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SCIENTIFIC VISUALIZATION FOR ENHANCED INTERPRETATION AND COMMUNICATION OF GEOSCIENTIFIC INFORMATION

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ABSTRACT

Ontario Power Generation's Deep Geologic Repository Technology Program has undertaken applied research into the application of scientific visualization technologies to: i) improve the interpretation and synthesis of complex geoscientific field data; ii) facilitate the development of defensible conceptual site descriptive models; and iii) enhance communication between multi-disciplinary site investigation teams and other stakeholders. Two scientific visualization projects are summarized that benefited from the use of the Gocad earth modelling software and were supported by an immersive virtual reality laboratory: i) the Moderately Fractured Rock experiment at the 125,000 m^3 block scale; and ii) the Sub-regional Flow System Modelling Project at the 100 km^2 scale.

I. INTRODUCTION

Modern geoscientific programs can generate very large and complex data sets given the sophistication of site investigation and monitoring methods used to undertake surface and subsurface characterization and to measure geosphere responses. Examples of such investigation and monitoring methods include remote sensing (Landsat, Radarsat, aerial photography), airborne geophysics (magnetic and electromagnetic surveys), surveying and geologic mapping (overburden, bedrock lithology, fracture geometry), surface geophysics (gravity, resistivity, radar, seismic surveys), borehole drilling and logging, hydraulic testing, hydrogeochemical sampling, seismic monitoring, stress measurements and many more. [1]

These modern data sets are acquired for the purpose of developing a conceptual descriptive model, which in many cases is then used to develop numerical models for the purpose of simulating geosphere responses to an array of future conditions and/or to further the understanding of past conditions that have influenced present day site characteristics. Examples of such numerical simulations include geosphere responses to mine and pit excavations, oil and groundwater extraction, waste disposal, civil construction, and seismic events. Increases in computing power and the concomitant increases in numerical model complexities also results in the generation of very large, simulated data sets that often represent transient geosphere behaviour. The availability of these large, measured and simulated data sets does not necessarily make the development of a conceptual geosphere model any easier. One example is from the oil exploration industry, where up to 95% of the 3D seismic data, collected at a cost of millions of dollars, was not interpreted because there was simply too much data to analyze.[2] In this example, it was recognized that the key to rapid and improved interpretation was to visualize only the data that was petrologically important and therefore design methods were needed that combined 3D seismic data, underlying geology and formation fluid characteristics.

The synthesis, analysis and communication of large and complex site characterization and numerical simulation data sets now require the implementation of sophisticated scientific visualization techniques. For the geoscientist, these techniques have firmly emerged as powerful tools in the evaluation and processing of volumetric data, such as 3D seismic in the oil industry [2], and in facilitating data fusion to enhance exploration drill hole targeting [3] and streamline the mine planning and design process. [4] One of the key aspects of these technologies is the use of computers coupled with sophisticated visualization software to enhance the powerful pattern recognition capabilities of the human eye and brain combined, for example when data are presented as moving images. A second aspect is the development and use of large-scale visualization systems that promote collaboration between multi-disciplinary teams, who can simultaneously view and work with large volumes of 3D data. Such an approach helps ensure that the maximum value has been extracted from the application of modern investigation and simulation methodologies for the benefit of developing defensible and transparent conceptual site descriptive models. Of equal importance is the benefit that scientific visualization tools can bring to quickly and confidently communicate the nature and quality of geoscientific data and models to non-specialized project stakeholders.

It is within this context that Ontario Power Generation's Deep Geologic Repository Technology Program (DGRTP), in collaboration with MIRARCO-Mining Innovation of Sudbury, has been undertaking applied research into the application of scientific visualization technologies for the purpose of improving the interpretation and synthesis of field data, the development of defensible conceptual descriptive models and the communication between multi-disciplinary site investigation teams and other stakeholders. This paper will introduce the scientific visualization tools being applied within the DGRTP and will summarize on-going and recently completed visualization work programs that have used both measured and modelled data from the site scale to the sub-regional scale.

II. BACKGROUND

One approach being considered for the long-term management of nuclear fuel waste in Canada is a Deep Geologic Repository (DGR). As described by McMurry et al. [5], this approach involves sealing the used nuclear fuel in durable metal containers, which are then placed in an engineered repository constructed deep in stable crystalline rock of the Canadian Shield. A clay buffer material would surround each container, and backfill material and other seals would close off the emplacement rooms. Rock and groundwater conditions surrounding the repository would provide for stable mechanical and chemical conditions that would further promote waste containment. Such a repository system, based on multiple engineered and natural barriers, would maintain long-term safety for humans and the environment far into the future.

Building confidence in the safety assessment predictions for a nuclear fuel waste DGR is partly a function of the confidence in the conceptual site descriptive model and the associated geosphere performance assessment (PA) that underpins the safety assessment. In 1998, a federal Environmental Assessment Panel (EAP) responded [6] to Atomic Energy of Canada Ltd's (AECL) 1994 Environmental Impact Statement (EIS) and 1996 Second Case Study (SCS) on the proposed concept for long-term management of Canada's nuclear fuel waste. [7,8] Jensen and Goodwin [9], in their review of the EAP response, highlighted four geoscience issues that would have to be addressed to improve confidence in geosphere PA methodologies. These four issues include: i) verification of abstracted geosphere PA models; ii) methods for dealing with conceptual flow model uncertainty; iii) the linkage between detailed geosphere models and integrated performance assessment models; and iv) transparency and traceability in the geosphere PA process. The development and use of scientific visualization tools, from 3D earth modelling software to large-scale visualization systems, are important elements of a strategy for building confidence in geosphere performance assessment models.

The use of scientific visualization tools is particularly important in the case of a performance assessment in the crystalline rocks of the Canadian Shield, where fractures are the main pathways for water movement and contaminant transport. Groundwater movement may occur in single fractures or in complex, three-dimensional, networks of fractures and will be a function of the magnitude of hydraulic gradients and the presence of flow boundary conditions. [5] Natural fracture networks have been shown in field studies to be characterized by a wide range of scales, from the millimetre to the kilometre scale, and to exhibit fractal correlations between fractures. [10] The presence of this multi-scale heterogeneity adds a significant complicating factor in the assignment of flow and transport properties to numerical models used in simulating the advective, dispersive and diffusive processes that control transport. Various models, based on single continuum, double porosity, double permeability, stochastic continuum, and/or discrete fracture network conceptualizations have been developed and applied to fractured rocks, according to different simulation strategies. In any approach, the characterization and generation of heterogeneous spatial patterns of hydraulic property fields (e.g., hydraulic conductivity, effective porosity, dispersivity, sorption/reaction properties, etc.) is a crucial step for modelling flow and transport, and the success of the model relies on how closely it mimics the actual system heterogeneity [11], both geologically and hydrologically.

One approach to increasing confidence in such models is through the use of scientific visualization tools that provide: 1) a demonstrated approach that the descriptive model characteristics are a direct function of the proper interpretation of measured field data; 2) a demonstrated approach that these model characteristics are supported by multidisciplinary data sets and multiple lines of reasoning; and 3) a demonstrated linkage between numerical model simulation results and measured geosphere response constraints.

The visualization case studies described in this paper made use of large and complex data sets generated as part of the DGRTP's Moderately Fractured Rock experiment and the Sub-regional Modelling Study. The benefits of enhanced interpretation and communication through the application of scientific visualization tools will be discussed. In both cases, the Gocad earth modelling software served as the platform for integration and analysis of large, complex, geoscientific data sets and MIRARCO's Virtual Reality Laboratory further facilitated their interpretation and communication to multi-disciplinary task force members.

II.A. Gocad

As part of the work programs described in this paper, MIRARCO made use of the Gocad earth modelling software platform (see www.mirageoscience.com or www.earthdecision.com for further information), "which allows the mapping of all data to a single, world coordinate system. Gocad's object model provides the means of mapping any scalar or vectorial data value to any point in this world coordinate system. This greatly simplifies the integration of data from multiple sources: lithological, geological, hydrological, geometric, seismic, etc.. Data fusion occurs when the software's scripting language queries and mathematically processes the data. This fusion provides a new view of existing data, identifying hidden relationships or allowing the discovery and explanation of complex data interdependencies." [4] Although lacking the important element of 3D visualization, example snapshots of Gocad common earth models developed for these DGRTP work programs are provided in coming sections.

II.B. Virtual Reality Laboratory (VRL)

The late 1990's saw a growing acceptance in the oil and gas exploration industry of the use of large collaborative and semi-immersive visualization systems such as large flat screens, curved screen theatres, and fully immersive CAVEs (CAVE Automatic Virtual Environment). [3] Benefits to the oil and gas industry of fully immersive tracked environments were listed as: geometric accuracy of displayed data, full immersion and wide field of view, moderate numbers of viewers/collaborators and 3D interaction and editing of data. In 2001, Laurentian University in Sudbury, Ontario, opened an immersive virtual reality laboratory as part of the Centre for Integrated Monitoring Technology (CIMTEC). This facility, operated by MIRARCO-Mining Innovation, was primarily designed to bring the benefits of immersive visualization and multi-disciplinary collaboration to the mineral exploration and mining industries. [4] The VRL, shown in Figure 1, in combination with advanced earth modelling software, projects three dimensional, dynamic images onto a 9 x 22 foot, curved screen, providing up to 20 persons in the theater with the sense of being immersed in their mine design, geology, geochemistry and geomechanics data sets. Key benefits to mine design of immersive 3D visualization within the VRL were listed as: data fusion, knowledge transfer, technical conflict resolution and collaboration.

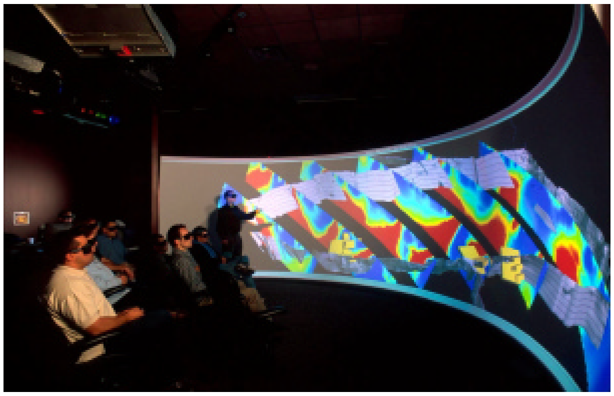


Figure 1: View of MIRARCO virtual reality laboratory showing collaborative session (courtesy of Falconbridge)

III. MODERATELY FRACTURED ROCK EXPERIMENT

The Moderately Fractured Rock (MFR) experiment was undertaken at the 240-m level of AECL's Underground Research Laboratory (URL) located within the Lac du Bonnet batholith near Pinawa, Manitoba (Figure 2). Site characterization and modelling activities produced a data set that was both complex and multi-disciplinary combining observational, modelled and interpreted data for a 125,000 m^3 block of fractured plutonic rock. The observational and interpreted MFR data sets included bedrock lithology, fracture geometry, borehole radar and permeability for a network of 16 boreholes extending to lengths of 250 metres.

Figure 3a illustrates the MFR borehole network, which included four boreholes drilled from the 130-m level and the remainder from the 240-m level of the URL. Figure 3b is an idealized representation of the 1781 fractures logged in the 16 boreholes.

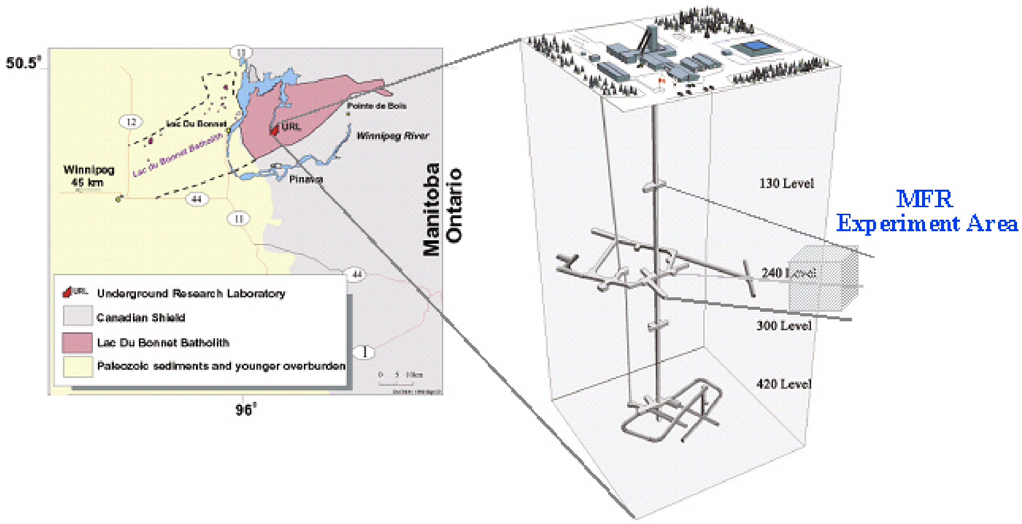


Figure 2: Location of Lac du Bonnet Batholith, Underground Research Laboratory and the MFR experiment area [11]

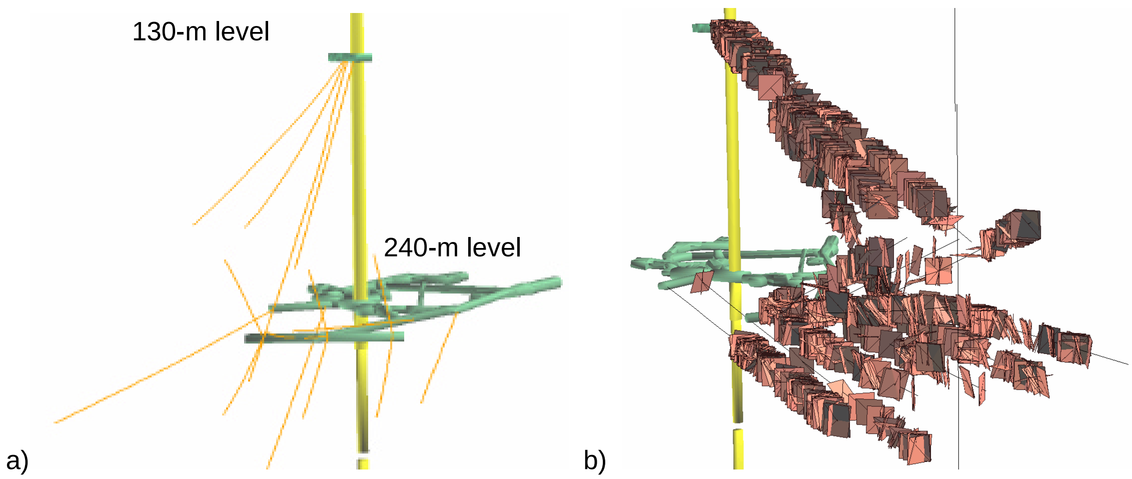


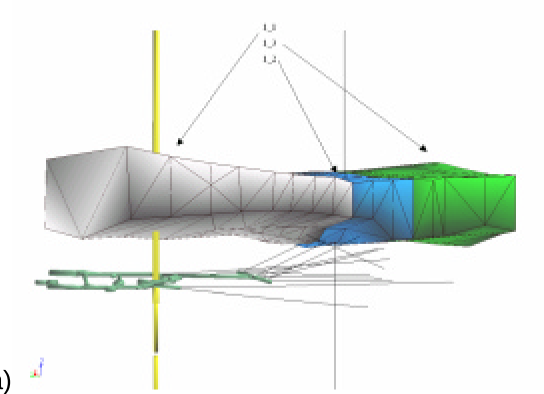
Figure 3: a) View of MFR borehole network with URL shaft and excavations; and b) graphical representation of 1781 logged fractures idealized as 10m x 10m planes

The primary purpose of the MFR experiments was to demonstrate numerical modelling capabilities and assess the validity of the Equivalent Porous Media (EPM) approximation. Further, the experiments were used to estimate values of effective geosphere transport properties and the uncertainty in their values, which is a critical issue associated with justification of parameter inputs to simplified performance assessment models. Even though the MFR experiment was at the small scale, it incorporated many of the tasks that would be faced by a DGR site characterization team: 1) validating and integrating the complex, multi-disciplinary data into a common interpretive platform; 2) interpreting and querying the data set to look for the presence, absence or coincidence of important features that would form the basis for a conceptual descriptive model; 3) communicating the characteristics and uncertainty in the conceptual model to members of a numerical modelling task force charged with planning and undertaking additional activities, such as hydraulic and tracer tests and associated flow and transport simulations; and 4) iterative refinement of the conceptual model based on a clear understanding of the 3-dimensional, spatially coincident, measured and simulated domain responses. These tasks were facilitated through the use of the Gocad earth modelling software, the development of project-specific software plug-ins, the application of 3D GIS-type (Geographic Information System) queries and MIRARCO's immersive Virtual Reality Laboratory[12] where the 3D data could be viewed with a true sense of depth and spatial relationship.

III.A. 3D Data Queries

A powerful scientific visualization methodology involved the use of 3D GIS-type queries that interrogated the large data sets for the purpose of visualizing the spatial distribution of regions within the modelled domain that exhibited certain characteristics considered important in controlling geosphere response. Investigation of relationships within the complex MFR fracture data sets, shown in Figure 3b, also benefited from the development of a Gocad plug-in that converted complex 3D views of selected portions of the fracture network into a more traditional, and familiar, 2D, stereonet-based visualization (Gonet)[12] . Another key fracture visualization tool, developed as a Gocad plug-in, was a fracture plane creator, which provided the following added functionalities: i) representing fractures as idealized planes with assigned heights and widths, as in Figure 3b; ii) colour-coding fractures based on linked attributes such as orientation, infilling, aperture, permeability; and 3) displaying fractures only captured within specific regions of the model, such as geologic subdomains and packer intervals.

An example application of the above scientific visualization tools to undertake a detailed investigation of the MFR data sets follows. Figure 4a illustrates a portion of the MFR Gocad model referred to as fracture domain B1. This subdivision of the MFR experiment area was presented as part of the development of a geological model that would support flow and transport modelling based on the EPM approximation[13]. The geometry of fracture domain B1 was defined primarily by a fractured and pervasively altered granite immediately beneath a fracture zone. A clear representation of fracture orientations within the domain would provide some support to numerical modellers regarding the potential nature of anisotropy in hydraulic conductivity that would have to be incorporated into their EPM model. The stereonet-based visualization of fracture orientations (poles to planes), as output from the Gonet plug-in, is shown in Figure 4b. This stereonet plot indicates that most 774 logged fractures in domain B1 are sub-vertical with generally two preferred orientations: northeast and mostly northwest.



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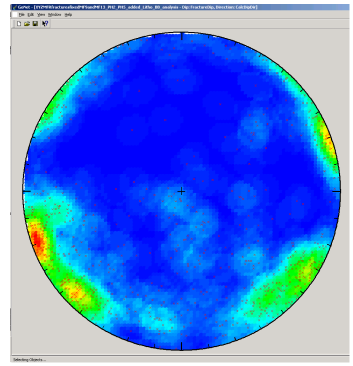
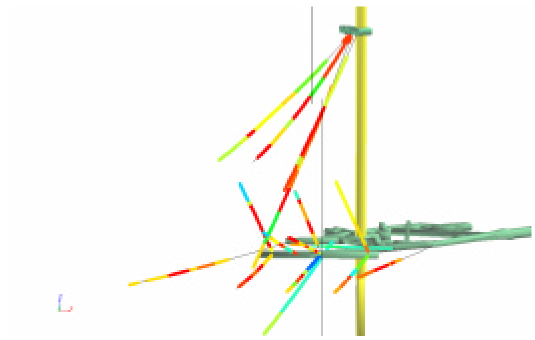


b)

Figure 4: a) MFR domain B1; and b) colour-contoured, equal area, stereonet plot of poles to all fractures within B1

To further examine anisotropy in the hydraulic conductivity field of the MFR domain, MIRARCO undertook an illustrative case study that coupled the results of a 3D stress model for the URL with the fracture orientation data from the MFR boreholes.[14] This case study incorporated a methodology for identifying whether fractures were favourably orientated for dilation or slip-failure and would therefore be considered “critically-stressed” in terms of their potential for enhanced permeability. When applied to fracture domain B1, this methodology identified 49 out of the 774 fractures to be “critically-stressed”, most being sub-horizontal. The Gocad common earth model further permitted a comparison between permeability estimates obtained from a packer interval hydraulic test database (Figure 5a) and the critically-stressed fractures. Figure 5b illustrates the location and orientation of the critically-stressed fractures from domain B1, painted by permeability (log k) from Figure 5a. The majority of the critically-stressed fractures were subhorizontal and associated with interval permeabilities at the high end of the measured range (log k > 10^{-17} m^2). This combined view of various dimensions of data (fracture orientation, fracture location, dilation/slip tendency and permeability) is a good example of the application of scientific visualization tools for the detailed analysis of complex, multi-disciplinary data sets for the purpose of enhancing conceptual site model development.



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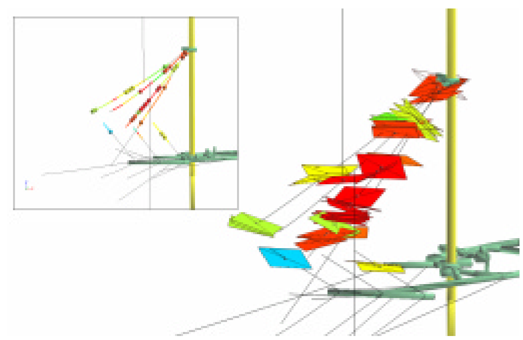

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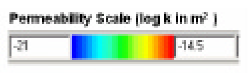

Figure 5: MFR borehole network: a) borehole packer intervals painted by log permeability estimated from hydraulic tests; and b) critically-stressed, B1 fractures painted by log permeabilities from a)

III.B. 5D Visualization

Another key scientific visualization tool that can further add value to the development of a defensible conceptual descriptive model is the use of 5D animation (x, y, z, time and drawdown/concentration) where measured, interpreted and modelled domain responses can be viewed and compared within a single coordinate system. This capability was developed by MIRARCO as a series of Gocad plug-ins for object and property sequence viewing. Three MFR modelling teams, who had independently developed and parameterized alternate 3D models of the MFR domain using aspects of the geological model[13] and results from hydraulic and tracer tests, were asked to simulate one of the MFR's constant rate withdrawal tests (the 14-day, PT4). Simulated drawdowns for specific time steps from all three model grids were imported into the single, world coordinate system of the Gocad model and compared using the 5D animation tools in the immersive VRL. Not only could the simulated drawdowns from the three models be compared to each other for each time step, but they could also be compared to the actual measured drawdowns from PT4, which had been mapped onto the corresponding MFR borehole intervals. For illustrative purposes, snapshots of the measured and modelled drawdowns are shown in Figure 6 at 10 days following the start of the withdrawal test.

In comparing the 3 simulations of PT4 to one another, the most notable difference was in the size of the drawdown iso-surfaces. The horizontal response, as measured across the bottom of the MFR domain (Figure 6d), was also absent in all models. Models 1 and 3 (Figure 6a and Figure 6c) apparently exhibited much less drawdown than measured. The distribution of drawdown in Model 2 (Figure 6b) had a general magnitude similar to that measured, however the response was notably narrower. Recognizing these differences was greatly facilitated through the use of advanced visualization techniques and tools.

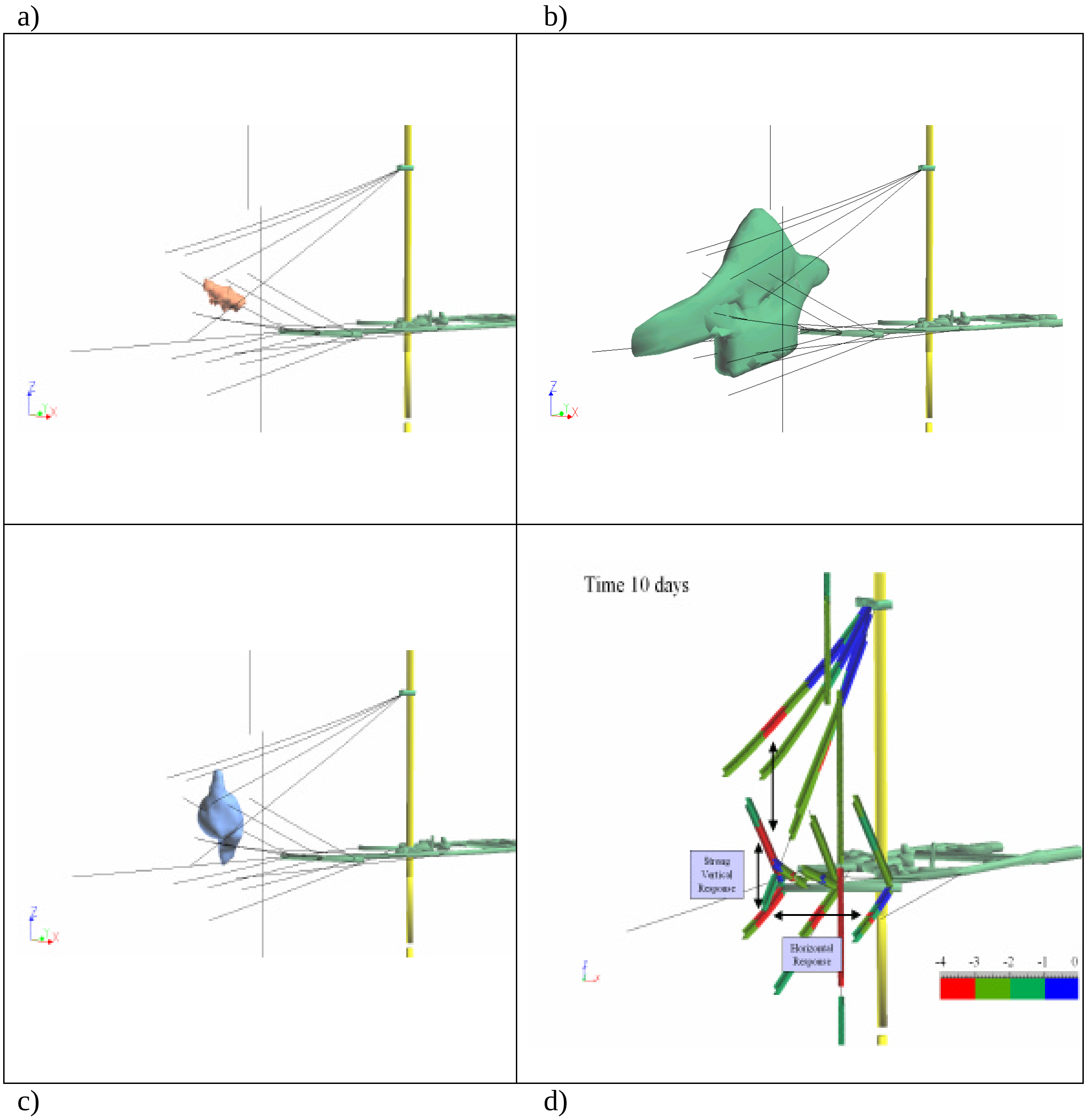

Figure 6: Modelled and measured drawdown for withdrawal test PT4 at 10 days: a) 3 m isosurface for Model 1; b) 3 m isosurface for Model 2; c) 3 m isosurface for Model 3; and d) measured hydraulic head response in borehole intervals (m). [Withdrawal interval located near left (west) side of MFR borehole network]

This approach, undertaken within an immersive virtual reality environment, and which allowed “the data to speak for themselves”, proved to be a powerful means for three separate numerical modelling teams to quickly examine the impact of alternate approaches to conceptualization and calibration of flow and transport models of the MFR domain, as well as to begin building consensus on the critical aspects of a conceptual site descriptive model.

IV. SUB-REGIONAL FLOW SYSTEM

A larger scale application of scientific visualization and virtual reality technologies is included in the DGRTP's Sub-regional Flow System Modelling project, which serves to apply and test non-invasive site characterization techniques, first-generation conceptual model development approaches and numerical flow simulation methodologies within a hypothetical, 100 km^2, Canadian Shield setting. One of the principal objectives of this study is to communicate, through visualization, how a sub-regional, Canadian Shield flow system could evolve through an entire glacial cycle; one glacial cycle is typically 120,000 years and could include several episodes of ice-sheet advance and retreat, bracketed by long, periods of peri-glacial conditions with extensive permafrost penetration. The impact of such extensive changes in surface boundary conditions on the performance of a DGR is being investigated through numerical modelling efforts supported by the application of scientific visualization technologies such as the VRL.

The conceptual site descriptive model for the hypothetical sub-region incorporates multiple geostatistical realizations of a Fracture Network Model (FNM) based on the interpretation of surface lineaments. [15] The use of scientific visualization tools facilitates the analysis, quality control and communication of the FNM generation process, the geometric complexity of the FNM realizations, the fidelity of these realizations to site surface features and to fracture propagation criteria, the nature of transient boundary conditions associated with long-term climate change, and the resulting simulations of flow system evolution. Figure 7 provides a series of snapshots that illustrate the surface constraints on the sub-regional, geostatistical fracture network model and the complexity of one example realization.

V. CONCLUSION

The use of proven scientific visualization technologies, along with the on-going development of new tools, has been demonstrated at both the local site scale (125000 m^3) and the sub-regional scale (~100 km^2 by 1.6 km depth) to greatly enhance the comprehension, interpretation and communication of the often complex relationships within and between extensive, multi-disciplinary, geoscientific data sets. These work programs are serving to demonstrate that scientific visualization tools and methodologies make a valuable contribution to the interpretation and communication of geoscientific information by:

- Serving as a platform for an electronic information database.
- Facilitating the integration, validation and interpretation of complex data sets.
- Providing a means for examining the credibility of site characterization and experimental findings.
- Improving communication consensus-building within a multi-disciplinary task force.
- Demonstrating an interface and feedback mechanism between site characterization activities and modelling.
- Establishing a transparent process from data acquisition to conceptual site model development.

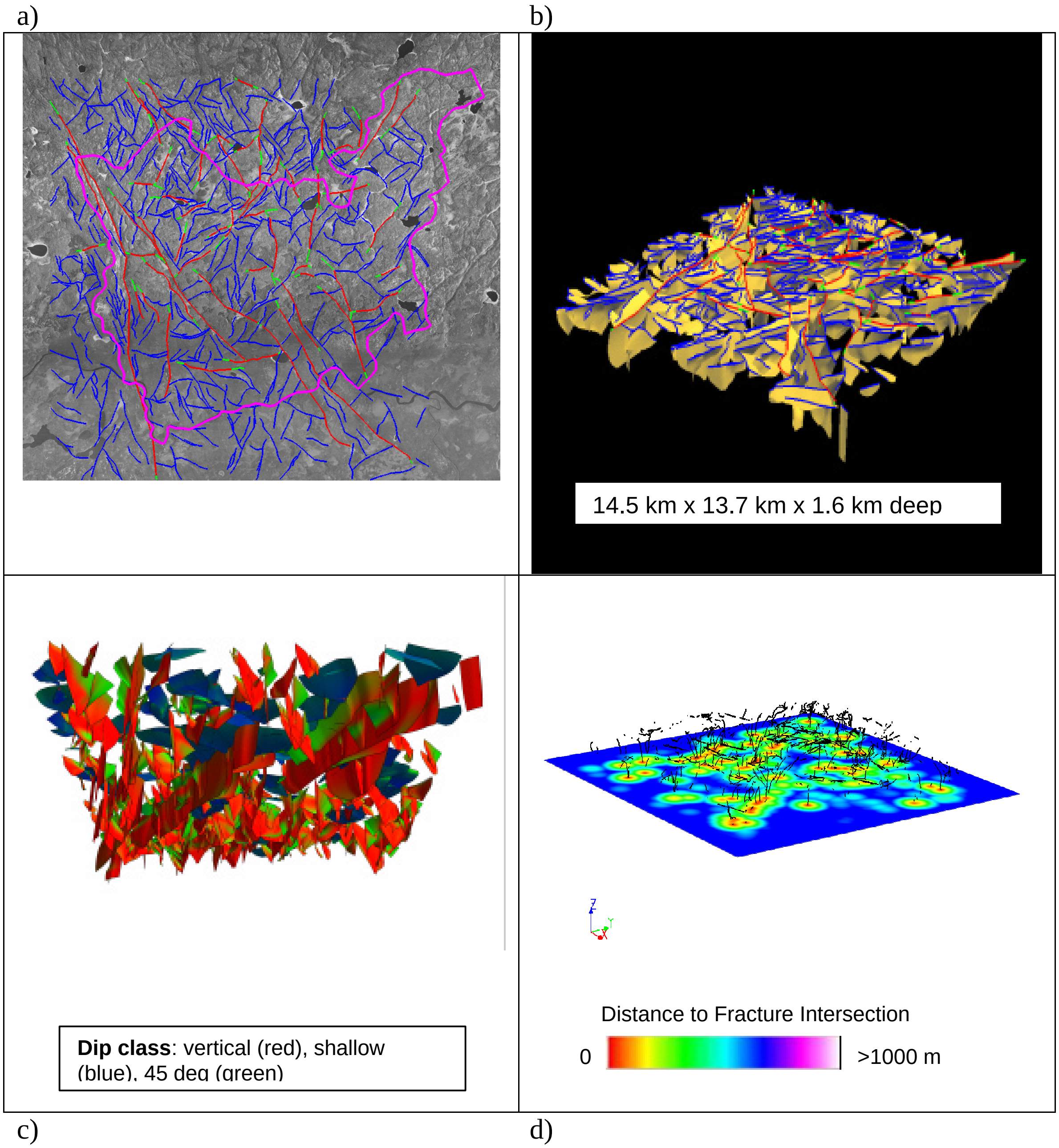

Figure 7: a) Sub-regional aerial photograph with deterministic lineaments (red), stochastic lineaments (blue) and flow model domain boundary (~100 km^2); b) 3D FNM realization constrained to surface lineaments; c) 3D FNM viewed from below and painted by dip class; d) Distance to fracture intersections (black segments) at mid-plane of model

The DGRTP has explored the application of visualization technologies, such as the Gocad earth modelling software and the immersive virtual reality laboratory, with the purpose of developing the necessary tools and methodologies to increase stakeholder confidence in geosphere performance assessments and associated safety assessments for a deep geologic repository.

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