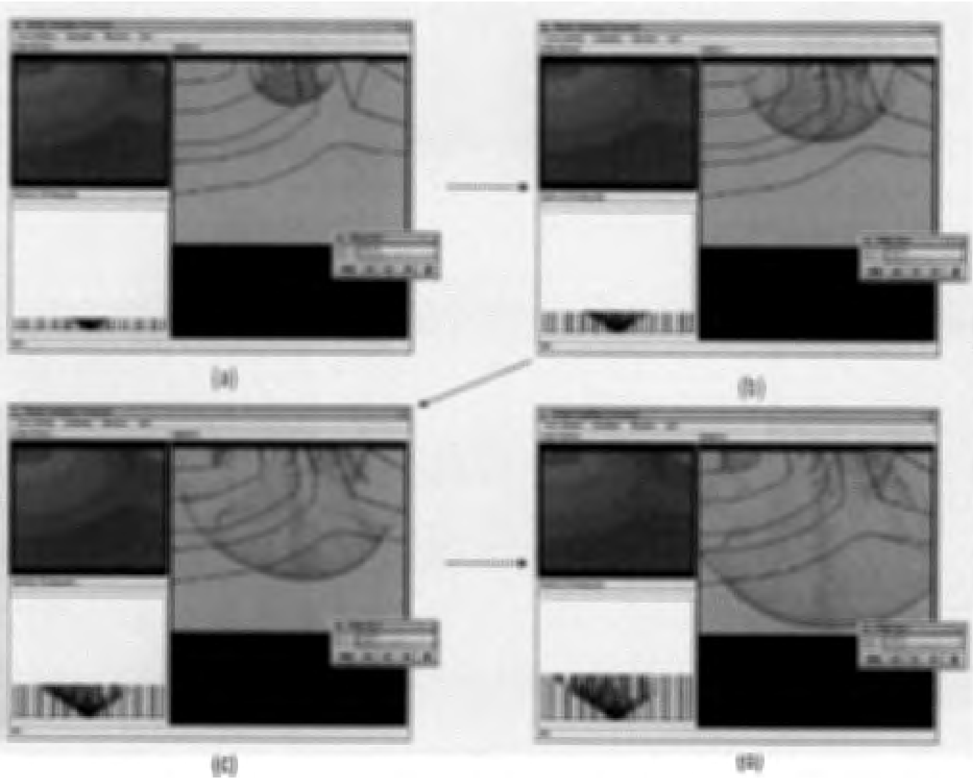

FIGURE 5 Figures (a)-(d) show a series of snapshots of the simulation results window. Note that propagation of the simulated seismic wave is animated concurrently with the corresponding synthetic seismogram (in the lower left corner of the window). The animation is controlled by the video panel tool shown in Figure 6.

FIGURE 6 Video panel tool for seismic wave propagation animation. It provides stop-start and frame-by-frame stepping functionality to the animation.

scattering, interference and surface waves. Five out of seven said they were also able to correlate the animation to the synthetic seismograms.

Next, the students were asked to perform two types of measurements from their observations of the wave animation. Firstly, they needed to determine the relative velocities of the layers. All students correctly identified the material with the highest velocity. Four out of the seven identified the slowest material and were also able to determine the boundaries with the greatest velocity differences. Secondly, using the video panel and a table of common rock velocities, they were asked to estimate the total vertical height of the model. All students estimated this to within 12 percent of the correct value.

We observed that the video panel was an important element aiding usability and visualisation. Also, superimposing the layers of the model aided the examination of seismic wave propagation. Once the students could see the underlying layers, the more complex interactions became intuitive. On the whole, the animation appears to be a useful aid in explaining the general physics of wave propagation and seismology to students.

DISCUSSION

It is not the aim of this project to provide a comprehensive geological modelling system. Instead, we offer one solution to a particular type of problem: a technique for building and validating models of complex localised geological structures. From this work, we believe important lessons can be drawn that may affect future studies in this area.

COMPARISONS TO RELATED WORK

Our system and the mainstream mining and modelling packages target distinctly different problem areas. In general, the commercial mining packages work with large amounts of densely sampled data and create models of familiar structures, normally using interpolation techniques. We are more interested in modelling localised geological structures where less information is available and the input and interpretation of the geologist is critical. We therefore subscribe to the same philosophies as *Noddy* and the AGCRC.

Because we have integrated structural and geophysical constraints in a forward modelling system, our project has many similarities to *Noddy*. Indeed, we believe that *Noddy* and SME may complement each other very well when considering structures such as Vredefort. SME could easily be extended to incorporate some of the geophysical modelling capabilities of *Noddy*, but it may be better to use these systems together, thereby harnessing their combined strengths.

It is encouraging to note that *Noddy* has also been used in the teaching of geo-science concepts. In particular, it has been used to show the interaction of geological formations in 3-D and the relationship between geophysical data and the geological origins of the structure [Giero *et al*, 1993]. We believe that SME will provide similar benefits in the teaching of geology and geophysics. The results of our user testing indicate its educational potential. SME could also be used to demonstrate the seismic responses resulting from different structures and varying source characteristics. This information could aid interpretations of real seismic sections.

Despite the many similarities to *Noddy*, there are several important differences. The most obvious of these is the method of model construction. SME enables the user to directly manipulate the model using interactive construction tools. Shapes that cannot be described by the deformations provided by *Noddy* could still be constructed using SME. The other major difference is the use of synthetic seismograms instead of gravity and magnetic responses for model validation. The potential field responses produced by *Noddy* map the underlying properties of the structure to a 2-D image. Interpretations made from these mappings must consider their inherent ambiguities. The seismic sections produced by SME will give depth information to the user. Here too lie ambiguities that limit the resulting interpretations, but they are of a different nature.

LIMITATIONS AND FUTURE WORK

To improve SME's modelling capability, more sophisticated modelling tools must be supported. Functionality to model and integrate different geological entities would be particularly beneficial. At the moment it is difficult, perhaps impossible, to accurately model faults and certain other geological formations.

The current version of SME generates only raw seismic data. To improve interpretation, this data could be processed using stacking and migration algorithms. This would allow direct comparison to seismic sections used in practice. In addition, exporting and importing modelling and geophysical data would allow the system to interact with similar packages. Importing real seismic data would aid the comparison between real and synthetic seismograms and therefore improve the validation process.

Presently, the geological layers modelled using SME are completely homogeneous with respect to density and velocity. It would be useful to allow variations of these properties within each layer. It is also important that each layer following the same trajectory be connected. That is, they should share a single surface acting as an interface between them - there should be no "gaps" between layers. Although our software does try to connect adjacent layers, this has not always been successful.

The model validation could be further improved through the incorporation of alternative techniques such as gravity and magnetic analysis. Our choice of seismic analysis was only the most logical first step - there is no reason why potential field data cannot be included in the validation process. Future versions of SME will hopefully incorporate these methods to provide a more complete and accurate modelling tool.

COMBINATIONS

As this field of research grows, there is potential for an integration of modelling and visualisation techniques and the establishment of common standards [Hobbs & Henley, 1995; Cox *et al*, 1997]. Already, many projects are aimed at providing specific solutions for niche problems that are not catered for by the larger commercial modelling systems. These projects attempt to supplement, not replace, the work already achieved by other groups. This is how we see the future development of SME. We believe there is potential for using our methods in combination with other tools in order to construct and validate complex models. For example, a model of Vredefort built in SME could be converted to a voxel model and imported into Noddy for faulting and intrusions. The geophysical data produced could be used, along with the synthetic seismograms created by SME, for validation.

CONCLUSIONS

We believe that SME offers an innovative approach to validating geological models: it provides a user-driven modelling methodology and interactive construction techniques guided by an iterative validation process. Furthermore, we believe that there are valuable lessons to be learnt from this type of investigation – both in understanding the modelled structures and in developing new modelling techniques.

Testing and feedback revealed SME to be highly promising in satisfying the requirements of flexibility, efficiency and effectiveness. It also compares favourably with customary construction techniques. Results indicate that the visualisation features effectively aid the user in understanding model attributes and seismic data and thus show that SME could be beneficial in the education and visualisation of geoscience concepts.

SME is a flexible, interactive modelling tool and its iterative approach is well suited to forward modelling applications. Although we were able to successfully model the Vredefort structure using SME, more work is required to make it a robust research tool. In the previous section we described SME's limitations and our plans for future work in detail. These issues will be explored further in an ongoing refinement of the software. The present status of the SME project can be accessed through the internet at http://www.uct.ac.za/depts/cigces/visual.htm.

ACKNOWLEDGEMENTS

The paper benefited considerably from the constructive criticism of two anonymous referees. We would also like to thank the NRF (National Research Foundation of South Africa) and the Council of Geoscience for financial support.

REFERENCES

Bloomenthal, J., 1990. Calculation of reference frames along a space curve. In: A.S. Glassner (ed), Graphics Gems, Chapter 10: Modeling and Transformations. Academic Press, Boston, MA, pp. 567-571.

Bronsvoort, W.F., 1990. Direct Display Algorithms for Solid Modelling. Unpublished PhD thesis. Delft University of Technology, the Netherlands, 77 pp.

Cox, S., D. Watson, P. Hornby & C. Gunn, 1997. 3-D complex geology modelling. In: Abstracts, Geodynamics and Ore Deposits Conference. Australian Geodynamics Cooperative Research Centre, Ballarat, Victoria, pp. 76-79. (Available: http://www.-agcrc.csiro.au/publications/9697/agso/a206.html)

Durrheim, R., 1986. Recent reflection seismic developments in the Witwatersrand basin. In: M. Barazangi & L. Brown (eds), Reflection Seismology: a Global Perspective. American Geophysical Union, Geodynamics Series 13:77-83.

Farrell, S.M., M.W. Jessell & T.D. Barr, 1996. Inversion of geological and geophysical data sets using genetic algorithms. Society of Exploration Geophysicists International Exposition and 66th Annual Meeting, Denver, Colorado, 10-15 November 1996, Expanded Abstracts, Volume 2, pp. 1404-1406. (Available: http://www.agcrc.csiro.au/publications/9697/monash/a117.html)

Foley, J., A. van Dam, S. Feiner & J. Hughes, 1990. Computer Graphics: Principles and Practice (2nd edn). Systems Programming Series. Addison Wesley, Reading, MA, 540 pp.

Gibson, R.L., W.U. Reimold, & G. Stevens, 1988. Thermal-metamorphic signature of an impact event in the Vredefort Dome, South Africa. Geology 26: 787-790.

Giero, A.A., M.W. Jessell, M.W. Valenta, G. Jung & J.P. Cull, 1993. Geological and geophysical modelling in the classroom. Australian Educational Computing 8: 109-112.

gOcad, 1999. Association Scientifique pour la Geologie et ses Applications (ASGA), ENSG, Nancy. http://www.ensg.u-nancy.fr/GOCAD/

Hart, R.J., M.A.G. Andreoli & M. Tredoux, 1990. Geochemistry across an exposed seduction of Archean crust at Vredefort, South Africa, with implications for mid-crustal discontinuities. Chemical Geology 82: 21-50.

Hart, R.J., M.A.G Andreoli, W.U. Reimold & M. Tredoux, 1991. Aspects of the dynamic and thermal metamorphic history of the Vredefort crypto-explosion structure: implications for its origin. Tectonophysics 192: 313-331.

Hobbs, B.E. & S. Henley, 1995. Computing for the exploration and mining industries to the year 2000. APCOM XXV Conference No. 4/95, Australasian Institute of Mining and Metallurgy. Australasian Institute of Mining and Metallurgy Publications Series, Brisbane, Qld, 586 pp.(Available: http://www.ned.-dem.csiro.au/research/ visualisation/ papers/ hh.html)

Hornby, P., 1999. 3-D complex geology modelling. http://www.agcrc.csiro.au/projects/3046CO/index.html

Houlding, S.W., 1994. 3-D Geoscience Modeling: Computer Techniques for Geological Characterisation. Springer-Verlag, Berlin, 309 pp.

Jessell, M.W. & R.K. Valenta, 1996. Structural geophysics: integrated structural and geophysical modelling. In: D.G. DePaor (ed), Structural Geology and Personal Computers. Elsevier Science Publishers, Amsterdam, pp. 303-324.

Lin, T., M.O. Ward, W.L. Power & D.M. Landy, 1995. From databases to visualisation – providing a user friendly visual environment for creating 3-D solid geology models. APCOM XXV Conference No. 4/95. Australasian Institute of Mining and Metallurgy Publications Series. Australasian Institute of Mining and Metallurgy, Brisbane, Qld, 586 pp. (Available: http://www.ned.dem.csiro.au/research/ visualisation/ papers/ lin.html)

McClay, K., 1987. The Mapping Of Geological Structures. Geological Society of London. Open University Press, London, 161 pp.

Power, W.L., P. Lamb & F.G. Horowitz, 1995. From databases to visualisation – data transfer standards and data structures for 3-D geological modelling. APCOM XXV Conference No. 4/95. Australasian Institute of Mining and Metallurgy Publications Series. Australasian Institute of Mining and Metallurgy, Brisbane, Qld, pp. 65-70. (Available: http://www.ned.dem.csiro.au/research/ visualisation/ papers/ power.html) Regi, 1999. http://www.agcrc.csiro.au/projects/3046CO/regi/index.html

Reshef, M. & D. Kosloff, 1985. Applications of elastic forward modelling to seismic interpretation. Geophysics 50: 1266-1272.

Sims, D.L., 1992. Applications of 3-D geoscientific modelling for hydrocarbon exploration. In: A.K. Turner (ed), Three Dimensional Modelling with Geoscientific Information Systems. Series C: Mathematical and Physical Sciences, Volume 354. Kluwer Academic Publishers, Dordrecht, pp. 285-289.

Tredoux, M., R.J. Hart, R.W. Carlson & S.B. Shirey, 1999. Ultramafic rocks at the centre of the Vredefort structure: further evidence for the crust-on-edge model. Geology 27: 923-926.

Turner, A.K., 1992. Application of 3-D geoscientific mapping and modelling systems to hydro-geological studies. In: A. K. Turner (ed), Three Dimensional Modelling with Geoscientific Information Systems, Series C: Mathematical and Physical Sciences, Volume 354. Kluwer Academic Publishers, Dordrecht, pp. 327-364.

van Mount, S. 1990. A forward modelling strategy for balancing cross sections. American Association Petroleum Geology Bulletin 74:521-531.

Vidale, J. & D. Helmberger, 1988. Elastic Finite Difference Modelling of the 1971 San Fernando, California, earthquake. Bulletin of the Seismological Society of America 78: 122-141.

Watson, D.F., 1997. Finding non-convex hulls. Abstracts, Geodynamics and Ore Deposits Conference. Australian Geodynamics Cooperative Research Centre, Ballarat, Victoria, p. 101. (Available: http://www.agcrc.csiro.au/publications/9697/csiro/a230.html)

White, D. & A. Boland, 1992. A comparison of forward modelling and inversion of seismic first arrivals over the Kapuskasing Uplift. Bulletin of the Seismological Society of America 82: 304-322.

RESUME

Au début les techniques géologiques de modélisation et de visualisation étaient limitées à des coupes transversales manuelles ou des perspectives isométriques. La modélisation par ordinateur a automatisé cette tâche jusqu'à un certain degré, mais les approches traditionnelles ne permettent pas une validation itérative durant le procédé de modélisation. Quand la structure est complexe et les données éparses, comme c'est souvent le cas en géologie, des techniques interactives de modélisation 3-D devraient être utilisées ; celles-ci permettent d'interroger des données nouvelles et des données existantes, guidé par l'expérience géologique du modeleur. Utilisant le dôme de Vredefort en Afrique du Sud comme étude de cas, nous décrivons un environnement de modélisation sismique (EMS) pour démontrer le potentiel de ce type de modélisation et de visualisation géologique sur ordinateur. EMS offre une nouvelle approche pour une modélisation interactive 3-D de structures géologiques complexes utilisant une extension de représentations par balayage et de modélisation progressive contrôlée par l'utilisateur avec analyse sismique pour validation. Une incorporation de techniques de validation permet très tôt la confirmation ou le rejet des modèles. Testée par un groupe d'étudiants en géologie de troisième année, la construction et l'exploration d'un modèle 3-D du EMS fournit clairement aux utilisateurs une compréhension supérieure grâce à la visualisation. EMS offre donc un potentiel à la fois comme outil d'enseignement et de recherche.

RESUMEN

Inicialmente, las técnicas de modelización y visualización en geología se limitaban a producir manualmente cortes transversales o perspectivas isométricas. La modelización por ordenador automatizó estas tareas hasta un cierto punto, pero los enfoques tradicionales no permiten la validación iterativa durante el proceso de modelización. Cuando la estructura es compleja y los datos son pocos, como es frecuentemente el caso en geología, debería emplearse técnicas interactivas de modelización tri-dimensional, capaces de extraer información a partir de datos existentes y nuevos, bajo el control de la experiencia geológica del modelador. Utilizando el domo de Vredefort en Africa del Sur como estudio de caso, se describe un contexto de modelización sísmica (SME para Seismic Modelling Environment), para demostrar el potencial de este tipo de modelización y visualización geológica por ordenador. SME ofrece un enfoque original para la modelización tri-dimensional interactiva de estructuras geológicas complejas, mediante una extensión de las representaciones de barrido y la modelización prospectiva controlada por el usuario, en combinación con el análisis sísmico para la validación. La incorporación de técnicas de validación permite confirmar o rechazar los modelos en tiempo oportuno. La construcción y exploración iterativa de un modelo tri-dimensional en el contexto de SME fueron ensayadas con un grupo de estudiantes de geología de tercer año, lo cual suministró claramente a los usuarios una comprensión más profunda gracias a la visualización. Por lo tanto, SME es un instrumento que tiene potencial tanto en educación como en investigación.