Simulation and Visualisation of Flow and Transport in Fractured Rocks

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Abstract

Groundwater flow and solute transport in fractured rocks are dominated by small scale discrete flowing fractures, as well as large geological structures such as faults. This paper presents an integrated approach for discontinuity data analysis, and simulating and visualising flow and transport through both small and large scale features, based on the conceptualisation of discrete fracture networks. The discontinuity data analysis and simulation of flow and transport are accomplished by using FracMan, linked to advanced visualisation using the Vulcan software. A generic site study for a deep geological disposal of radioactive wastes in a fractured crystalline rock is conducted to demonstrate the application of the proposed approach.

Introduction

The methodology to be presented in this paper has very wide applications where fracture dominated flow is a primary concern, such as exploration of fractured hydrocarbon and geothermal reservoirs, underground storage of hydrocarbon products, geological disposal of radioactive waste, and some mining and civil engineering problems. For clarity, only one application is discussed throughout this paper - it is the geological disposal of radioactive waste.

Deep burial in geological formations has been the preferred option to permanent disposal of high level radioactive waste in many countries (Savage, 1995). A repository is an underground disposal facility which consists of tens of emplacement drifts where canisters of nuclear waste are stored and sealed off. The geological formation provides the final, and possibly major, barrier to prevent radionuclide travelling from a repository to the biosphere. The principle mechanism for radionuclides transport from a repository to the biosphere is through the interconnected geological discontinuities (termed as fractures in this paper for convenience) and large scale geological structures, such as faults.

In a fractured rock, some fractures are more conductive than others and only a sub-set of fractures are hydraulically significant. The flow pathways in the host rock for a potential repository are normally part of a sparse and heterogeneous interconnected fracture network. The discrete fracture network (DFN) approach (Long, 1985; Dershowitz and Einstein, 1988; Cacas *et al.*, 1990; Swaby and Rawnsley, 1996) should be used to characterise the site and to assess potential flow pathways from the repository to the biosphere.

The major weakness of the current DFN approach lies in the lack of “intelligent” visualisation of the flow field and radionuclide movements in a network, reducing the ability to analyse their relationships with the topography, repository structures, and the geological framework of the site. Such “intelligent” visualisation should be interactive and dynamic in three dimensions and allow the modeller to interrogate the data. The fact that the potential host rock consists of sparse fracture networks and is very heterogeneous makes visualisation even more important in understanding the data (measured or simulated) and educating the public about the major issues regarding the long-term safety of a repository.

After introducing the discrete fracture network modelling methodology, this paper presents a fully integrated interface between FracMan, a discrete fracture network modelling package (Dershowitz *et al.*, 1995), and Vulcan, a fully interactive 3-D visualisation, mine planning and geological modelling system (Maptek, 1995), providing a solution to the visualisation requirements for the DFN modelling. An illustration example is also presented to demonstrate the application of the Vulcan “intelligent” visualisation of the FracMan calculated flow field and radionuclide movements.

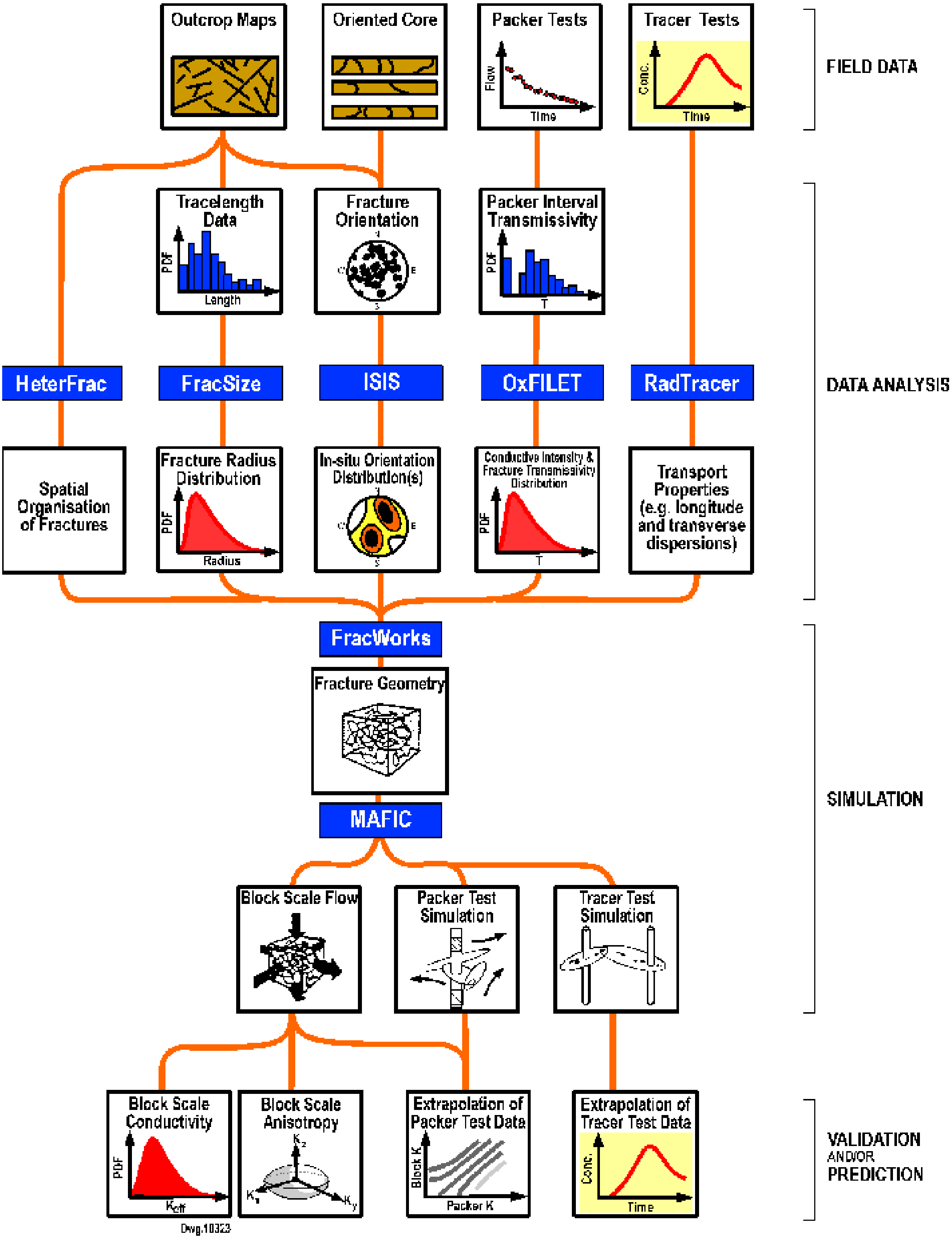

Fig. 1: FracMan modelling flow chart from discontinuity data analysis to flow and transport calculations in fractured rocks and the corresponding FracMan components.

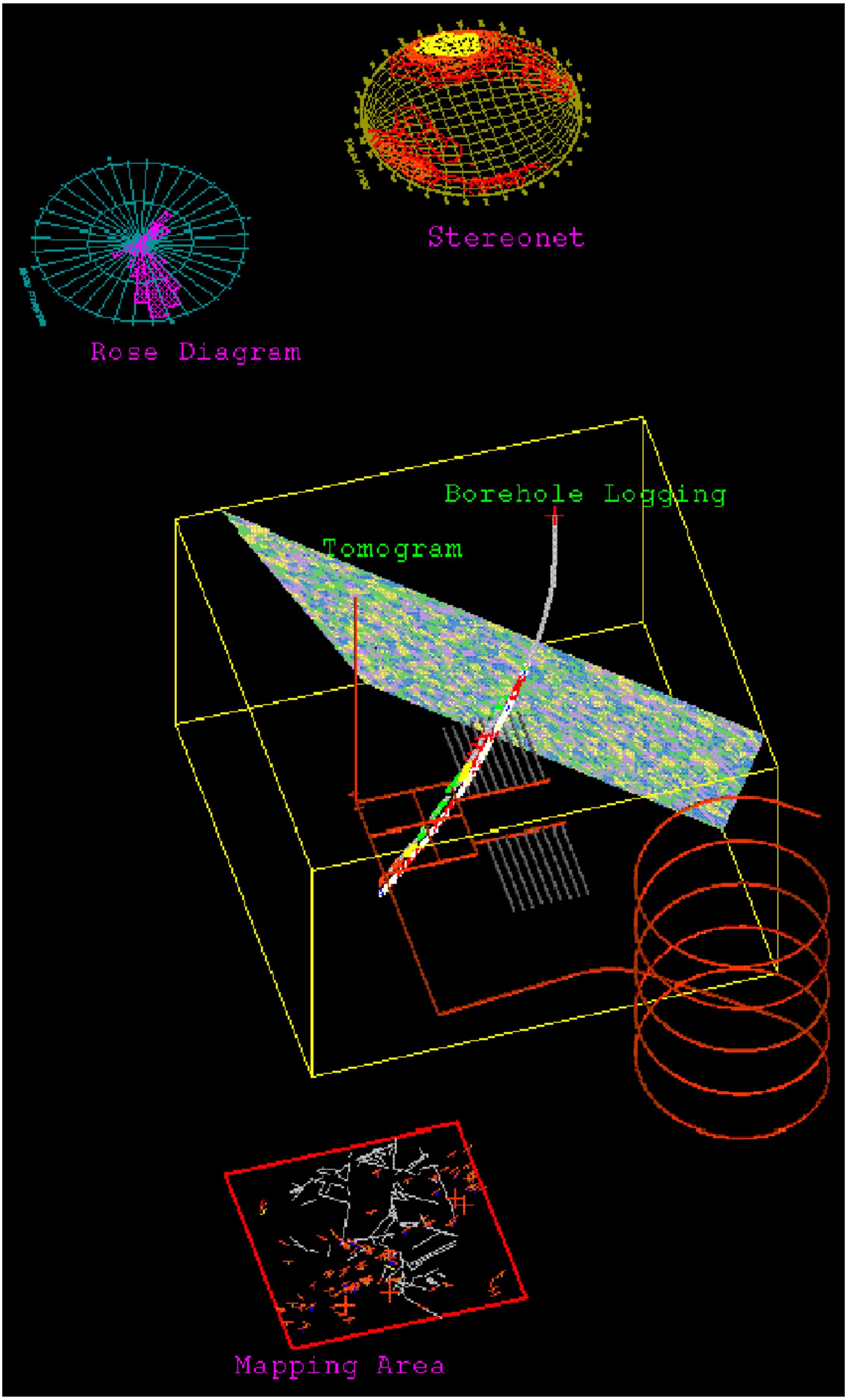

Fig. 2: Some data types which can be held in Vulcan. Displayed are the repository structure (the ramp, the shaft, and waste emplacement drifts); borehole logging data (different colour represents different types of discontinuities); fracture orientation data (represented in stereonet and diagram); mapped fracture data on a surface exposure, and tomogram from geophysical measurements.

Discrete Fracture Network Modelling

To assess the suitability of a geological formation as the potential host rock, extensive geological and hydrogeological site investigation is conducted to characterise fractures and faults in the region of the repository. Such investigation will enable repository safety assessment to be carried out to quantify the potential risks of the flow paths from the repository to the biosphere.

The discrete fracture network modelling for a potential repository site comprises the following self-consistent approach (Wei and Chakrabarty, 1995):

1. Analyse geological and hydrogeological data gathered from site investigation activities;
2. Construct 3-D DFN conceptual model(s) for the site based on data;
3. Calibrate model(s) to large scale observations from imposed hydraulic disturbances (e.g. large scale hydraulic tests and/or underground excavation) and tracer tests;
4. Back to step 1 or 2 depending on the stage of site characterisation, and success of step 3;
5. Conduct preliminary repository safety assessment to assess the suitability of the site;
6. Depending on the output of step 5, go back to step 1 with more data gathering activities, or abandon the site;
7. Conduct final repository safety assessment (more cycles may be needed).

The key to the above process is to develop DFN conceptual model(s) for the site which represent the current understanding of the site at each stage of site characterisation. The model(s) should be developed and evolved from steps 1 to 4 above with further refinement from step 6, and used for post-closure safety assessment in steps 5 and 7. Using an equivalent continuum model (either deterministic or stochastic) to replace a DFN model in the safety assessment is not defensible in principle (La Pointe *et al*., 1996).

In addition to locating large scale geological structures, site investigation also requires outcrop mapping, core logging and many other measurements to characterise the spatial distribution of geological features at all scales, as well as hydraulic and tracer testing to determine their flow and transport property distributions. A DFN model conceptualises a geological formation by representing conductive fractures explicitly, using the following parameters which can be directly inferred from these measurements:

1. Fracture spatial organisations at all scales
2. Fracture orientation distributions
3. Fracture size distributions
4. Fracture intensity and its dependency on depth (if any)
5. Fracture hydraulic and transport properties (such as transmissivity) and their distributions.

The FracMan discrete fracture network package (Dershowitz et al., 1995) has been developed to provide extensive tools to infer DFN parameters from measurements; generate fracture networks in 3-D and carry out flow and solute transport simulations in the generated network (Figure 1). The generated fractures are represented as polygons (4 to 20 sided). These fractures are discretised into triangular finite elements for flow and transport calculations using the flow solver - MAFIC. FracMan provides a 3-D interactive user-interface for data analysis and fracture network generation.

Interface between Fracman and Vulcan

The primary purpose of the interface between FracMan and Vulcan is to "intelligently" display the flow and transport solutions from the flow solver (MAFIC). This is facilitated by the fact that ***triangles*** are the basic elementary objects in both packages. From FracMan, each triangle embeds both geometrical (x,y,z coordinates) and physical (transmissivity, storativity, dispersion etc.) properties, as well as the calculated flow and transport solutions (pressure and flow rate at each node, solute particles within each triangle) as a function of time. This triangulated data format can easily be imported into Vulcan.

Murray (1996) and Lee (1996) have demonstrated that Vulcan can be used to serve as a "data bank" for various data gathered during site investigation, as well as underground structures. All complex structures (geological or man-made) within Vulcan can be triangulated and exported into FracMan. Part of the data will be transferred into boundaries for FracMan simulations, such as shafts/tunnels and topography. Most importantly, the fault data can be imported into FracMan and used in a variety of ways depending on the hydrogeological conceptualisation of the faults. For example, the two envelopes of a fault may be used as a bounding region for the generation of fractures in-between the envelopes; or using the central plane of the fault as a reference object and generating fractures in its vicinity with decreasing fracture intensity away from the fault.

Vulcan can be used to hold a variety of site characterisation data from borehole logging, seismic and hydrogeological testing within several of its internal data structures (Table 1). The whole variety of data types and applications are integrated within a unique 3-D modelling interface. Figure 2 shows a generic site study for the application of Vulcan to hold various types of data.

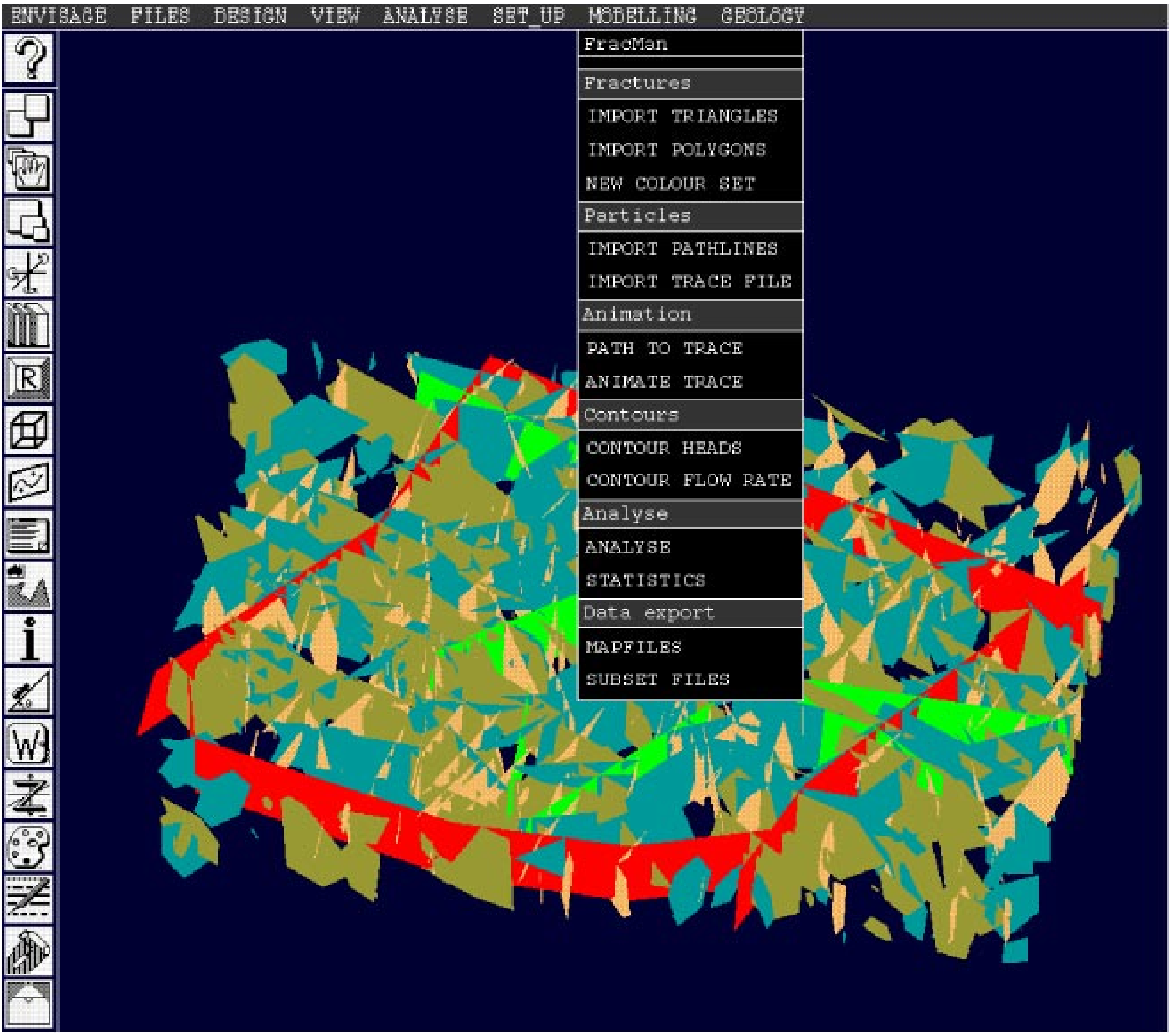

Fig. 3: Vulcan FracMan interface menu. There are six categories of functions: “Fractures” (import fracture data in triangulated mesh format or polygons - FracMan flow solution is only embedded in the triangle data); “Particles” (import particle movement data from FracMan particle tracking simulations); “Animation” to animate particle movement; “Contours” (calculate and display contours for the calculated pressure heads and flow rate); “Analyse” to allow the user to integrate the netowrk; and “Data Export”.

Outputs From Vulcan Visualisation

A set of routines were developed in Vulcan to interface with FracMan that would:-

1. Easily import FracMan fracture network systems that could contain up to one million triangular elements.
2. Display in three dimensions mesh structure as a whole or any sub-set(s) specified by fracture ranges, sets, transmissivity ranges or sub-regions.
3. Display and animate the calculated flow field from FracMan using flexible colour schemes for each triangle, or calculate and display local and regional head contours.
4. Display and animate the simulated particle transport movements from FracMan.
5. Analyse network properties anywhere in the 3-D network.
6. Import FracMan polygon fractures.
7. Export Vulcan triangle data or subset of FracMan data files.

The interface menu is shown in Figure 3. Differing views of the network can be rapidly produced, using the virtual look, walk, slice, rotation, zoom-in and zoom-out display tools. The use of Vulcan’s visibility switching and frame-based displays will allow instantaneous exploratory displays, where mesh densities obscure 3-D visibility.

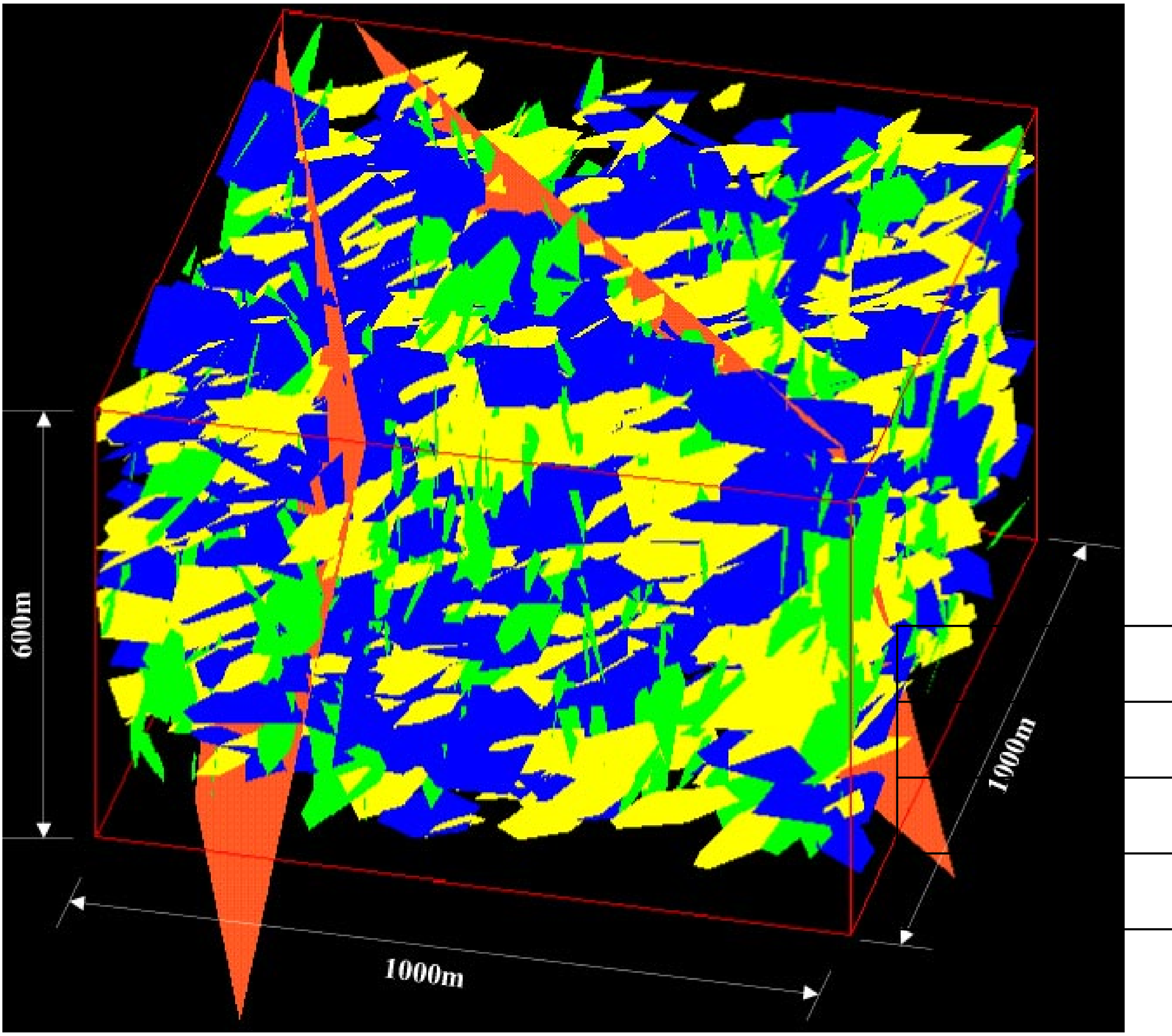

Fig. 4: Fracture network of the illustration example coloured by sets (two faults and three sets of fractures). Attributes of the fracture sets are listed in Table 2.

Solute transport and radionuclide pathway simulations have been visualised and then animated, using Vulcan's CAD database, linked to the animation module. Particle movement through the network is monitored through a series of time steps, allowing close inspection of the relationships between the network, repository design and other geological structures and hydrogeological units.

Hydraulic properties of the network such as transmissivity and calculated flow field can also be held in a "block model" structure. The block model interpolates these fracture properties into 3-D solid space. This structure then allows rapid display of the variable on any plane through the model.

To complete the set of tools, interactive analysis of the network produces a report of hydraulic heads, node numbers, triangle number, transmissivity and set number for any element selected within the network. This allows the modeller to interrogate and reconcile the simulation outputs against the input parameters of the numerical model.

Illustration Example

The Model: the model presented here is generic and does not resemble any particular site, but possesses all the basic elements of a potential site. The purpose is to show the linkage between FracMan and Vulcan and how the discrete fracture network modelling results can be visualised. Although the importance of the physics of the model inputs and outputs cannot be over-emphasised, this paper focuses on the display functionality.

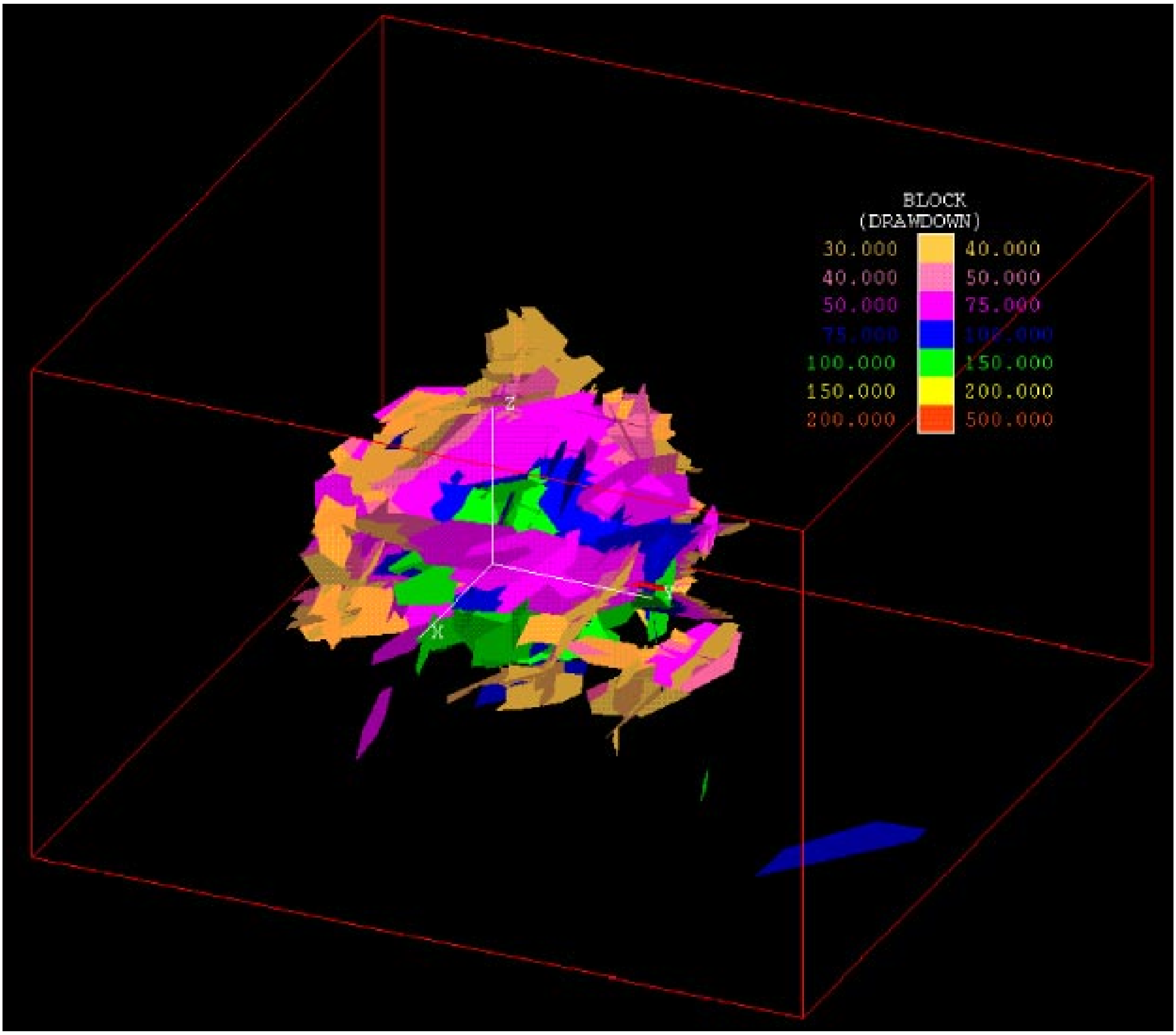

Fig. 5: Portion of the fracture network which has a pressure drawdown greater than 30 m due to the excavation of an emplacement drift. Colour scheme is based on drawdown values. Heterogeniety of the pressure responses in the network is clearly seen, especially when the network is rotated interactively in real-time within Vulcan.

A discrete fracture network was generated using FracMan within a 1000m x 1000m x 600m region, which included two faults, as shown in Figure 4. The input parameters are listed in Table 2 for information. It is assumed in this example that fracture distribution in space follows a Poisson process. Normally, during a practical application, significant effort is devoted to derive these parameters from geological and hydrogeological measurements, such as borehole logging, geological mapping, hydraulic tests, and tracer tests. The two faults in the model are located deterministically, with transmissivity of 10^{-7} m^2/s. Fractures and faults within FracMan can also be modelled with variable apertures.

Boundary Conditions: it is assumed that there is a 5% hydraulic gradient from West to East. The base of the modelling region is assumed to be a “no flow” boundary, while all the other external boundaries are assigned constant head conditions consistent with the regional hydraulic gradient.

One of the waste emplacement drifts is located at the centre of the modelling region and 300m below ground surface. Two modelling conditions for the drift have been conducted: open and post closure. When the drift is open, i.e., the in-use period of the repository, only the groundwater flow calculation is conducted, with the drift boundaries assigned to atmospheric pressure. When the emplacement drifts are closed, i.e., filled with extremely low permeable materials, both groundwater flow and solute transport calculations are performed. Around 500 particles are simulated which are assumed to be released from the buried canisters in the drifts.

Type of Site Characterisation Data	Vulcan Data Type	Vulcan Functions
Borehole Logging (fracture type, orientation, intensity etc.)	Borehole Database	Dbeute, Geology, Bhgute. Database editor; borehole graphics display
Discontinuity Data, such as geological outcrop mapping & discrete fracture networks	Geotechnical Database, Delauney Triangulation	Geotechnics module & Triangle Utilities, FracMan data transfer interface
Geological Formations & Faulting	Delauney Triangulation, Grid Models, Block Models	Triangle and grid modelling utilities. Block Construction and Viewing
Hydrogeological Properties	Borehole Database, Block Models	Dbeute, Bhgute, Block Construction and Viewing
Repository Design	Design Database	Computer Aided Design (CAD) tools
Fluid Flow Field & Solute Transport Pathways	Design Database, Delauney Triangulation	FracMan data transfer interface, CAD tools, Animation
Seismic Measurements	Grid and Delauney Triangulation	Triangle and Grid Modelling

Table 1: Vulcan Data Types and Functionality.

Fracture Attributes	SET 1	SET 2	SET 3
Orientation distribution (pole)	Fisher distribution mean (135°,20°), dispersion parameter = 30	Fisher distribution mean (70°,10°), dispersion parameter = 20	Fisher distribution mean (0°,90°), dispersion parameter = 10
Equivalent Radius in 3-D (m)	truncated exponential distribution: Mean = 50m, truncated between 20m and 100m	truncated exponential distribution: Mean = 50m, truncated between 20m and 100m	truncated exponential distribution: Mean = 60m, truncated between 40m and 100m
Elongation aspect ratio (horizontal to vertical)	2	1	1
Intensity (# per metre in the mean pole direction)	0.016 1/m	0.016 1/m	0.025 1/m
Transmissivity distribution (m^2/s)	log-normal distribution logarithmic mean = -10	std.dev.= 1.32	log-normal distribution logarithmic mean = -9 std.dev.= 1.32
log-normal distribution logarithmic mean = -10 std.dev.= 1.32	Transport dispersion (m, longitudinal and transverse)	Longitudinal: 0.2m Transverse: 0.1m	Longitudinal: 0.2m Transverse: 0.1m
Longitudinal: 0.2m Transverse: 0.1m	Effective Molecular diffusion (m^2/s)	10^{-9}	10^{-9}

Table 2: Parameters used to generate the demonstration fracture network

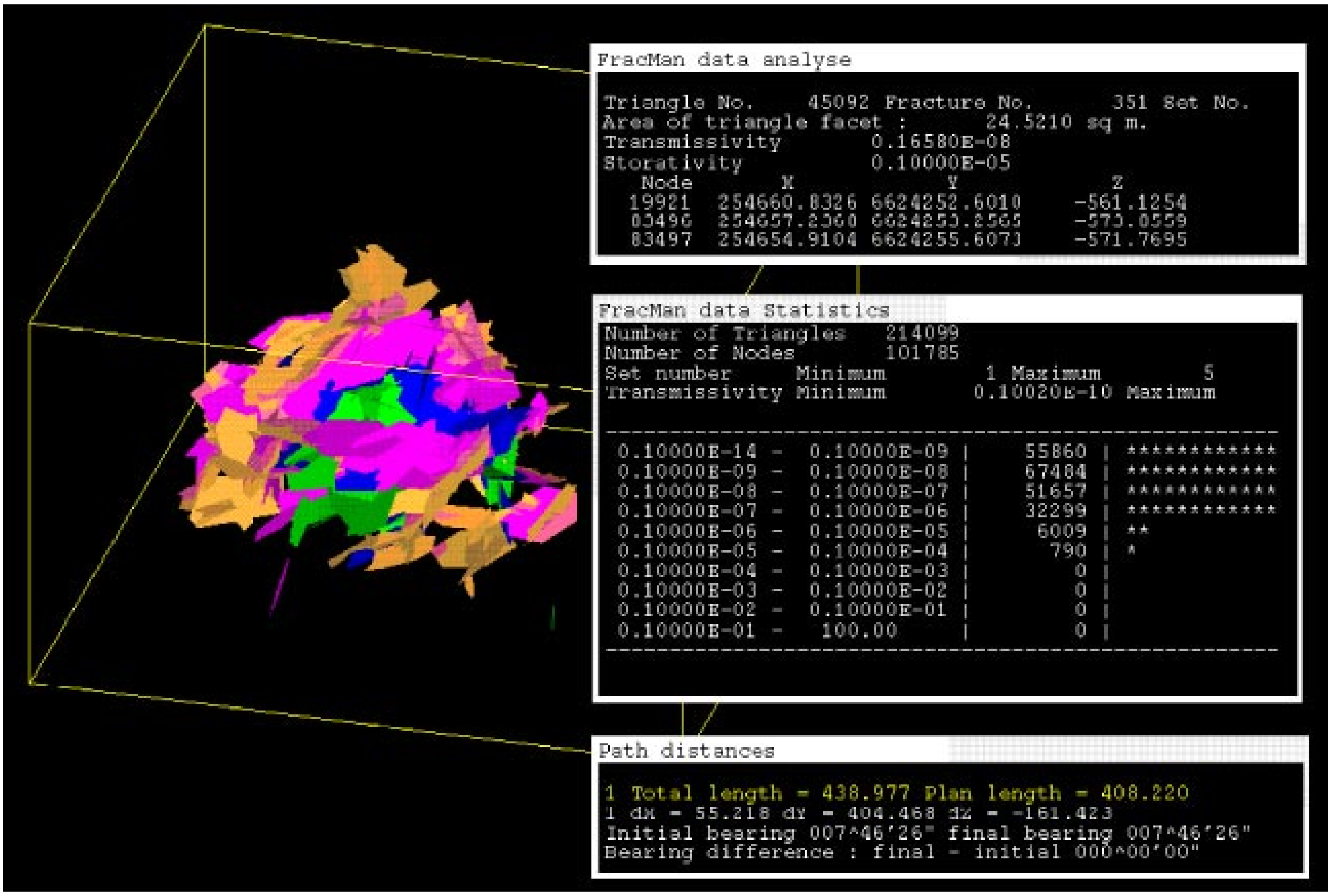

Fig. 6: Interrogation of the network is at fingertip. Details of any triangles, statistics of both hydrogeological properties (e.g. transmissivity and storavity) and flow solutions (e.g. heads and flow rates) in the network, and geometrical measures (e.g. distance and areas) can be easily obtained using the "Analyse" tool.

The Simulation Results: when the simulated drift is open, it acts as a "sink" and imposes great hydraulic disturbance nearby. Figure 5 shows the portion of the fracture network which has pressure drawdowns greater than 30m, as a result of such disturbance. The data interrogation and analysis function of the Vulcan FracMan interface is demonstrated in Figure 6, which shows details of a selected triangle, statistics of transmissivity in the network, and the distance between two selected points on the network. The block modelling within Vulcan can be used to interpolate pressure or flow rate from fractures into 3-D solid space, and then the data can be "draped" onto a plane as shown in Figure 7. This figure illustrates the interpolated pressure field on a horizontal plane and the two faults. This function can be extremely useful for assessing heterogeneity of hydraulic responses in the horizontal and vertical directions, or along a regional fault(s).

When the repository is back filled with extremely low permeable materials, the drift is no longer acting as a "sink", and the groundwater flow system will be driven by the regional flow gradients (5% from West to East). Figure 8 shows the flow field under such conditions in the simulated region. The assumed West to East hydraulic gradient is clearly illustrated. The hydraulic head distribution in space is heterogeneous, but the two faults do not distort the flow field. When the particles are released from the repository, some particles move upwards, others downwards, but all move towards the East, as shown in Figure 9. When the particles reach the fault, they start to move along the fault towards Southeast. Although a few particles do cross the fault, but they all return and move along the fault. By displaying selected portions of the fracture network, and using the analysis tools in Vulcan, this interface offers the modeller the capability to examine the nature of the pathways.

Real time animation and interrogation of all the results is possible from the interface, but cannot be fully presented within this paper.

Conclusions

By introducing an interface between the two well established computer packages, this paper has presented an integrated approach for discontinuity data analysis, and simulating and visualising flow and transport through both small and large scale features, based on the conceptualisation of discrete fracture networks. In this approach, FracMan is used in analysing discontinuity data and deriving parameters for a DFN model for a potential site, and performing flow

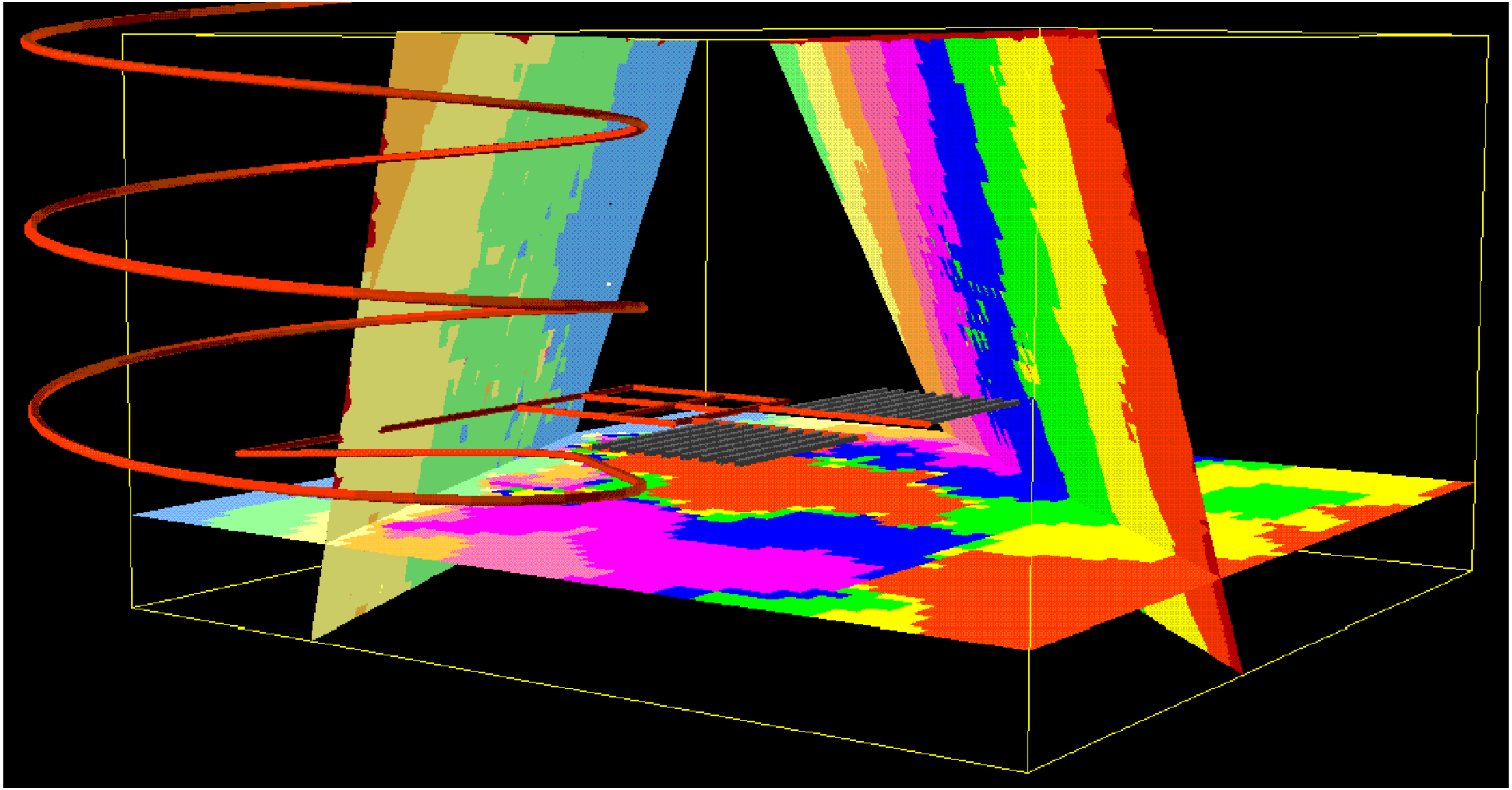

Fig. 7: Interpolated flow field on a horizontal plane and the two fault planes using Vulcan block modelling. The fow field is from the case when a drift is open. Heterogeneous responses are clearly seen on the horizontal plane. Much less heterogeniety is observed on the two fault planes. This is because the faults are simulated with constant transmissivity.

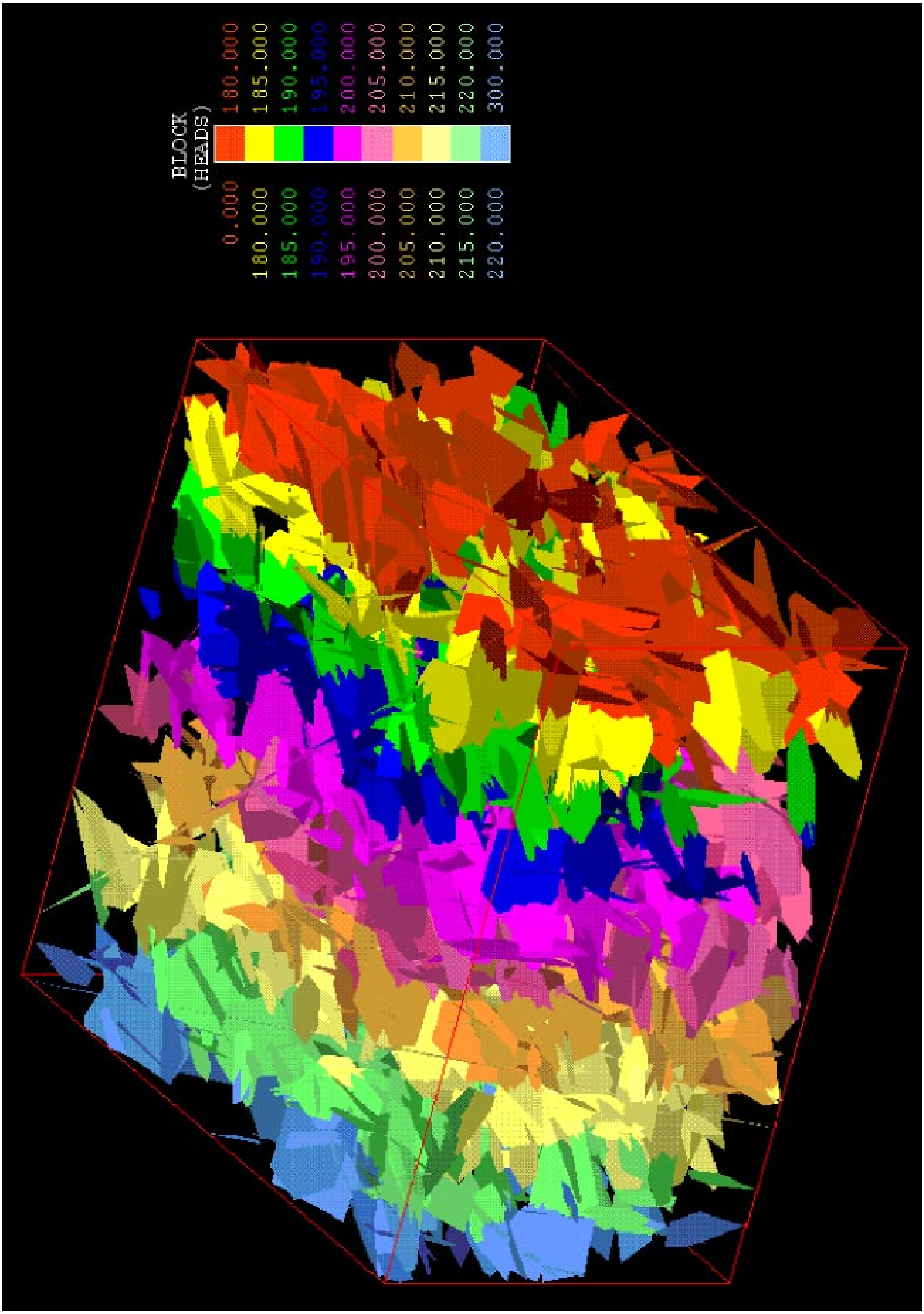

Fig. 8: The calculated steady state flow field in the fracture network when the repository is back filled with extremely low permeable materials (5% hydraulic gradient from West to East - from the left hand side to the right). The faults have not distorted the flow field, although the hydraulic head distribution in space is far from homogenous.

and transport calculations through the fracture networks. Vulcan is used as a central "data bank": holding all the model inputs from site data acquisition and outputs generated from FracMan. Therefore, Vulcan does not only produce a