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PROBABILISTIC FRACTURE NETWORK MODELS FOR PRELIMINARY SITE CHARACTERIZATION

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ABSTRACT

Ontario Power Generation's Deep Geologic Repository Technology Program has developed a geostatistical procedure for creating 3D fracture network models (FNMs) that honour the types of information typically available for preliminary site characterization: detailed information on the locations of surface lineaments from aerial photography and remote sensing; regional tectonic information on stress; geomechanical and structural geology principles; field data gathered from geologically analogous sites.

This approach provides a systematic and traceable method that is flexible and that accommodates data from many different sources. The detailed, complex and realistic models of 3D fracture geometry produced by this method can serve as the basis for developing rock property models to be used in flow and transport studies. In addition to being ideally suited to preliminary site characterization, the approach also readily incorporates field data that may become available during subsequent site investigations, including ground reconnaissance, borehole programs and other subsurface studies.

The FNMs from this method are probabilistic in the sense that they consist of a family of equally likely renditions of fracture geometry, each one honouring the same surface and subsurface constraints. Such probabilistic models are well suited to studying issues that involve risk assessment and quantification of uncertainty.

The geostatistical procedure for simulating FNMs is described, its use in case study examples is presented, and the realism of its fracture geometries is tested using field data collected from the Lägerdorf chalk quarry in northern Germany.

I. INTRODUCTION

Fractures play a dominant role in fluid flow and transport[1]; the predictive power of flow and transport simulators can therefore be considerably improved when they use 3D models of fracture networks as one of their inputs[2]. Existing procedures for simulating fracture network geometry typically simplify the undulating and curvilinear nature of fracture surfaces, approximating them as planar facets[3]. Though this approximation is suitable for many flow and transport studies, it is unacceptable in situations where models of fracture geometry need to exactly honour known locations of a large, detailed and geometrically complex set of fractures.

Ontario Power Generation (OPG) is developing tools to assist the Deep Geologic Repository Technology Program (DGRTP) with building geosphere models that are realistic because they integrate diverse types of data and are consistent with increasingly detailed surface and subsurface knowledge. One specific data integration task involves construction of 3D fracture network models that honour the limited information available at the time of preliminary site characterization: surface lineaments, general structural geology principles, regional tectonic considerations and site-specific information on geomechanical characteristics. These various pieces of information provide constraints on fracture location: very strong constraints at surface in regions of good bedrock exposure, and weaker constraints at depth and in regions of poor bedrock exposure.

A geostatistical simulation method has been developed for creating complex, detailed and realistic 3D fracture network models that honour the various pieces of information available at the time of preliminary site characterization. It can also accommodate data that become available in later years, such as borehole data and information from other subsurface investigations. This method produces a family of equally probable renditions of 3D fracture geometry, each one different in detail, but all consistent with the same constraints.

II. OVERVIEW AND IMPLEMENTATION

Sequential gaussian simulation (SGS)[4,5] is a geostatistical procedure that is widely used for creating data-conditioned stochastic models of spatial phenomena. In a typical SGS study, the procedure is applied to volume-averaged rock properties (such as porosities or permeabilities), and is performed at the nodes of a regular grid. In the procedure discussed here, SGS is applied to geometric attributes (strike of a fracture trace, or dip of a fracture surface). Furthermore, the locations at which SGS is applied are not nodes of a regular grid; instead, the procedure is applied at the tips of iteratively propagating fractures, which entails that the locations of the simulations nodes depend on the details of what has been simulated in previous iterations.

The original motivation for using an iterative procedure like SGS was to mimic the procedure proposed by Renshaw and Pollard[6]. Their approach to 2D fracture simulation is based on geomechanical principles, propagating fracture tips when stress at fracture tips exceeds a critical threshold. Their approach created very realistic synthetic images of fractures in a variety of stress environments, including many subtle features commonly observed in the field, such as zones of small *en echelon* features that bridge gaps between larger separate fractures.

Though undeniably successful, fracture simulation based on geomechanical principles proved to be prohibitively computationally intensive and has never been extended satisfactorily to 3D. By using the same broad approach — an iterative procedure for propagating fracture tips — but replacing geomechanical principles for fracture propagation with geostatistical rules, one is able to mimic much of the realism with less computational effort.

II.A. 2D Propagation of Surface Features

Figures 1 through 6 show the major steps in the first phase of the fracture simulation: 2D propagation of surface traces.

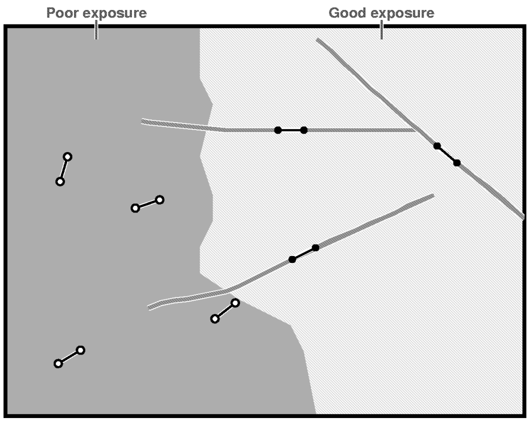

Figure 1. Initial seeding of the midpoints of the fracture traces.

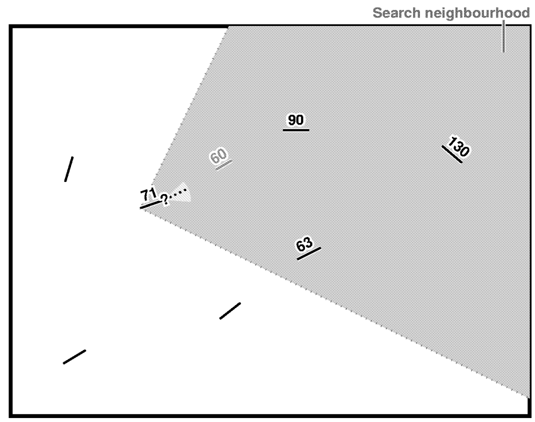

Figure 2. An example of the propagation of a free endpoint.

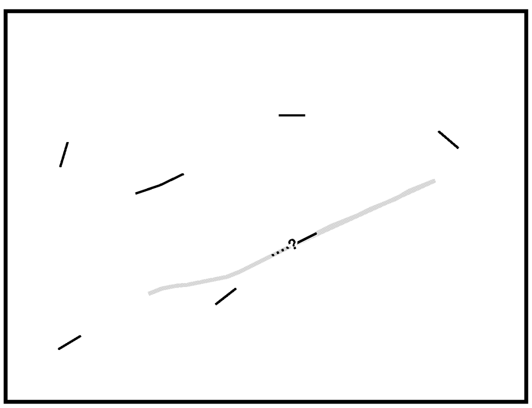

Figure 3. An example of the propagation of a constrained endpoint.

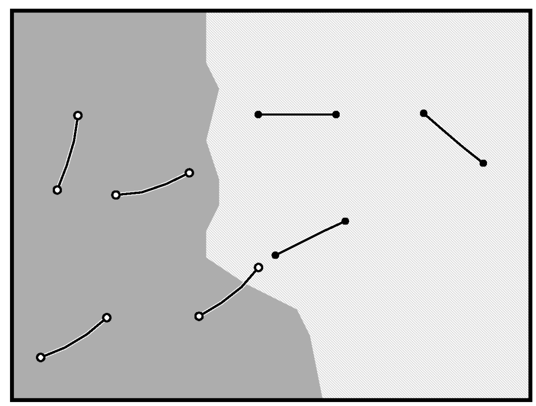

Figure 4. After one complete iteration through the endpoints.

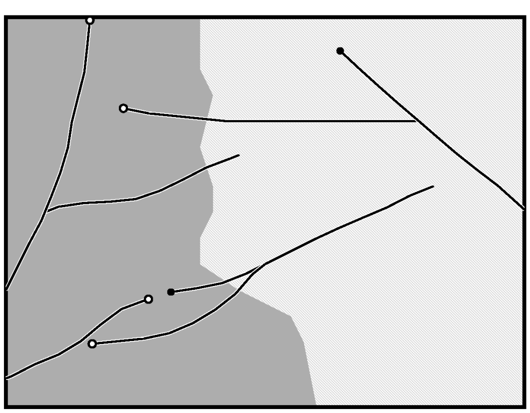

Figure 5. After five complete iterations through the endpoints.

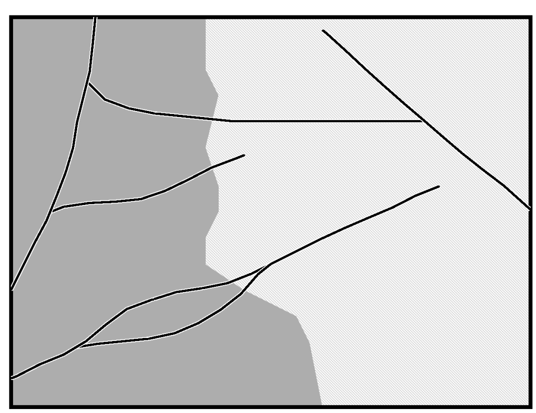

Figure 6. Final outcome of simulated fracture traces at surface.

The procedure begins with the seeding of the initial fracture segments, each one of which is assigned an initial direction of propagation and an intended final length. For deterministic fractures that can be identified from aerial photography or surface reconnaissance (the grey lines in Figure 1), the initial fracture segment is seeded at the midpoint, the initial direction of propagation is determined from the lineaments orientation at its midpoint and the intended final length is the length of the known fracture. In areas of poor bedrock exposure (the darker region on the left of Figure 1), additional fractures are seeded to bring the number of fractures up to the number predicted by the user-specified model of fracture density. These hidden fractures are assigned their locations according to a clustered Poisson process; their initial orientations are drawn from the model of azimuth distribution and their intended final lengths from the model of fracture length distribution. The filled dots in Figure 1 mark "constrained" endpoints, those whose propagation will be governed by the trace of known fractures. The open dots mark the "free" endpoints, those whose propagation will be determined by sequential gaussian simulation.

Figure 2 shows how free endpoints are propagated. These are visited in a random order and each one is propagated a fixed step length. The direction of propagation is determined by simple kriging[4,5] using the closest segment of each nearby fracture as conditioning data. In the example shown in Figure 2, the azimuth data used in the kriging for the free endpoint marked by the question mark are shown in black. One additional piece of data (shown in grey) is included in the kriging: a point halfway to the nearest neighbour, with an orientation parallel to the line segment that connects the endpoint being propagated to its nearest neighbor. For the example in Figure 2, the distribution of possible azimuth directions has a mean of 70° and a standard deviation of 12°; this is shown by the pie-shaped slice centered on the mean and with an angular width of two standard deviations. A specific direction (the dashed line) is randomly drawn from the distribution and the endpoint is propagated in that direction.

With simple kriging being performed on the strike of the fracture traces, a variogram model is required for this strike attribute. For long features that are very nearly linear, the variogram of the fracture's strike will show strong spatial continuity, typically modelled with quadratic behavior at short distances and with little or no nugget effect. For features that undulate, are kinked or meander, the variogram of strike will show less spatial continuity and may be modelled with a small nugget effect. The use of variogram information on the strike ensures realistic portrayal of the fractures' undulations.

Figure 3 shows how constrained endpoints are handled differently. For simulated fractures that track deterministic features, their propagation simply follows the trace of the identified fracture. In the example in Figure 3, the constrained endpoint marked with the question mark is propagated along the trace of the deterministic trace shown in gray. As each endpoint is propagated, a new line segment is created. As in a conventional sequential simulation procedure, each newly simulated segment is available for use in all subsequent simple krigings.

When the propagation of a free endpoint collides with a previously simulated endpoint, that endpoint is terminated with a user-specified probability. Setting this truncation probability to 1 guarantees that when fractures meet, one of them will terminate, a pattern common with faults. Using lower probabilities allows fractures to cross each other, a pattern common with joints.

If both the free endpoints of a hidden fracture are terminated before the fracture reaches its intended length, then the remaining unused length is assigned to a fracture still being propagated. This preserves total fracture length in the study area, at the expense of increasing the variance of the fracture length distribution, a result of allowing more shorter fractures, as well as more longer ones.

Figure 4 shows the example after one complete iteration through all endpoints. As can be seen near the bottom of this figure, hidden fractures seeded in areas of poor exposure are allowed to propagate some user-specified distance into areas of good exposure.

Figure 5 shows the result after five complete iterations through all endpoints. Some of the fractures, such as the one whose initial propagation was shown in Figure 2, have reached their intended length and do not propagate any further. Others, such as the "hidden" one that first crossed into the area of good exposure in Figure 4, have terminated against other lineaments and do not propagate further. Some constrained endpoints, such as the eastern tip of the deterministic fracture noted in Figure 3, have been terminated because the lineament ends in an area of good bedrock exposure. Other constrained endpoints, such as the other end of the same feature, have passed into areas of poor bedrock exposure. When this happens, the endpoint becomes free and its propagation is governed by the SGS procedure since there is no longer a deterministic trace that can be followed.

Figure 6 shows the final result after several more iterations. The fractures originally identified in regions of good bedrock exposure have been honoured; additional fractures have been added in regions of poor exposure; certain features have grown together into larger connected fracture systems; fractures truncate against each other in a plausible manner.

II.B Propagation to Depth

Once the surface traces of the fractures have been simulated, the next step is the down-dip propagation of these traces to depth. This is accomplished using the same SGS procedure that was used to govern the 2D propagation of free endpoints. For the 2D propagation of surface traces, the geometric attribute being simulated was the strike direction of the fracture. For the down-dip propagation, the simulated attribute now becomes the dip of the fracture surface.

In the same way that each endpoint was propagated using SGS in 2D by simulating an appropriate strike direction, each line segment is now propagated down-dip, with SGS being used to simulate an appropriate dip. If the dip of a particular fracture is known (from surface reconnaisance measurements, for example), then this known dip can be used. The more common situation is that the dip is not known precisely, but only approximately. For example, regional tectonic considerations often imply that a certain set of fractures are likely the type of low-angle features commonly found in compressional environments; similarly, high-angle and sub-vertical features are usually more common in tensional environments.

When the dip of a particular fracture is not known precisely, SGS can still be guided to plausible values for the simulated dip by appropriate choices of the local mean used in the simple kriging, and by the sill of the variogram, which governs the kriging variance and the spread of the local conditional probability distributions of dip. Adjustments to the local mean can also be used to cause low-angle features to flatten with depth, a characteristic common of compressional “thrust” faults.

When there is no site-specific information on the fracture location at depth, as is typically the case for preliminary site characterization, all line segments are treated as “free” segments: they are not constrained to follow a specific down-dip trajectory. In applications where subsurface investigations do provide specific information on fracture location at depth, this type of data is easily accommodated in the same way that it was for the 2D propagation. The line segments corresponding to certain fractures can be treated as “constrained” and can be required to follow a specific trajectory.

II.C Properties of Simulated Fracture Networks

Once the down-dip propagation of the fracture surfaces is complete, we have a complete 3D model of the geometry of the fracture network that:

- honours the surface traces of all identified fractures and, if available, subsurface information on the location of specific features;
- includes additional stochastic fractures in areas where poor exposure causes deterministic fractures to be under-represented;
- honours the fracture length distribution;
- honours the fracture orientation distribution; and,
- honours the user’s assumptions about how fractures truncate against one another.

Several applications of this method to different case study examples confirm that the resulting geometry is plausible both from a geomechanical point of view, as well as from a structural geology point of view[7,8].

Figure 7 shows an example from a sub-regional flow model of the kind of risk assessment information that can be developed from these probabilistic fracture network models. The map in Figure 7 shows the probability of encountering a fracture at a particular depth below the surface. Such a map can assist with the selection of regions that have a good chance of avoiding major fractures, such as the black square in Figure 7, which is the footprint of a hypothetical waste repository.

The probabilities shown in Figure 7 are calculated directly from a set of 100 equally likely renditions of the 3D fracture network, each honouring the same set of surface lineaments. For each pixel on the map in Figure 7, the probability (in %) of encountering a fracture is simply the number of renditions in which a fracture passes through that particular pixel.

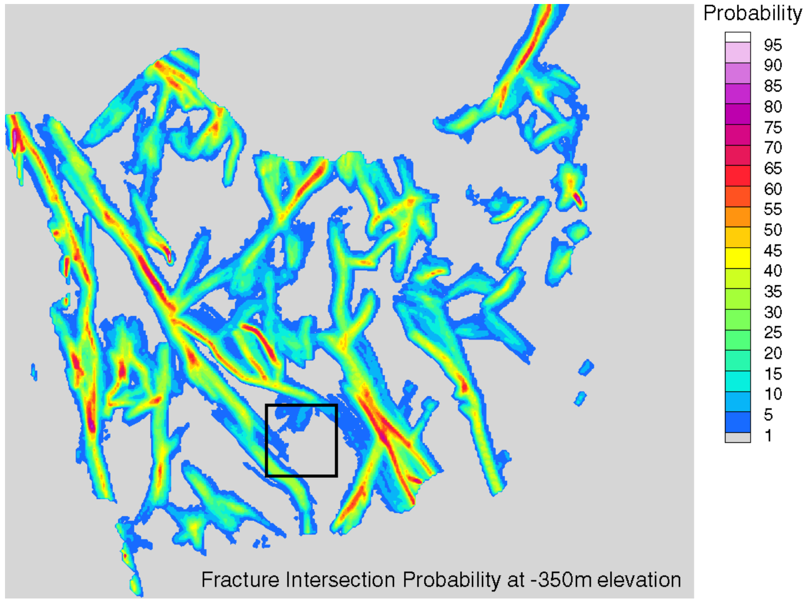

Figure 7. Fracture intersection probabilities calculated from a probabilistic FNM.

LÄGERDORF CASE STUDY

From December 1990 to May 1992, GEO-RECON, a Norwegian consulting company, undertook a fracture mapping program[9] at the Lägerdorf quarry in northern Germany on behalf of the Joint Chalk Research Program, a multi-company research program that focused on subjects related to North Sea chalk reservoirs. This data set was used to check the ability of the FNM simulation procedure to create fracture geometries that realistically portray geometries actually observed in field data.

The Lägerdorf data set consists of highly detailed maps of fracture traces for 12 parallel faces of one wall of the quarry as it was advanced in small increments (roughly 1 to $1\frac{1}{2}$ metres). Each face map spans a region approximately 230 metres long by 40 metres high. All sections are inclined at approximately 50°. The faces were available for mapping during production, where the excavation process continuously scrapes a layer of $1\frac{1}{2}$ m thickness off the quarry wall by an abrading conveyor belt. During the period when the 12 faces were mapped and described structurally, the quarry wall was advanced 25 metres. The set of 12 face maps therefore represents a high resolution $2\frac{1}{2}$D fracture data set of a 230×40×25m volume.

Figure 8 shows the face maps of the fractures on walls 7 through 11. There are three major directional sets:

1. A set with steep westerly dips; these are particularly dense near two major shear zones identified as S1 and S2 on the map for Wall 10 on Figure 8.

2. A set with steep easterly dips; these are less common than the first set, but have similar lengths.
3. A set with shallow easterly dips; these are particularly dense along two marl layers identified as M1 and M2 on the figure below. They tend to be shorter than the steeply dipping fractures. As shown in the examples in Figure 8, the major shear zones offset the marl layers.

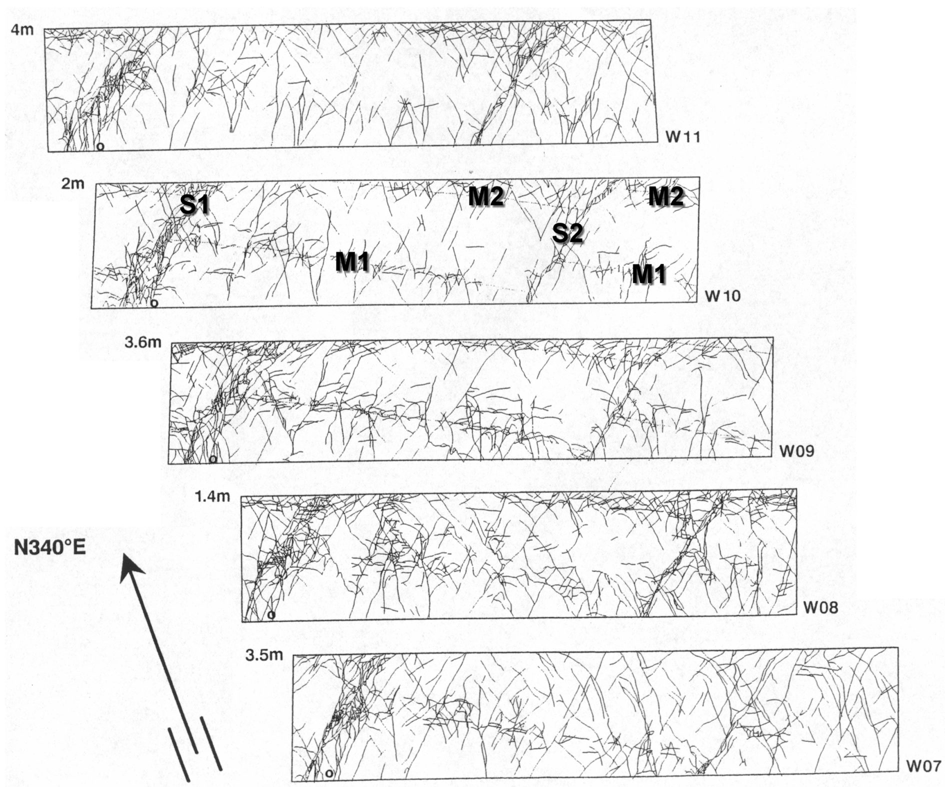

Figure 8. Lägerdorf quarry fracture maps on walls 7 through 11.

To test the SGS-based geostatistical procedure for fracture simulation, the stack of parallel face maps was rotated so that the walls are essentially horizontal, with Wall 1 being at the top and Wall 12 being at the bottom. Following this rotation, we are able to treat the data from Wall 1 as a set of deterministic "surface" fractures that will be used as conditioning data for a simulation of 3D fracture geometry. In order to make the test as illuminating as possible, *all* data from Walls 2 through 12 were ignored. Once a set of simulations of 3D fracture geometry has been developed, each realization can be sliced along planes corresponding to the walls not used as conditioning data and the resulting simulated face map can be compared to the actual face map for each wall.

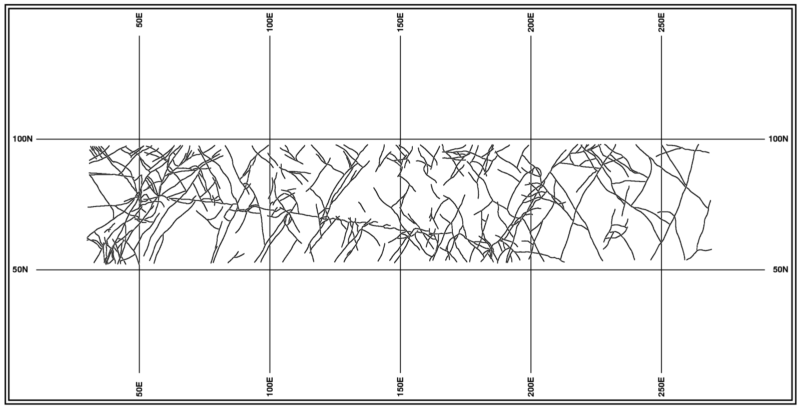

Figure 9. “Surface” fractures from Wall 1.

Figure 9 shows the conditioning data from Wall 1, the “surface” data for the test of the simulation procedure. In order to check the 2D propagation at surface, the area covered by the mapped fractures on Wall 1 was extended to create a border, construed as a region of poor bedrock exposure where no deterministic fractures have been identified and where the simulation procedure will need to create a plausible rendition of hidden fractures.

Figure 10 shows one realization of the simulated traces at surface. The deterministic features identified by GEO-RECON are all honoured, and pass quite seamlessly into the border region where the fracture traces are all simulated.

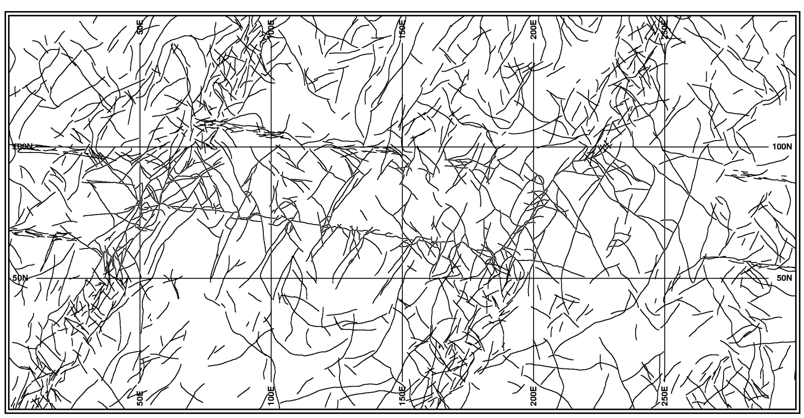

Figure 10. Realization No. 1 of simulated surface fractures.

Figure 11 shows two realizations of simulated traces along the surface corresponding to Wall 11, along with the actual data from Wall 11. While the simulated fractures do have a plausible overall appearance, some of the details have been shifted slightly. The marl layers, for example, do not appear on the simulations at the same location as they do on the actual face map. The reasons for this discrepancy are well understood.

By strictly limiting the data available to the simulation to the measurements gathered from Wall 1, our model of the orientation of the marl layers (and of the shear zones) is dependent entirely on the extrapolation of the planar orientation deduced from measurements

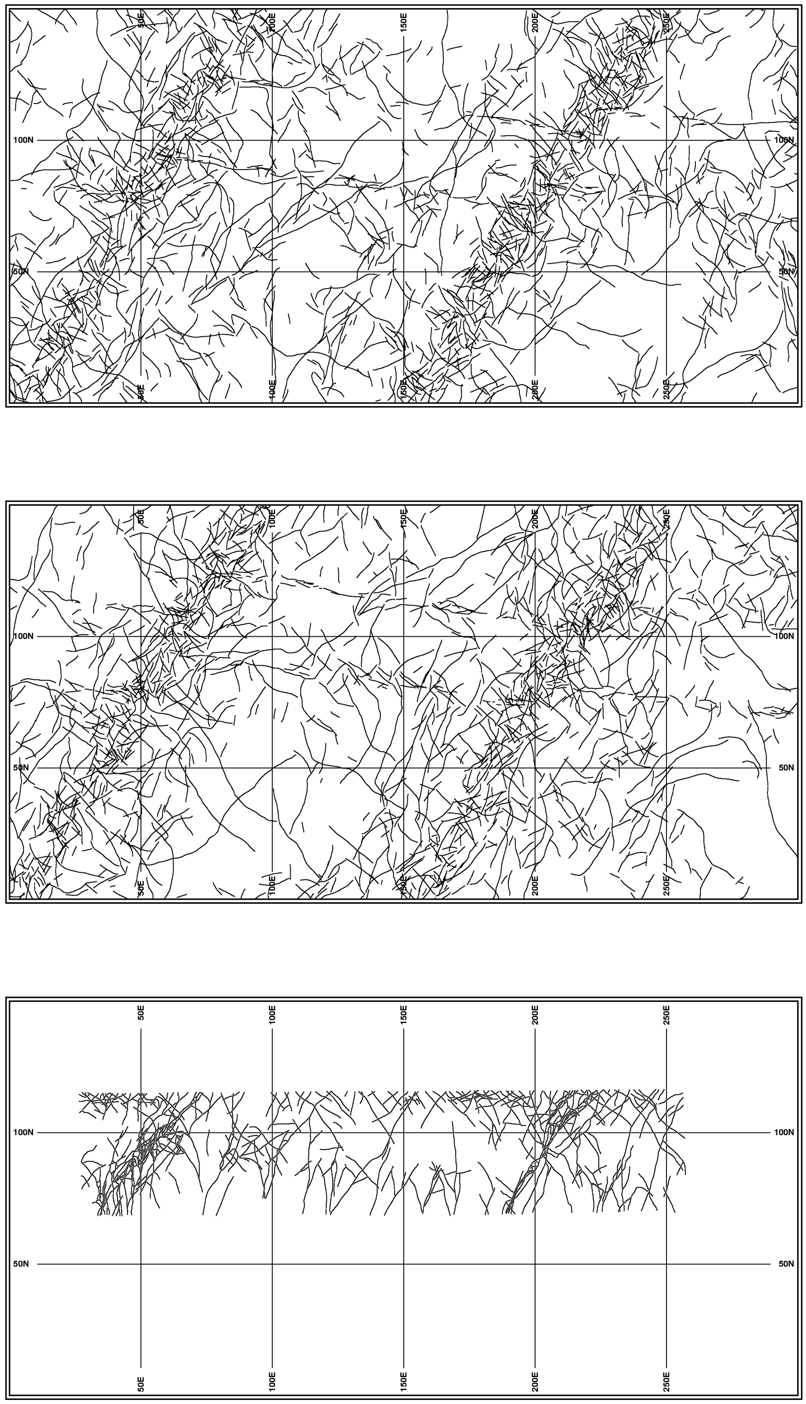

Figure 11. Simulated and actual fractures on Wall 11.

available on Wall 1. The orientation of the marl layers deduced from Wall 1 data alone is slightly different than the orientation one can calculate from the full data set. So although the simulated fractures are definitely off in their depiction of the exact location of the densely fractured zones, this error would easily be corrected once subsurface investigations such as boreholes provided accurate 3D information on the location and orientation of the major geological features.

Future studies will compare the actual field data to the statistical and geometric characteristics of the clusters of simulated fractures. Flow simulation will also be used to compare actual and simulated flow-related characteristics, such as peak arrival times of injected tracer. For the moment, the preliminary results from the Lägerdorf case study are encouraging. The SGS-based procedure does create 3D fracture network models that are visually plausible and that honour complex and highly detailed surface information.

IV. CONCLUSIONS

The proposed procedure for simulating fracture networks has now been tested on a variety of different problems at various scales. Studies at the regional scale and the sub-regional scale have demonstrated that the procedure is able to produce simulations that honour the surface traces of thousands of fractures while also producing fracture geometries at depth that are consistent with observations from geological analogs and with structural geology principles.

The Lägerdorf case study offers confirmation that the procedure does generate highly detailed and complex fracture patterns that are observed in actual field data.

ACKNOWLEDGEMENTS

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