Research to reality: Application of mining-induced seismic hazard maps.

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ABSTRACT: MIRARCO has pioneered the application of virtual reality technology for solving complex problems in the mining industry. Originally developed for use in the oil and gas industry, the technology is best suited for multidisciplinary evaluation of information at all the stages of the mining cycle. VR has proven to be beneficial in developing 3D geology models, planning exploration drilling and developing resource models. However, MIRARCO's work has demonstrated that it can also be extended to handle spatiotemporal data used for planning mine infrastructure, optimizing stope sequences and using mine monitoring data to understand how production practices impact the safety of the operation. The latter is particularly relevant to deep mining where rockbursts can have an adverse effect on both safety and the economic viability of the operation. Virtual Reality and visual interpretation is quickly shifting the data analysis paradigm for highly complex engineering problems, in this paper we focus on the development and application of the Seismic Excavation Hazard Maps for deep mines in the Canadian Shield. The technology was developed using virtual reality and scientific visualizations methods, thus it is only fitting that it be applied and used in its proper context – a large screen, immersive, stereoscopic virtual reality facility at the mine site.

1 INTRODUCTION

The Seismic Excavation Hazard Maps (SEHM) concept can be traced back to rockburst related research conducted in the 1990's in Canada (MRD, 1990-1995). While novel, the implementation of the concept was hampered by lack of suitable multi-dimensional analysis software and computational hardware to handle the large stress model and seismic datasets. With the current pace of technology development, the virtual reality (VR) developed technology will soon be available to the practitioner on the desktop. The importance is that the data processing and visualization methodology can be tested on a multi-disciplinary mine model prior to its evaluation in the collaborative, immersive virtual reality facility by a group of multi-disciplinary experts. In our experience, the VR facility itself is not a good working environment for individual practitioners who can be more productive using currently available 3D model building tools. The role of the VR facility is that of the data integration and visualization forum – it is not meant to replace the modeling tools, but to complement the analytical capability and to facilitate decision making at a much higher level. Its true benefit is realized when field observations are combined with the results of multiple models.

Proper use of VR and scientific visualization represents a fundamental paradigm shift in how we collect, store, process and interpret multi-terabyte datasets, formerly the domain of enterprise database managers. From an engineering practice perspective, the current paradigm shift from spreadsheet calculations (represented as graphs or charts) to an immersive, multi-dimensional representation where scientific visualization techniques provide the insight into the vast multi-disciplinary data sets is as evolutionary in its impact as was moving from the slide rule to the hand-held calculator, or subsequently, the move from the programmable hand-held calculator to the spreadsheet on personal-computers. The geoscientist and engineer (whether a rock mechanics practitioner or other specialist) now has a new tool in his/her arsenal to gain better insight into the complex world that is the rock mass.

This shift also provides an important opportunity. The calculator improved the speed and precision of arithmetic operations when compared to slide rules. The spreadsheet increased the complexity of the calculations and insured repeatability while increasing the amount of data that could be handled. VR and immersive projection systems not only allow very large datasets to be quickly assessed and explored, but also provide an increase in the dimension of the data that can be represented. When making a drawing we are projecting a 3D object onto the 2D plane of the paper.

Stereoscopic visualization adds a third dimension to this drawing space. The simple application of this technology is to use this additional dimension to project the missing spatial dimension, however, the real benefit of the technology is to use the third dimension as a projection of hyper-dimensions. This concept of hyper-dimensional projection is very well explained in a series of web videos (http://www.dimensions-math.org) or in Flatland (Abbott 1884), a book that Issaac Asimov described as "The best introduction one can find into the manner of perceiving dimensions".

1.1 *Mine Data*

The RAND report on the critical technologies for the mining industry (Peterson et al., 2001) recognizes that the knowledge management benefits of information technology (IT) will provide the greatest benefit to the industry. The report states that "although mine operations are generating more data, such information is rarely well utilized." The major challenge is first to separate the important information and only then decide on how to use it. It is the underlying principal that "Data is not as interesting as insight" (Peterson et al., 2001), that forms the basis for the new techniques in understanding the complexity of mining-induced seismicity hazards in the form of simplified, yet highly informative Seismic Excavation Hazard Maps.

Data in the spatiotemporal geographic information system (GIS) sense can be ordered into three main domains (Hogeweg, 2000); the spatial domain represents the physical location (in a defined coordinate system), the temporal when it occurs and the thematic, it has some characteristic properties (Figure 1). Data in each domain can be stored and analyzed independently, i.e., they can be stored in different tables in a relational database management system (RDBMS). However, it is more common to apply analytical techniques combining two domains as independent variables, e.g., the more common techniques applied to mining data in the data domain cube are:

- Geostatistics which uses the spatial and thematic domains.
- Animations to show changes to an object, generally movement or motion.
- Topological (relationship) changes over time
- Property and geometry variations with time.

True spatiotemporal analysis includes the dependency of all three domains. Mining-induced seismicity, by its nature, demonstrates this close dependency – location (event) is linked to the excavation of the rock mass and has characteristics of damage mechanism. The latter depends on stress changes, rock type and strength, various scales of structures and the mining history, amongst others. Therefore, spatiotemporal analysis techniques provide the best insight from the data. However, this is rarely done and examples quoting seismic clustering in the literature (Hudyma and Potvin, 2004, Lesniak and Isakow, 2009) only use the spatial and thematic domains to define the clusters. The latter authors use the term "space-time clusters", however time is used in the thematic sense as interval queries to the RDMS and, in fact, their clusters span the greater part of the data collection period.

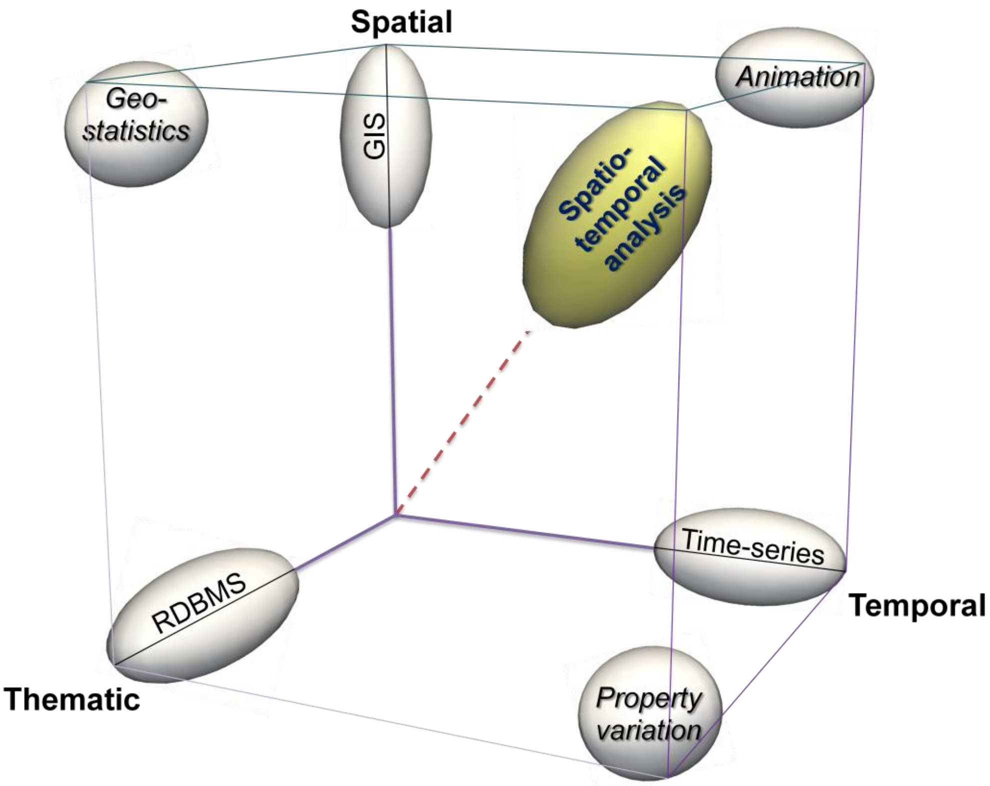

Figure 1. Spatiotemporal GIS information domain cube (modified after Hogeweg, 2000).

The clustering methodology developed and tested on deep-mine data in the Sudbury Basin extends the spatial seismic clustering methodology to true space-time (Oxford English Dictionary: "*n*. 1. *Physics*. Time and three-dimensional space regarded as fused in a four-dimensional continuum or manifold containing all events") by adding a scaled time component to the Squared Euclidean distance dissimilarity measure used in the agglomerative hierarchical clustering method determined (out of 100+ clustering methodologies and variations thereof) to be the best for our mining-induced microseismicity dataset. The reason for scaled time is obvious; the unit of measure for time is not compatible with space, also the results can vary drastically depending on whether time is recoded in units of minutes, hours, days or some other unit.

1.2 *Scientific and Information Visualization*

Modeling software also provides visualization capabilities, however, the advantage of scientific visualization is that it uses the geometric (easting, northing, elevation) data as a structural support for thematic (property) data. The goals between the modeling visualization and scientific visualization are also different; the former is used to create data/information, whereas the latter is used explore datasets to find new trends/knowledge. Most scientific visualization software relies on the concept of filters being applied to a dataset to extract or highlight knowledge. These filters can be connected into a visualization pipeline which, once correctly defined, can be applied to any number of datasets. This approach is particularly well suited when integrating data from multiple sources or when having to review multitudes of similar datasets.

Scientific Visualization relies more on the exploration of datasets that have been generated by simulation software whereas mining tends to rely on inferred datasets based on observational data. Examples of this type of inferred data are most exploration datasets where large volumes of space must be "defined" based on limited drill hole (or geophysical) datasets.

Another key difference lies in the use of the time as a fourth dimension. While many scientific fields of study model the change in a process or object over time, the modeling of time still remains rather limited in mining. Despite these fundamental differences both disciplines require a means of quickly identifying trends and anomalies. Relying on the human's visual analysis capability still remains one of the most effective means of identifying anomalies. Our goal is to develop alternative views of the world, in this case a virtual representation, to maximize the use of human perception and pattern recognition.

Information visualization attempts to visually identify trends in non-spatial data, often temporal data, relying heavily on data structures to store and query data information visualization abstracts location. An example of this type of encoding in mining would be the representation of all drifts and stopes in the mine as a series of networks with connectivity but without any geometry. Thus you could easily determine the shortest path from any stope to surface, and find the minimum length of drifting required to mine a zone. This type of relationship would provide a new level of parametric design capability for mining engineers, but far more importantly, it would remove many of the preconceived mine design notions inherent in our industry.

1.3 *Virtual Reality*

A number of mining researchers have applied principles of virtual reality to develop tactical applications such as safety training applications (Bise, 1997, Denby and Schofield, 1999a, 1999b Schofield, 2005) and line of sight for equipment design (Delabbio et al, 2003). These applications rely on the modeling of real objects such as tunnels and vehicles to improve the effectiveness of training. The foundational research work that MIRARCO is pursuing using virtual reality attempts to modify our perception of transient data to better understand the complex dynamics of deep mining. Using virtual reality as a means of improving the engineering process, MIRARCO has worked with leading mining companies to develop a unique approach to data integration, review and vesting. Collaborative Immersive Virtual Reality (Kaiser et al., 2002) has been used to:

- Improve the effectiveness of exploration projects
- Optimize location of drifts and cross cuts to minimize drift damage
- Optimize mining production sequences
- Develop underground support criteria
- Review underground planning and layout scenarios
- Review stress models
- Environmental assessment and flow modeling

This paper focuses on the innovations in engineering visualization techniques for mining-induced seismic research in an immersive, stereoscopic VR environment and how the research is adapted to an on-site VR facility at a deep operating mine in the Sudbury Basin.

2 INTEGRATED MULTI-DIMENSIONAL MODELS

The value of applying appropriate scientific visualization techniques in a virtual reality setting is highly dependent on the quality and continuity of data collected at the mine site. It is often taken for granted that data collected and models generated there from (in reality interpretations) conform to high standards. However, more often deficiencies and errors become glaringly apparent when visualized in a multi-dimensional platform and VR makes for an efficient first-pass quality control system. Improving data collection systems and applying strict quality control should be a continuing concern for all mining operations.

2.1 *Mine Map Overlays (MMO)*

“Mine map overlays for excavation performance assessment in burst-prone mines” is the concluding chapter in the Canadian Rockburst Support Handbook (Kaiser et al., 1996). Its primary objective was to provide a visualization tool to assess rockburst potential in seismically active areas of a mine. The procedure requires the following layers of information:

1. Mine stope and infrastructure layout (the geometry).
2. 3D geology model with UCS, elastic properties and density attributed to each unit
3. 3D elastic stress model (inputs from items 1 and 2 and site stress tensor).
4. Seismic record with calibrated scaling relationship for ground motion (ppv) estimation.
5. Support tables with peak load, ultimate displacement and total energy absorption capacity for support strength factor estimates (SF=capacity/demand).

Despite its comprehensive list of analyses, the MMO is highly reliant on the operator providing good quality 3D geological information and the availability of a properly sequenced 3D stress model, items that were not easily provided without considerable effort at that time.

However, with current 3D modeling, visualization and database technology, the listed items are more easily integrated into a mine geomechanics model. Examples of other geomechanics data analysis for underground excavation using VR are provided in Henning et al., 2003. The point is that each mine may have unique rock mechanics problems that may require various types of analyses generated by specialized software or interpretations generated by expert consultants often using simulations. We now have the technology to take the various sources and evaluate them in one common model. It is not sufficient to generate a report with tables and figures alone; the mine operator now requires the data, models and interpretations in a spatio-temporal GIS relational database format to allow the operator and experts to gain the required insight to make the proper high-level decisions to ensure safety and profitability of the operation.

2.2 *Geology models*

Building a proper 3D deposit model is a complex procedure that requires a multidisciplinary geosciences approach since large volumes of space must be interpreted or “filled-in” based on limited data (surface maps, drill holes, geophysics, geochemistry, etc). Knowledge and understanding of the deposit type, depositional environment, major orogenies and other factors leading to the current day ore distribution and structural geology provide guidelines to the experienced practitioner to build a proper site-specific 3D deposit model. Thurston et al. (2005) describe the modeling procedures and data treatment for the “Integrated 3D Geoscientific Deposit Modelling Project” for Canadian Shield lode gold and volcanogenic massive sulphide deposits in the Ontario portion of the Abitibi greenstone belt. For such a large undertaking, the Laurentian University VR laboratory was used for model validations by industry, consultants and academia.

The key point is that before we attempt to attribute geomechanical properties to the rock mass, we first must understand the lithological intricacies (variations) and structural relationships. Communication in an immersive, stereoscopic setting facilitates consensus from various experts to build the best model based on currently available data. In addition, data and interpretation gaps are typically found and addressed in the VR sessions to improve future models, resulting in improved data collection and auditing strategies.

2.3 *Seismic Excavation Hazard Maps*

A (micro)seismic event records a physical rock mass damage occurrence. Stress-induced damage events are generally confined to the vicinity of mined openings, whereas structure-induced (shear-slip) seismicity may occur at some distance from the mine excavations. In terms of data handling and processing (Figure 2), the former are dealt with by seismic density hazard criteria, whereas the latter are determined by applying the space-time clustering algorithm to isolate individual clusters in 4-dimensional space. Reduction in dimensionality is achieved by application of principal component analysis (PCA) in the 3-dimendional space of the cluster to identify the dominant (planar) orientation trends in the data (Kaiser et al., 2005 and Vasak et al., 2004). Seismic data is handled along a separate path for the hazard map component where only the dynamic (peak particle velocity) effects of large events are incorporated into the hazard map. The space-time seismic pattern processing and evaluation are handled separately.

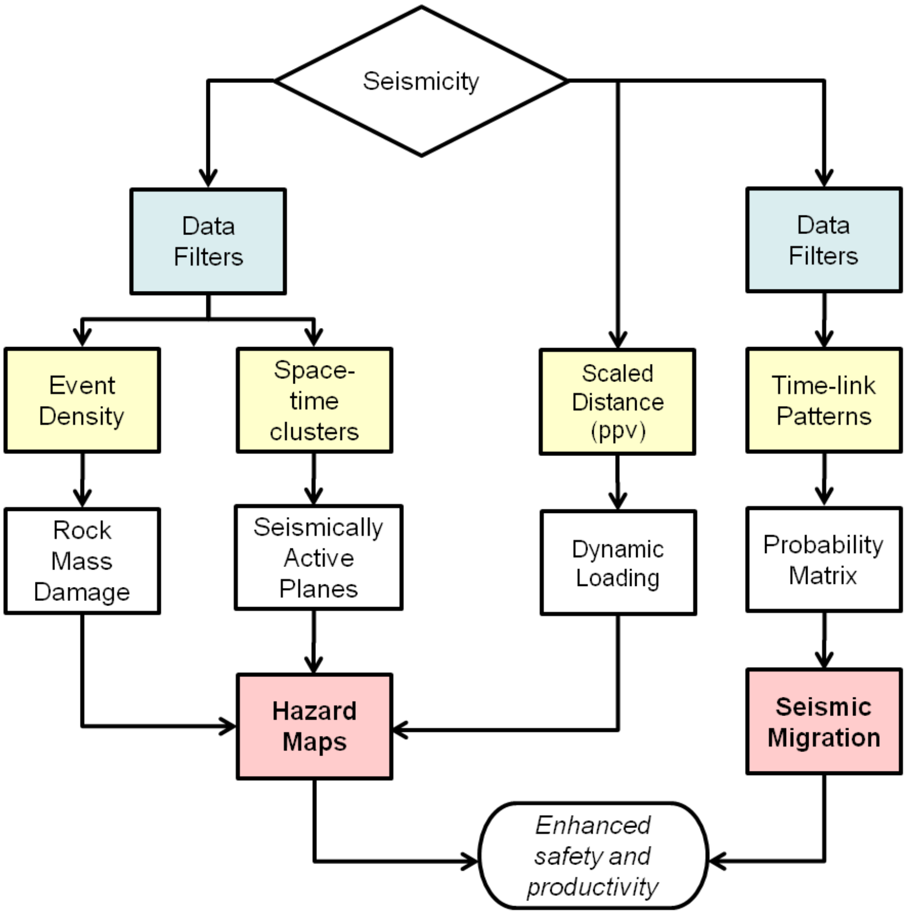

Figure 2. MIRARCO seismic data processing procedure chart, hazard factors and time-link logic are handled as two separate tasks

In general, stress-induced seismicity follows the mining front as new stopes are excavated and diminishes as an area becomes mined out and stopes are backfilled. However, structure-induced seismicity may recur in a mined out area at a later stage of mining. The implication is that hazard (and risk) conditions are not static, but change over time as mining progresses. More specifically, remote mining areas may trigger seismicity in other areas that cannot be accounted for by stress considerations alone. Keeping track of the past (history), current and potential future hazards is the key for advancing a coherent risk assessment and risk management strategy at rockburst prone mine sites.

The actual data integration, visualization and assessment can be quite complex. Throughout the research an attempt was made to simplify the data representation by reducing the dimensionality in novel ways to ensure data integrity, clarity and usefulness for insight. However, even this may seem complex as is illustrated in Figure 3, a snapshot at a particular time of the mining sequence showing seismic and microseismic data as a series of surfaces, lines, iso-surfaces, shapes, sizes and colours. Each has a prescribed role in a 3-D stereoscopic visualization environment and patterns, not distinguishable in the 2-D image, become apparent to the observer in a VR room.

To produce a practical and useful tool for the mine operator, the complexity of the data processing must be reduced to produce the seismic excavation hazard maps. Hazard ratings for the three factors are established according to their impact on mine infrastructure. The defined hazard ratings (Table 1) are visually displayed in Figure 4. The hazard map is 3-dimensional and can represent discrete periods of time. Future representations are determined by the mine stoping sequence and rock mass failure migration based on local mine conditions. The hazard factors may be combined or used independently depending on the site-specific conditions, since not all may be relevant to an operation.

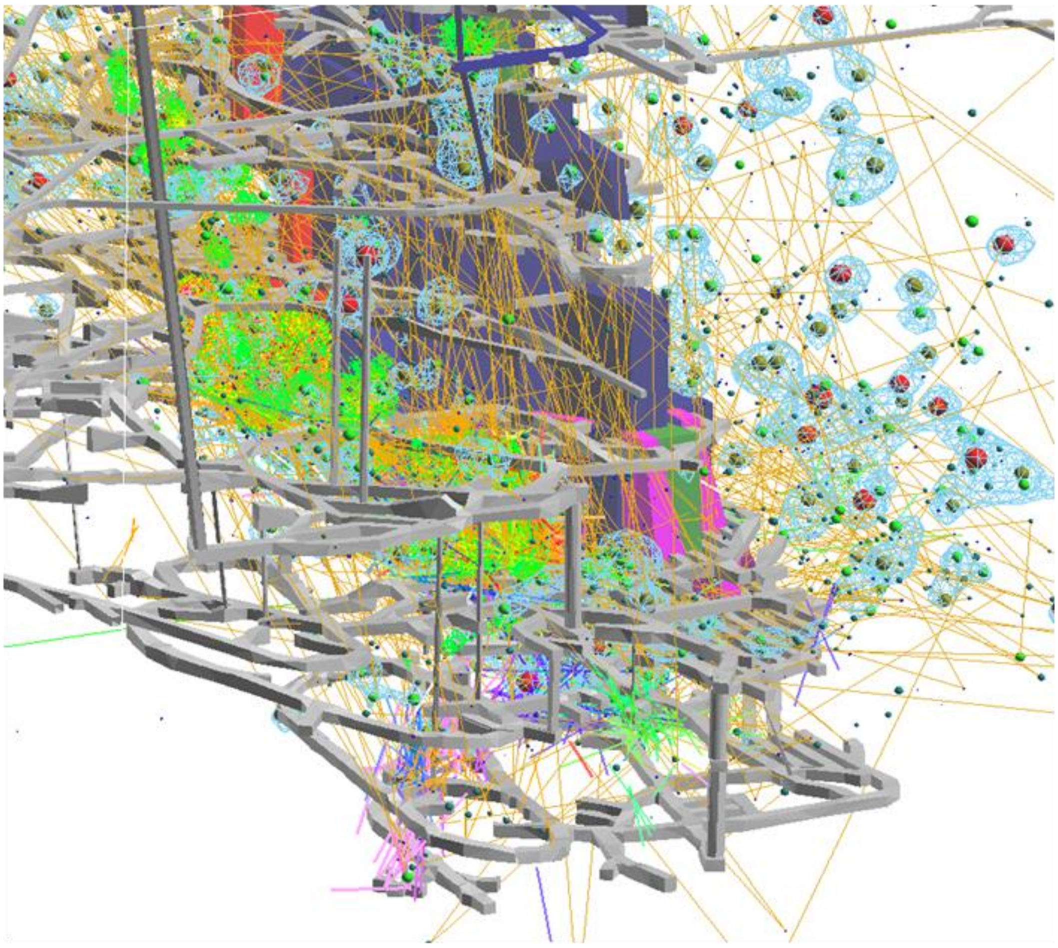

Figure 3. Seismic data processing and interpretation showing time (linkage lines) and source parameter relationships (colour/size) between mining induced seismic events – This is the researcher's viewpoint.

Table 1. Hazard impact ratings based on rock mass damage mechanisms.

Hazard factor	Hazard process	Hazard parameter impact rating (consequence)			
Microseismicity (MS)	Rock mass degradation	Negligible (N)	Low (L)	Moderate (M)	High (H)
Active planes	Slip, wedge, loosening	Negligible	Low	Moderate	High
Seismicity	Dynamic loading, peak particle velocity	Negligible	Low	Moderate	High
Parameter weighting		0	1	2	3

3 SEISMIC EXCAVATION HAZARD MAPS IN VR

Under the Ontario Research Fund's PERM, "Productivity Enhancement and Risk Management for Underground Construction and Mining", initiative (www.mirarco.org/FeaturePrj/perm.htm), the Seismic Excavation Hazard Map logic is now implemented as a near-real-time excavation hazard system at a deep mine in the Sudbury Basin. Due to the complex integration of large datasets from various sources, the high dimensionality (space and time are a minimum requirement) and complex spatial processing, a specialized visualization platform is required, especially for large screen stereoscopic visualization capability.

As a not-for-profit R&D company, MIRARCO is mandated to transfer new knowledge and innovation through innovative applied research, software tools, and the transfer of knowledge. A new open source visualization and data integration package called ParaviewGeo has been released to the exploration and mining industries (paraviewgeo.mirarco.org). Based on a scientific visualization software called Paraview, the software was developed to run on distributed and shared memory parallel systems specifically for the integration and visualization of large, complex datasets and has fully implemented stereoscopic capability, but is still functional on a single processor desktop. This allows the practitioner to have access to, and ability to view and interpret large datasets. ParaviewGeo is the platform for the SEHM data integration, processing and visualization and is available as a separate plug-in not available in the general downloadable version.

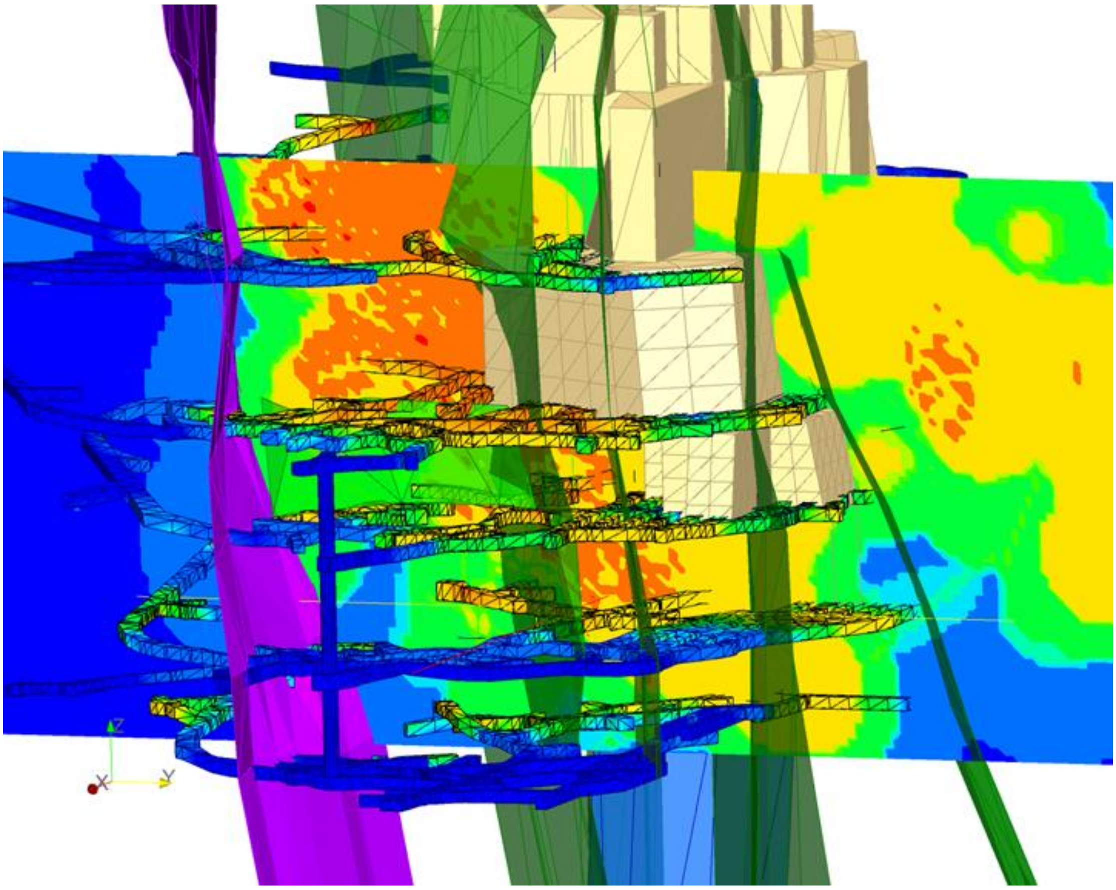

Figure 4. ParaviewGeo visualization of the Seismic Excavation Hazard Map showing a section and hazard projected onto mine excavations. This is the mine operator's viewpoint.

The seismic hazards are calculated for the rock mass volume, but can be represented in terms of iso-surface contours, or more traditionally as plans and sections (shown in Figure 4) or the data can be projected onto any other geometric object such as geological structures (e.g. faults), mine stopes or drifts (also shown in Fig 4.) A simple colour scale (blue, cool, low hazard to red, hot, high hazard) represents the hazard level.

The collaborative aspect of VR is further enhanced by linking VR facilities so that teams at different sites (e.g. mine site, head office or other satellite facility) can collaborate and make operational or planning decisions using real-time interaction and displaying live data with varied complexity. An example of this concept is the Northern Advanced Visualization Network (NAVNet, www.mirarco.org/navnet.php) that targets communities, professionals, students, and mining/exploration companies working in the North.

4 CONCLUSIONS

It is not the quantity or quality of data, but rather the quality of the decisions that are made based on the data that makes scientific (engineering) visualization in an immersive, collaborative virtual reality environment an invaluable resource.

The VR visualization technology developed at MIRARCO, Laurentian University is enabling innovations in planning and design through an enhanced ability to visualize overall impact of various factors in a complex environment. The VR technology is transitioning to the mine site and early adopters of the technology in North America include:

- Goldcorp - Red Lake Virtual Reality Studio, 2004
- Timmins Public Library (multi-use), 2006
- Kennecott Utah Copper, Rio Tinto, 2007
- Creighton Mine, Vale Inco, 2009

The stereoscopic hardware enables the use of more advanced software applications, particularly if the use of the added dimension provided by the stereo display is not “wasted” by projecting 3-dimensional data, but leveraged to display hyper-dimensions. These dimensions can be used to create a link between space and time and to provide a means of evaluating and exploration the effects of uncertainty on measured and synthesized data.

The future is clear, as the age of the visual scientist and engineer draws near, new innovations in processing and interpreting complex integrated data sets is required as the mining industry deals with complex issues related to mining at greater depth.

Seismic Excavation Hazard Maps can be used to assess hazards and more importantly, to provide the resource for the operator to identify risk mitigating measures for anticipated rock mechanics problems as mining progresses deeper.

The SEHM is an additional tool for the rock mechanics practitioner, not to be used alone, but as an integral part of a comprehensive geomechanics evaluation process.

High-level risk mitigation measures developed in the immersive, collaborative virtual reality facility will ensure safe, profitable and reliable ore extraction.

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