A methodology to construct training images for vein-type deposits ☆

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Abstract

Fracture models of vein formation can produce realistic training images (TIs) for use in multiple-point geostatistics. Vein formation is modeled by applying flow simulation to a fracture model to mimic the flow of an ore-bearing fluid through fractured rock. TIs are generated by assuming that veins form in areas of high flow where there would be preferential deposition of the mineral of interest. We propose a methodology to simulate mineralized veins by constructing a fracture model within the deposit, modeling the permeability and simulating the flow of ore-bearing fluids. The veins are defined by considering the areas of high flow. The methodology is implemented with a fracture model of the Whiteshell area in Manitoba. To assess the reasonableness of the TIs, comparisons are made to geological models of gold deposits in Quebec and Nova Scotia that display similar geometric characteristics such as braiding, thickening and thinning. A FORTRAN program TIGEN, based on GSLIB program formats is included and can be used to generate TIs from fracture models.

Keywords: Facies model; Geostatistics; Multiple-point statistics; Training image; Vein; Mineral deposit

1. Introduction

GRADE ESTIMATION often requires a prior geological model that defines the extension, shape and distribution of geological units. These units are characterized by a particular lithology, alteration and mineralogy that determine the behavior of the processed ore extracted by a mining method. Furthermore, the spatial continuity of ore grade changes from one unit to another. Therefore, constructing the geological model is key for the good performance of any numerical model of the grades within an ore deposit.

Several approaches exist to create the geological model. Deterministic modeling is the most common approach (Duke and Hanna, 2001; Sinclair and Blackwell, 2002); however, several geostatistical methods have become available for stochastic simulation of the geology (Deutsch, 2002; Armstrong et al., 2003). These conventional geostatistical techniques are often limited to calculating and using

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second-order statistics such as the covariance or variogram. Common practice has been to use variogram models to represent the geometry of mineral deposits in stochastic models. Multiple-point statistics (MPS) goes beyond two points and considers the relationship between multiple points (Guardiano and Srivastava, 1993). Practical analysis of data has been confined to the variogram because MPS requires a much larger number of samples, which are often expensive to obtain, and which are configured such that many replications of particular patterns cannot be found and used for statistical inference. This problem can be solved by using densely drilled production samples from blast holes (Ortiz and Deutsch, 2004) or by using a training image (TI) (Strebelle and Journel, 2000). The availability of dense sampling is not realistic in the early stages of mining and can only occur once mining has started and production data (blast hole samples) are gathered. In addition to this, the geological units are not always logged in blast holes. TIs appear as the primary solution to obtain the statistics required for MPS in the early stages of mining. A TI is a model that is exhaustively populated by the variable of interest (for example, an integer code specifying the geological units). A large TI ensures that statistics between any number of points can be obtained. The use of MPS is limited by the robustness of the statistical inference and the computational effort required to extract the relevant information. Solutions to these problems are becoming available, such as Zhang et al. (2004), Liu et al. (2004) and Arpat and Caers (2004). Even as these difficulties are overcome, MPS methods are still dependent on representative TIs, just as traditional variogram-based methods are dependent on the variogram model.

The problem facing the mining industry is that there are currently no TIs of geological units readily available for a practical application of MPS. There are TIs appropriate for fluvial and deepwater oil reservoirs (Pyrcz and Deutsch, 2003); however, the mining industry is limited to using data from extensively sampled areas. If mining geostatisticians wish to use MPS to model their deposit, they must seek a mined out area or a similar deposit that has been extensively sampled and use the statistics from that area to apply simulation methods that consider those MPS to their deposit of interest. This has drawbacks such as the difficulty in finding a deposit that has been both extensively sampled and is similar to the deposit of interest, as well as the reluctance of many companies to share their production data.

A practical solution to this problem is to create computer programs that can generate TIs given specific information about the deposit of interest. We propose a methodology to model the formation process of vein deposits. We do not extend our scope beyond vein deposits in this paper; however, we anticipate that similar consideration of depositional processes could be used to generate TIs for other types of mineral deposits. Our methodology to model the geological formation of veins begins with a fracture model that is representative of the deposit of interest. These models can be obtained from a variety of sources and require knowledge of fracture spacing, orientation, prevalence and density. If this type of information is known about the deposit, then the proposed methodology can be implemented by the practitioner to generate a realistic TI for use in multiple-point geostatistics. MPS-based techniques can then be used to carry the structure seen in the TI into the model (Journel, 2004). Not only are statistics between two points honored, the statistics between many points can be reproduced, thus enabling the model to display many of the characteristics of the TI, while also honoring the data specific to the deposit of interest.

First, a brief overview of the geological formation of veins will give the reader the necessary background to judge the effectiveness of the TI in mimicking this type of formation and the usefulness of the TIs. A description of each step in the TI generation process is then followed by a visual comparison of the TIs to geological interpretations of vein-type deposits.

2. Background: vein formation

This paper proposes a methodology for creating TIs for vein-type mineral deposits by modeling the geological formation of veins. Therefore, conceptual understanding of the formation of veins is necessary. Specifically, the type of ore-bearing fluid, its movement through fractured rock and the deposition of a mineral of interest from the fluid must be appreciated so that we can mimic the expected structures.

The nature of the ore-bearing fluid will greatly affect the type of ore deposit formed. Each ore-bearing fluid has its own unique properties: silicate-dominated magmas; water-dominated hydrothermal fluids; meteoric waters; seawater; connate waters; and fluids associated with metamorphic processes. Guilbert and Park (1996) describe the characteristics of these ore-bearing fluids in detail. This paper is primarily focused on how these ore-bearing fluids move through their surrounding rock and deposit ore to form mineralized veins. To this end, the type of ore-bearing fluid is only important insofar as it affects the viscosity and density of the fluid used in flow simulation.

The ore-bearing fluid travels through the host rock obeying physical laws dictated by the fluids viscosity and density, the host rocks permeability, interconnected pores, fractures, faults and the natural pressure gradients due to in situ stresses (Guilbert and Park, 1996). Veins are created when the movement of these fluids is guided by major structures such as faults or fractures and these fluids may even open new or closed fractures by hydro-fracturing (Guilbert and Park, 1996).

The movement of a fluid through rock is determined by the permeability of the host rock. Permeability is influenced by a number of factors such as porosity, interconnected pore spaces, fractures/faults and folds. Veins are created when the path of highest permeability through a rock is highly influenced by fracturing and faulting rather than by rock properties such as porosity and interconnected pore spaces. When this occurs, the fluid will preferentially flow though the faults and deposit minerals in vein-type structures. Different types of faulting and folding are shown in Fig. 1. Each type of faulting will result in a different type of vein structure.

TIs to be used in multiple-point geostatistics will be created by mimicking the vein formation process described above. The basis for this proposed methodology lies in the availability of a fracture model. There are several ways to create a fracture model. Stochastic simulation has been used to create fracture models (Chilès, 1989), although physical models are also available (Takayasu, 1985). In this paper, we focus on a fracture model

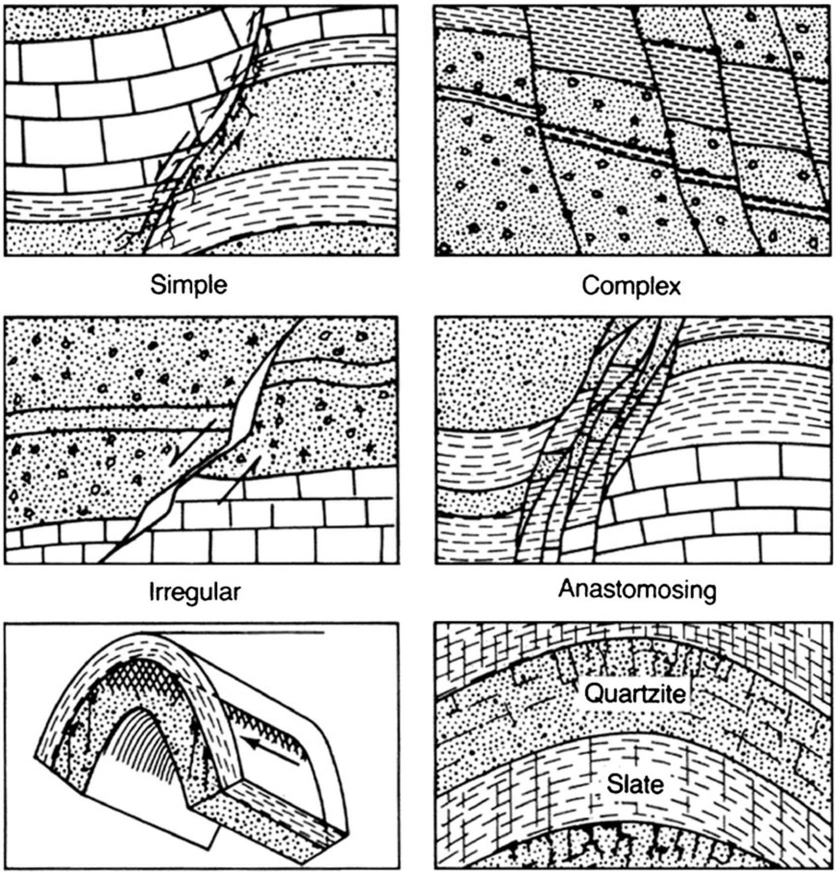


Fig. 1. Types of basic folding and faulting (Guilbert and Park, 1996).

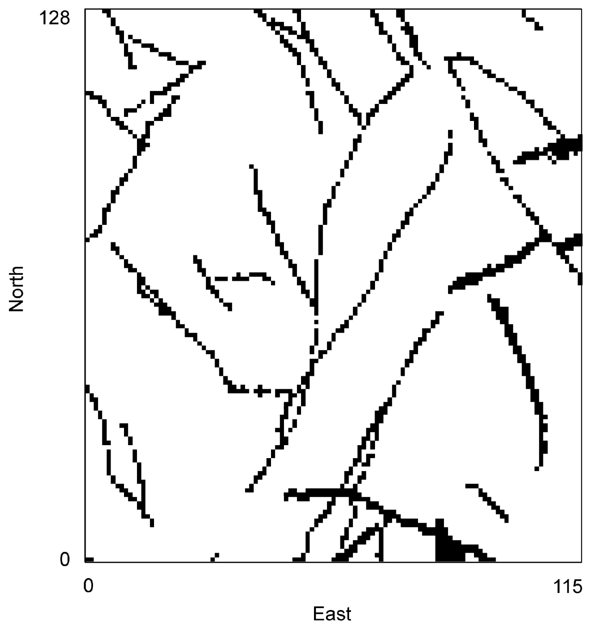


Fig. 2. Typical horizontal slice of Whiteshell fracture model. Originally fractures are planar features described by triangular facets but have been rasterized into a block model. Unit block size.

created for the Whiteshell area, in Ontario, Canada, as provided by Srivastava (2002).

One idea would be to use the fracture models directly as a TI, bypassing many of the steps in the proposed methodology; however, there are a number of undesirable features present in fracture models that make it desirable to use them as input to flow modeling first. Fig. 2 shows a section of Srivastava's (2002) fracture model for the Whiteshell area. The fractures are disjointed and end abruptly making this image inappropriate for use when modeling vein deposits. Moreover, the edges of the fractures are rough whereas veins typically appear smoother with a higher degree of connectedness. This is the motivation for using flow simulation through the fracture model, as desirable features such as smoothness and connectivity can be controlled. The resulting TIs appear to be more realistic.

3. Proposed methodology

In order to generate a realistic TI, the movement of the ore-bearing fluid through the fractured host rock will be modeled by applying a flow simulation to a fracture model. The TIs will be created by associating areas of high flow with vein locations. Specifically, the methodology for generating TIs for vein deposits consists of

1. generating a fracture model;
2. modeling the permeability of all areas in the model;
3. running a flow simulation on the permeability model; and
4. creating a TI by considering veins to be areas of high flow.

A detailed explanation and rationale for each step follows.

3.1. Step 1: fracture model generation

Fracture models can be obtained from: (1) programs that seed fractures and then propagate them according to known stress regimes; (2) programs that draw fracture characteristics from a distribution and place these objects randomly in a model; or (3) models of areas where the fractures and faults have been extensively mapped.

The fracture model is extremely important for the generation of a TI as it has a large influence on the features present in the final TI. The following should be considered when generating the initial fracture model:

- *Fracture spacing*—This will influence the density of veins in the TI.
- *Sets of fractures*—If there are multiple sets of veins in the deposit, fractures corresponding to all directions should be created.
- *Fracture orientation*—This will control the direction(s) of anisotropy.
- *Fracture terminations*—A high density of fractures could result in instances when a newer fracture will be truncated by an older fracture. This would affect the overall flow regime of the model.
- *Fracture shape*—The exact shape of a fracture differs with fracture type (braided, regular, irregular, complex, conjugate, etc.). Moreover, fractures often flatten with depth (Srivastava, 2002).

A realistic TI depends on the choice of an appropriate fracture model and should consider the features mentioned above. The fracture model of a specific deposit must be inferred from site-specific observations and other similar deposits.

3.2. Step 2: permeability

In order to run a finite-difference flow simulation on a fracture model, the permeability of the area must be established. Permeability can vary by depth, rock type, fracture type/orientation, etc. Unlike permeability modeling in the petroleum industry, which commonly depends on a stochastic approach conditioned to available well logs, core plugs and/or seismic data, this particular application requires a permeability model in the *absence* of conditioning data. The resulting TI will be used to create geologic features for the purpose of constructing heterogeneous models of mineral grades.

In the example presented in the next section, it is assumed that the area of interest is characterized by a binary mixture of fractured and non-fractured rock at an arbitrary grid resolution. The permeability of the fractures is uniform, but higher than the permeability of the surrounding host rock. Refinement of the TI and a sensitivity analysis of the resulting images to different flow thresholds (and hence permeability regimes) are considered in a latter section. This assumption of a binary permeability field is simplistic; however, it will serve to demonstrate the methodology. Within the available code there is the ability to consider heterogeneous permeability as well as variations in k_x, k_y and k_z.

3.3. Step 3: flow rate calculation

A steady-state flow simulation is then run on the permeability model to calculate the pressures in each block. The flow simulator used in the example is FLOWSIM (Deutsch, 1987), which applies a constant pressure gradient across the model in one direction with no flow boundary conditions on the other faces in the model, as shown in Fig. 3.

This flow simulation generates the pressure in each block of the fracture model. From the pressure difference between blocks, the flow into and out of each block can be calculated from Darcy's law:

$$Q = AK\,\Delta p/(L\rho g), \qquad (1)$$

where Q is the volumetric flow rate, A is the surface area of the face through which flow occurs, K is the hydraulic conductivity, Δp is the change in pressure across the volume, L is the length of flow, g is the acceleration constant due to gravity and ρ is the density of the ore-bearing fluid; in this case water is used as the ore-bearing fluid. In this version of Darcy's law the change in elevation is ignored.

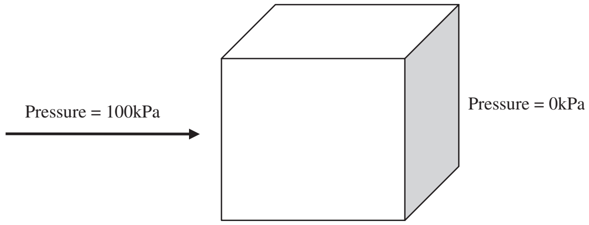


Fig. 3. Pressure gradient in x direction with box representing 3D fracture model.

The calculation of the total flow rate through a single block in the model is the sum of the flow through each face of the block. The net flow rate in a block will be zero because of conservation of mass; therefore, the absolute flow rate from each block into (or out of) the block is summed to obtain the flow through the block. This results in a flow rate that is actually twice the flow rate through the block because the absolute flow rate is used. The relative magnitudes of twice the flow rate will still give an accurate picture of where the veins are located, so this Q is used.

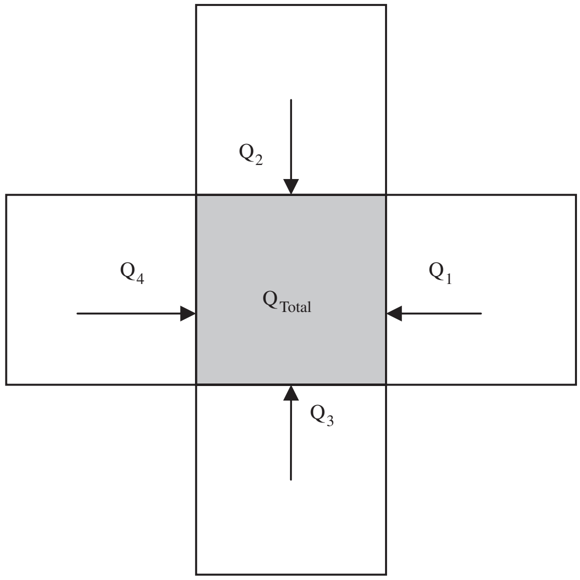
Since FLOWSIM only considers flow in the direction of the pressure gradient, multiple flow simulations considering flow in all three principal directions should be considered. The absolute flow rate for a block is calculated for each pressure gradient (see Fig. 4) and the sum of the four flow rates is taken as the total flow rate through the block. This is not the actual flow rate in the block, but a high value for this flow rate will correspond to a high flow rate for the ore-bearing fluid.

3.4. Step 4: locate veins

The final step is to apply a threshold cutoff to the flow rates. Veins are identified by blocks that have a high flow rate. This threshold can be adjusted depending on the desired vein structure. The highest flow rates are located in the blocks that contain fractures with the flow rate gradually decreasing in nearby blocks. Narrow veins can be generated by applying a relatively high threshold on the flow rate. If this threshold is decreased, additional blocks will fall above the threshold, thus generating a thicker vein structure.

4. Example

The proposed methodology is applied to a section of Srivastava's (2002) fracture model of the



$$Q_{total} = |Q_1| + |Q_2| + |Q_3| + |Q_4|$$

Fig. 4. Calculation of total flow rate in a block for two pressure gradients.

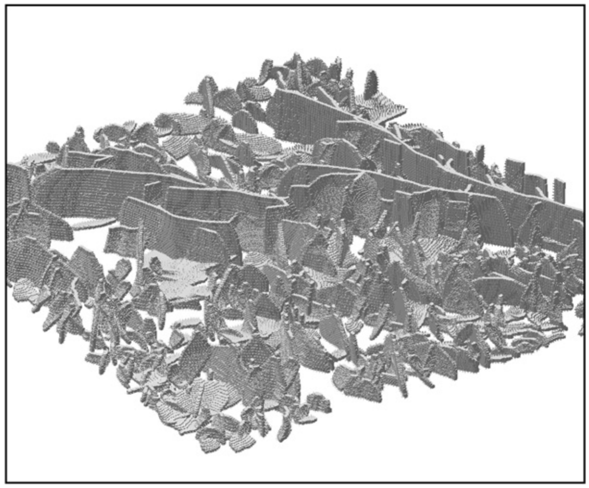


Fig. 5. View of fracture model. Fractures are shown in gray, host rock is transparent. NTS but area covered is 12×12 km.

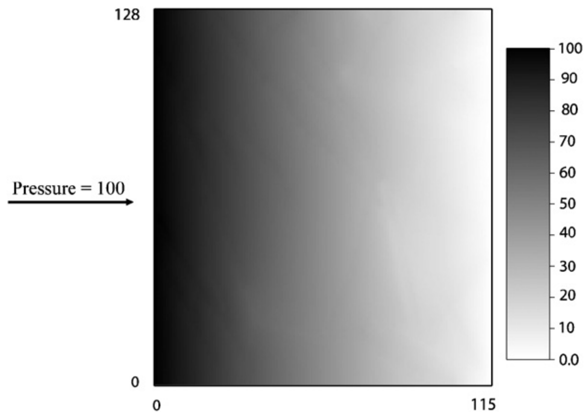


Fig. 6. Slice of pressure with a horizontal pressure gradient generated from FLOWSIM (Deutsch, 1987). Pressure is shown in kPa. Unit block size.

Whiteshell area in Ontario. Fig. 5 is an image of the fault model. To illustrate the methodology, only a small area (approximately 10%) of this fault model is used to generate the TIs in this paper. This smaller area consists of over 160 000 blocks (specifically, $115 \times 128 \times 11$); Fig. 2 shows the orientation of the faults in this area for a specific aerial slice of the 3D model. This horizontal slice will be used throughout this paper to examine the effects of changing different parameters in the process to generate different TIs. All TIs are generated in 3D.

4.1. Steps 1 and 2—fracture model and permeability

The fracture models used for this paper were generated by Srivastava (2002) by merging geostatistical techniques with fracture modeling principles. This fracture model is a discrete fracture model where each fracture is defined by a triangular mesh or surface. For the purposes of flow simulation, a block model is created from the discrete model; blocks containing a fault are assigned a high permeability and areas without faulting are assigned a low permeability. The exact permeability values are varied in order to assess the effect of permeability on the final TI.

4.2. Step 3—flow rate calculation

A flow simulation of the permeability model is run using FLOWSIM (Deutsch, 1987) and the pressure in each block is obtained. Pressure gradients in the x and y directions are considered. Fig. 6 is a slice showing the pressure in each block and is typical of all pressure slices in the model. When the pressure gradient is in the y direction the result is visually identical but rotated. As described previously, the pressure in each block is used with Darcy's law to calculate the absolute value of the flow rate in each block for each pressure gradient.

The flow rates for both the x and y direction pressure gradients are shown in Fig. 7 with the pressure gradients indicated. Two areas where the effect of changing the gradient direction is most noticeable are highlighted. Moreover, notice that there are many anomalies near the boundaries of the faults. Often low flow rates are seen on the fault boundaries, this is not desirable as there should be high flow near the faults and low flow between faults. Fig. 8 shows the effect of combining the flow rates in the x and y directions. The program TIGEN can be used to generate the flow rates in the x and y directions.

Many of the anomalies seen near the fault boundaries in Fig. 7 are not as prevalent in Fig. 8 because the flow rates in the two directions are combined. The areas of low flow are still present in Fig. 8, but the flow rates are more continuous at the boundaries between high and low flow rates. This boundary effect may be further mitigated by also considering the flow rate in the z direction.

4.3. Step 4—locate veins

The images in Table 1 show how different aspect ratios for the permeability affect the final TI. The aspect ratio is defined as the value of the permeability for the blocks containing a fracture divided by the permeability of the blocks without a fracture. For example, an aspect ratio of 2:1 assigns fractured areas a permeability of 2 mD while the host rock receives a permeability of 1 mD. Different thresholds on total flow rates are also applied to generate multiple TIs. Decreasing the threshold assigns more blocks to be mineralized and has the effect of allowing the vein to expand further into the surrounding rock, in this way thicker veins can be created. Moreover, a cleaning algorithm, maximum a posteriori selection (MAPS) (Deutsch, 1998), could be used on each TI to smooth out rough areas and create a more continuous TI. MAPS uses a moving window average and applies weights to each nearby block depending on the distance from the block in the center of the moving window.

5. Discussion

The distance the vein extends into the rock matrix can be controlled using either the aspect ratio or the threshold cutoff; increasing the aspect ratio or the cutoff will restrict the veins expansion into the rock matrix. This allows the user to create different TIs based on the geology of the veins being modeled.

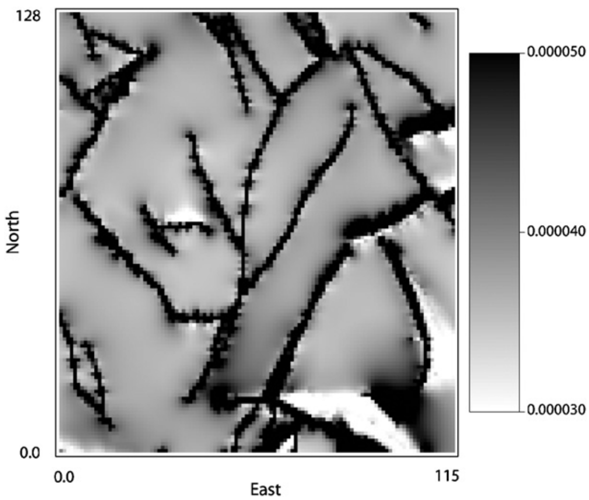


Fig. 8. Combined flow in model for pressure gradients in x and y directions. Pressure is shown in kPa. Unit block size.

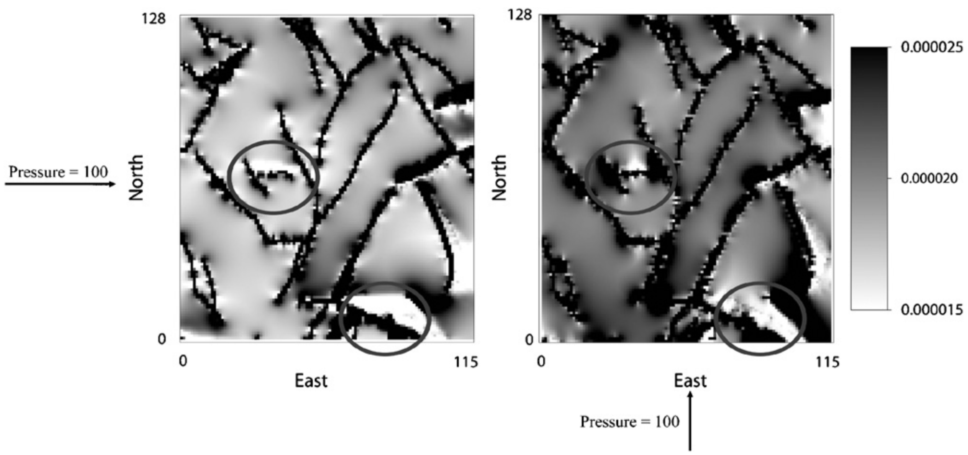


Fig. 7. Total flow in model for pressure gradients in x (left) and y (right) directions. Pressure is shown in kPa. Unit block size.

Table 1
Horizontal sections of TIs showing the effect aspect ratio and threshold have on images

	Aspect ratio = 3:1	Aspect ratio = 10:1
Low threshold on flow rate		
Medium threshold on flow rate		
High threshold on flow rate		

In general, the TIs seem to connect unconnected faults in a logical manner. The faults in the fracture model are connected to nearby faults using the path of least resistance due to the nature of the flow simulation; some locations where this occurs are highlighted in Fig. 9.

As mentioned previously, the disjointed nature of the fracture model is not seen in the TI generated using a flow simulation, making the TI appear more realistic. To better assess the realism of these images, they are compared with geological interpretations of actual vein deposits. Fig. 10 compares the TI with a geological interpretation of a gold mine in Nova Scotia. The circled regions show areas of similarity. Both images show thickening of the veins in areas where there are high degrees of fracturing, as well as braided characteristics. There is more braiding in the gold mine cross-section, but it can be seen that some of this braiding occurs in the TI and a change in the fracture

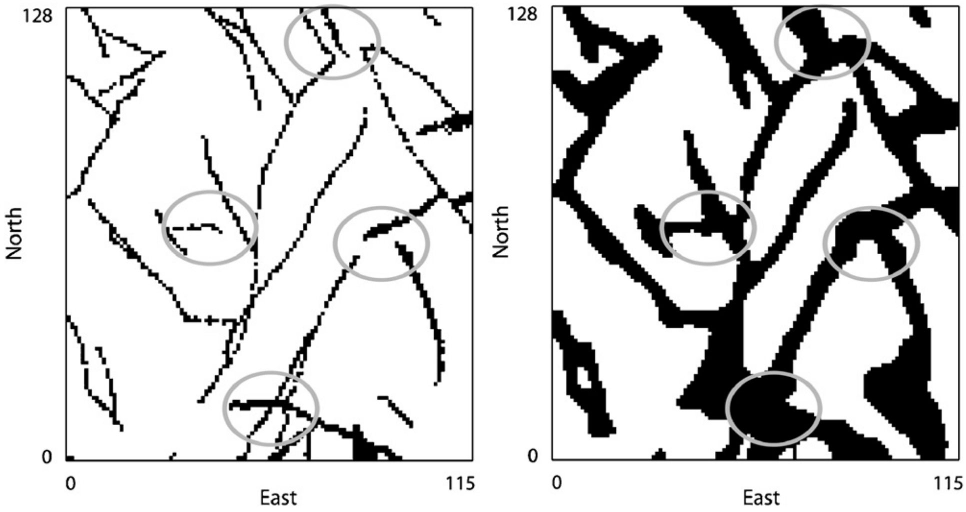


Fig. 9. Left—initial fault model; Right—TI with a 10:1 aspect ratio and a high-flow cutoff. Unit block size.

model could control the level of braiding seen in the TI.

Similar features can also be seen in the TI and the Louvicourt Goldfield deposit shown in Fig. 11. The thickenings are very similar, as are the areas that show some pockets of rock surrounded by veins. Braiding is also evident in both images as was seen before in Fig. 10.

It should be noted that there is a significant difference in scale between the fracture model used and the deposits shown in Figs. 10 and 11. In practice, an appropriately sized fracture model would be created at the scale of the deposit of interest. In this comparison we are only interested in assessing the geological realism of the TIs resulting from the proposed methodology and do not suggest that the TIs generated with Srivastava's (2002) fracture model are appropriate for the deposits shown in Figs. 10 and 11, only that they contain many of the same geological features. Important characteristics such as braiding and thickening of the veins mimic what is seen in the two gold deposits. Further manipulation of the fracture model would likely result in increased similarity between the TI and the gold deposit interpretations.

It should be highlighted that the criteria for validating these TIs are subjective, since the TIs will be considered as a good model of the lithofacies of the deposit if they are similar to the interpretation the geologist generates based on expert knowledge and the information gathered through several sampling and logging campaigns. The actual geological architecture may differ from this interpretation, and so will the TIs.

TIs can be conditioned to hard and soft data subsequently using a multiple-point simulation method, providing a model for the geology that can account for the uncertainty of the interpretation. TIs should be considered only if they make sense from a geological viewpoint. The methodology proposed aims at providing a way to materialize the geological knowledge into a numerical model.

6. Future work

The realism of the TIs must be assessed by experts in vein deposit geology prior to its implementation. Note that the TIs in this paper were generated with no advice from a geologist or an expert with knowledge of vein deposits. Consultation with an expert in vein-type ore deposits would result in a more thorough and accurate analysis of the reality and reasonableness of these TIs. Notwithstanding this required expert input, there remain many avenues for investigative research.

Firstly, only one area of Srivastava's (2002) model was considered. Examining different areas of the model with different structures will help to identify both positive and negative aspects of these TIs. Moreover, creating fracture models with features such as anisotropy, different fracture spacing, density, orientation, etc. will increase the diversity of available TIs. This could result in more realistic TIs as the user would be able to better

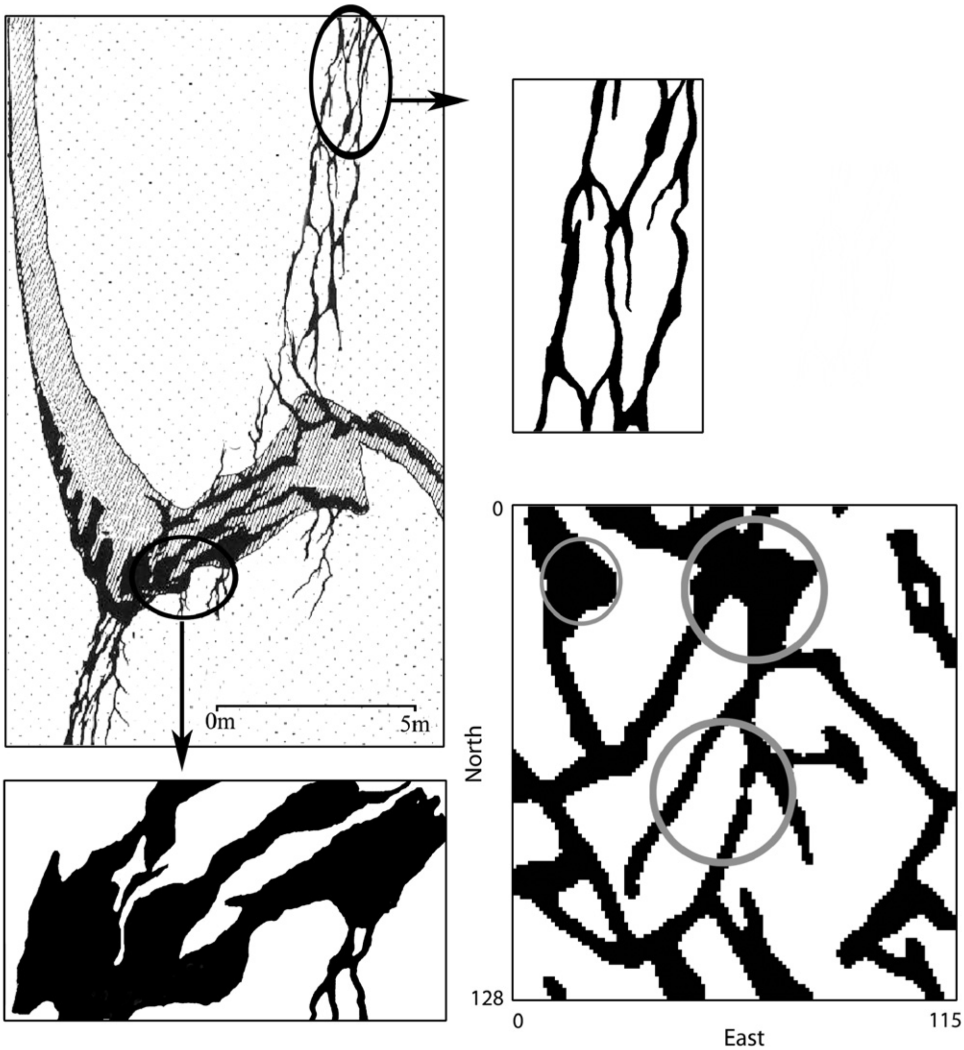


Fig. 10. Upper left, upper right and lower left—West Lake gold mine, Mount Uniacke, Nova Scotia; areas are enlarged to assist in comparing scale of features present in TI, also hatching is removed in enlarged figures for clarity (modified from Guilbert and Park, 1996). Lower right—rotated TI with a 10:1 aspect ratio and a high cutoff. Unit block size. Highlights—braiding and thickening.

control the look of the final TI. Ideally, fracture modeling software would be integrated into the TI software.

Secondly, generating a TI to match known deposit characteristics was not attempted. It would be interesting to use exploratory information such as fracture spacing, density, orientation, length and surrounding rock permeability to see how effective a multiple-point simulation with a TI generated by this methodology would be. An extension of this would be to then model the area using a traditional simulation approach and compare the results to the multiple-point geostatistical simulation using the TI.

Thirdly, the pressure gradient was only applied in the x and y directions to generate TIs. A natural extension of this would be to add the z direction gradient to more accurately reproduce the geological formation of the veins. Further, an analysis of the effect of adding the different directions of flow was not attempted. Comparing the effects of using all three directions to using only one or two directions of flow would be useful; perhaps using all three directions is redundant and using only one or two of the major directions of anisotropy would be sufficient to generate TIs.

Finally, the analysis in this paper was limited to examining two-dimensional slices of the three-

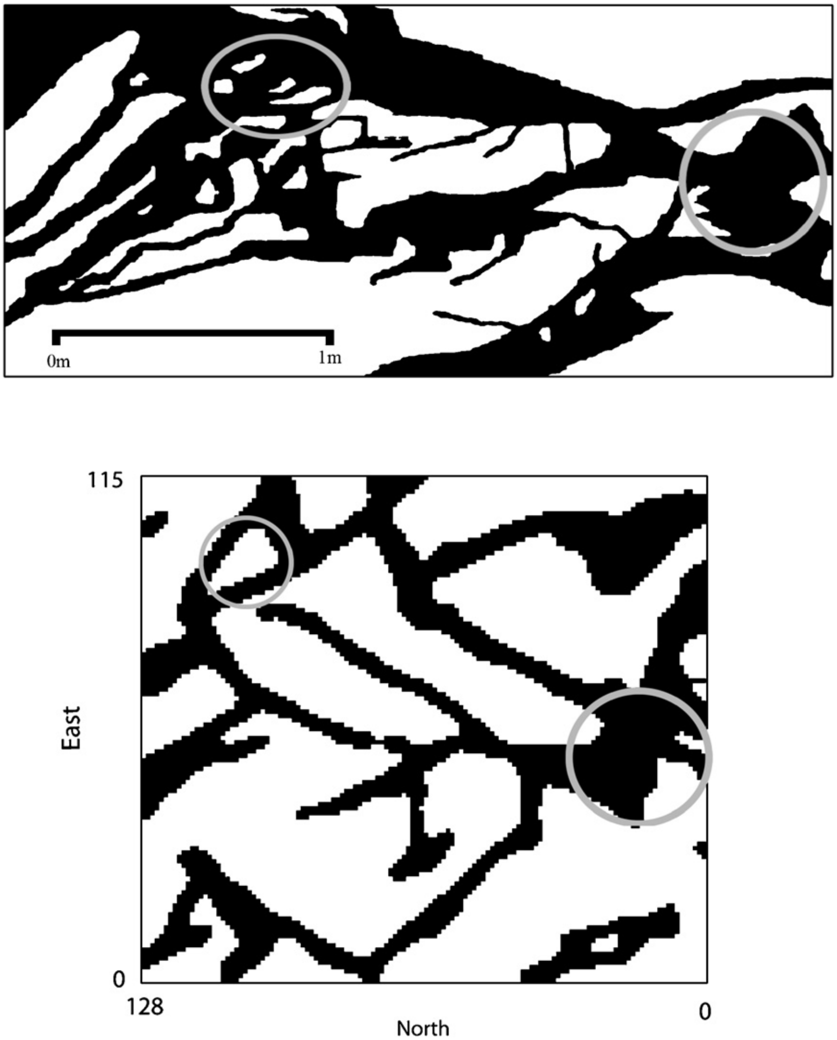


Fig. 11. Top–Louvicourt Goldfield deposit at Val d'Or in Quebec (modified from Robert and Poulsen, 2001). Below—rotated TI with a 10:1 aspect ratio and a high cutoff. Unit block size. Highlights—rock pockets surrounded by veins and thickening of veins.

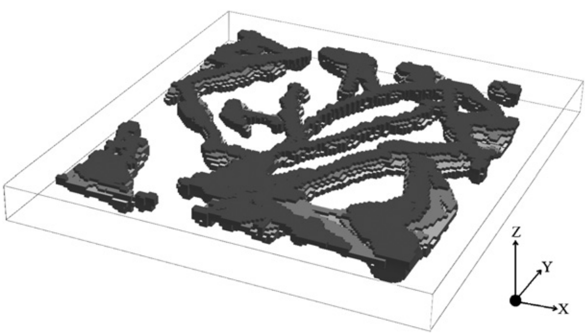


Fig. 12. Three-dimensional rendering of a TI. Aspect ratio = 4:1. Threshold = high. TI is binary showing vein locations, coloring is based on depth. Dimensions of model are $115 \times 128 \times 11$ with unit sized blocks.

dimensional TIs. A more detailed analysis of the TIs in three dimensions could expose potential problems in the methodology (see Fig. 12).

7. Conclusions

Although the images were only visually inspected and compared to images of geological models of actual deposits, there are some striking similarities between the two; this is encouraging and hopefully the line of future research presented will only increase these similarities.

TIs are of little use if they are not flexible enough to adapt to site-specific geological knowledge. One major advantage of this method is that multiple TIs could be created for any type of vein deposit—braided, thick, thin, multiple orientations, etc. All that is required is a fracture model of the deposit and then MPS could be applied to the modeling of the geologic units; however, there are currently many difficulties with implementing MPS that were not considered in this paper. Even though realistic TIs can be generated for vein-type deposits, there are still many challenges preventing the implementation of MPS. Having these images prepared for the day when software can effectively implement MPS is a useful step.

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