Extended abstract for *Applied Structural Geology for Mineral Exploration and Mining, International Symposium* (Kalgoorlie, 23-25 September 2002)

Rapid geological modelling

E.J. Cowan [1], R.K. Beatson [2], W.R. Fright [3], T.J. McLennan [3] and T.J. Mitchell [3]

[1] SRK Consulting,
25 Richardson Street,
West Perth WA 6872
Australia

[2] Department of Mathematics and Statistics,
University of Canterbury,
Private Bag 4800, Christchurch
New Zealand

[3] Applied Research Associates NZ Ltd,
Ground Floor, St Elmo Courts,
47 Hereford Street, Christchurch,
New Zealand

Introduction

Leapfrog™ software allows the construction of three-dimensional (3D) geological models from raw drill-hole data in a matter of minutes to hours, as opposed to days of manual digitisation. The method allows testing of various geological scenarios in rapid succession, including user-defined geological trends, which is not possible with techniques currently available in the resource industry.

Structural analyses of mineral deposits rely heavily on information from drill-holes but the sheer volume and 3D complexity of drill-hole data can be overwhelming to an interpreter. Adding to this dilemma, 3D geological modelling tools currently available in commercial mining software packages have limited modelling capabilities and require complex manipulation. Therefore building a model from drill-hole data may take days, if not weeks, of manual digitisation. Once generated, a mesh based model is difficult to modify, and some companies may opt not to generate 3D models of deposits due to the time-intensive and costly nature of the exercise. Furthermore, even if the models are built, the largely qualitative nature of the models may not allow objective structural interpretation to be conducted.

Leapfrog™ provides an alternative technique to generate geological wireframes from drill-hole datasets by utilising a rapid 3D interpolation method. The unique advantages of this technique are:

- The construction of geological wireframes from drill-hole data to be generated semi-automatically within a matter of hours directly from composited data.
- Qualitative geological interpretation can be rapidly incorporated into the workflow. A range of geological ideas can be therefore used to generate various "what if?" scenarios for testing.

Traditional modelling methods

The traditional method of geological modelling requires the interpretation of geology in sections during digitisation. The geological interpretation is therefore written into the modelling, and cannot be separated from the digitisation process. A 3D model is then constructed using tie-lines between the sections, and a triangulation algorithm is then applied to generate a 3D shell from the tied sectional polylines. In addition to being time-consuming, the main disadvantage of this method is the fact that the model produced is unique to each individual geologist's interpretation, and may not easily be replicated by others.

Another favoured method for modelling grade data is to interpolate the grade to regularly spaced 3D grid nodes (voxels), and then either view the data with a volume visualisation software, or create isosurfaces from the gridded data using a marching cubes meshing algorithm (Lorensen & Cline 1987). Although these methods are effective at generating grade boundaries, the resolution of the grade shells depends directly on the resolution of the voxels. The commonly jagged nature of the marching cube meshes is not ideal for structural interpretation of the data, and large datasets and/or grid nodes, may pose additional problems by slowing down the interpolation process to the extent that the method becomes impractical. The main disadvantage of this method are 1) the fact that geological intuition cannot be easily incorporated into the modelling process, and 2) the interpolation process may require a geostatistical study of assay data (i.e., variography), and this step alone can be very time consuming.

A framework for a new geological modelling method

Given the above limitations of traditional modelling methods, a practical geological modelling tool should ideally feature the following functionalities:

1. The underlying meshing process must be a based on a quantitative method that generates meshes that honour data values. The results can be therefore reproduced by any user.
2. The ability to incorporate geological intuition must be separated from the meshing routine, so that evolving geological concepts can be updated and integrated without affecting the quantitative meshing routine.
3. The meshing process must be fast, and be able to generate meshes within hours without the intermediate step of variography
4. The meshing process must be able to process entire mine datasets, of up to a million composited scattered data (i.e., non-gridded data).
5. The ability to incorporate new drill-hole data, or new geological interpretations must be fast. This will facilitate testing of new geological ideas.

We have adopted a scheme illustrated in Figure 1 to model geologically realistic 3D grade shells.

Although the following scheme applies to assay data processing, lithological data can also be wireframed using a similar scheme:

1. ***Data validation and compositing***: This can be conducted on most mine database packages.
2. ***Raw grade 3D interpolation and meshing***: Extracting iso-grade surfaces from a global interpolation function describing the spatial grade distribution. This process yields the first-order grade trends that can be objectively deduced from the sampled data.
3. ***Incorporating geological morphology***: Approximate geological trends are interpreted and quickly digitised in 2D sections by viewing the meshes generated from step 2. Data "snapping" is not required, but this step is to digitise the first-order overview of the geologist's interpretation of the grade data, combined with any other information that is available. This provides a qualitative framework for the natural grade trends that are geologically expected which may not be reflected in typically under-sampled drill-hole data.
4. ***Interpolating the morphological information***: An interpolation function is fitted to the digitised data generated from the above interpretation.
5. ***Morphologically constrained grade interpolation***: Grade data interpolation of step 2 is repeated, but this time constrained by the morphological interpolation function generated in step 4. This processing step results in grade interpolations that honour the quantitative data, and are also consistent with the qualitative geological model digitised in step 3.

The only manual input required during the entire process is Step 3. This input, however, can be accomplished in tens of minutes, not tens of hours as in the traditional method. Once the geological intuition is converted to a morphological interpolation function at Step 3, this qualitative information can effectively be slotted into largely a quantitative processing workflow. New drill-hole data can be readily introduced, as the processing steps can be repeated at step 2, and morphological models can be modified. Since the digital representation of geological morphology are polyline-based (and not mesh based), these can be edited much more readily using available editing tools. In addition, entirely new geological interpretations can be added at step 3 (Figure 1). The ability to rapidly form geological models from gross trends allows testing of contrasting geological concepts, and their effects on the constrained grade interpolation can be readily assessed.

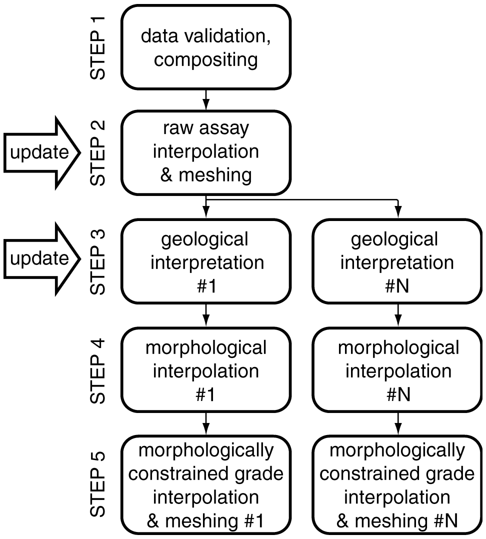


Figure 1 (LEFT). Geological modelling workflow scheme discussed herein.

Interpolation with radial basis functions

A rapid three-dimensional interpolation method is a requisite for the above workflow scheme (Figure 1), and we use a fast form of radial basis functions (RBFs) to interpolate grade and lithological data in 3D space. RBFs are a family of interpolation functions that were first introduced into the geological literature by Hardy (1971) to interpolate scattered topographic data. RBF techniques have been considered to be the best surface interpolators due to their ability to provide the smoothest surface of interpolation (Franke 1982), which is ideally suited for geological modelling.

Interpolation methods used in the minerals industry are invariably local techniques (polygonal, kriging, inverse-distance weighting). In contrast, RBFs are a group of global interpolation methods. That is, the interpolant is dependent on all data points. Because of the computationally demanding nature, even as recently as a decade ago RBFs were considered impractical to interpolate large datasets, and the practical upper data limit number was in the order of 100,000 data points (Sibson & Stone 1991). Recent advances in numerical techniques to solve large sets of linear equations have lead to significant advances in the ability of RBFs to interpolate large datasets (Beatson et al. 1999). Now, the practical limit of RBF interpolation is only limited by computer hardware (random access memory and processing speed). Using this method, a typical mine assay dataset (approx 200K to 700K composites) can be interpolated and meshed in several hours on a personal computer.

Conclusions

We have used Leapfrog™ on a variety of exploration and grade control data, and below is a summary of its advantages:

- The raw interpolation of assay data yields important grade continuities that are not immediately obvious from sectional views (Figure 2).
- The wireframes generated are smooth and can be created at any desired resolution, therefore very useful for geological modelling (Figures 3 and 4).
- Meshing of single domain assay data can be obtained very rapidly (Figure 5).
- Meshing of entire mine assay data can be conducted in a matter of hours (Figures 2, 5, 6-8), as opposed to days of manual digitisation.
- More than one geological interpretation can be used to generate different models, as the editing process is not labour intensive (Figures 6-8).
- Reducing the timeline of geological modelling creates new opportunities for testing multiple working hypotheses (Figures 6-8).
- The models are updatable, and can be regenerated as new data or information becomes available.
- The only method available that allows subjective geological interpretation to be incorporated into an overall objective modelling workflow.

Acknowledgements

ARANZ acknowledges the support of the NZ Foundation for Research, Science & Technology, contract number ARAX0201. We are grateful for the feedback from our Leapfrog™ trial clients, and the permission to use the processed data. All solids were generated with Leapfrog™. The solids, with the exception of Figure 5, were imported into, and rendered with, Gemcom™ software.

References

Beatson, R.K., Cherrie, J.B. & Mouat, C.T., 1999, Fast fitting of radial basis functions: Methods based on preconditioned GMRES iteration, Advances in Computational Mathematics, 11, 253-270.

Franke, R. ,1982, Scattered data interpolation:Tests of some methods, Math. Comp.,38, 181-200.

Hardy, R.L., 1971, Multiquadric equations of topography and other irregular surfaces, J. Geophysical Res., 176, 1905-1915.

Lorensen, W.E. & Cline, H.E., 1987, Marching Cubes: a high resolution 3D surface reconstruction algorithm, Computer Graphics, 21 (4), 163-169 (Proc. of SIGGRAPH).

Sibson, R. & Stone, G., 1991, Computation of thin-plate splines, SIAM J. Sci. Statist. Comput., 12, 1304-1313.

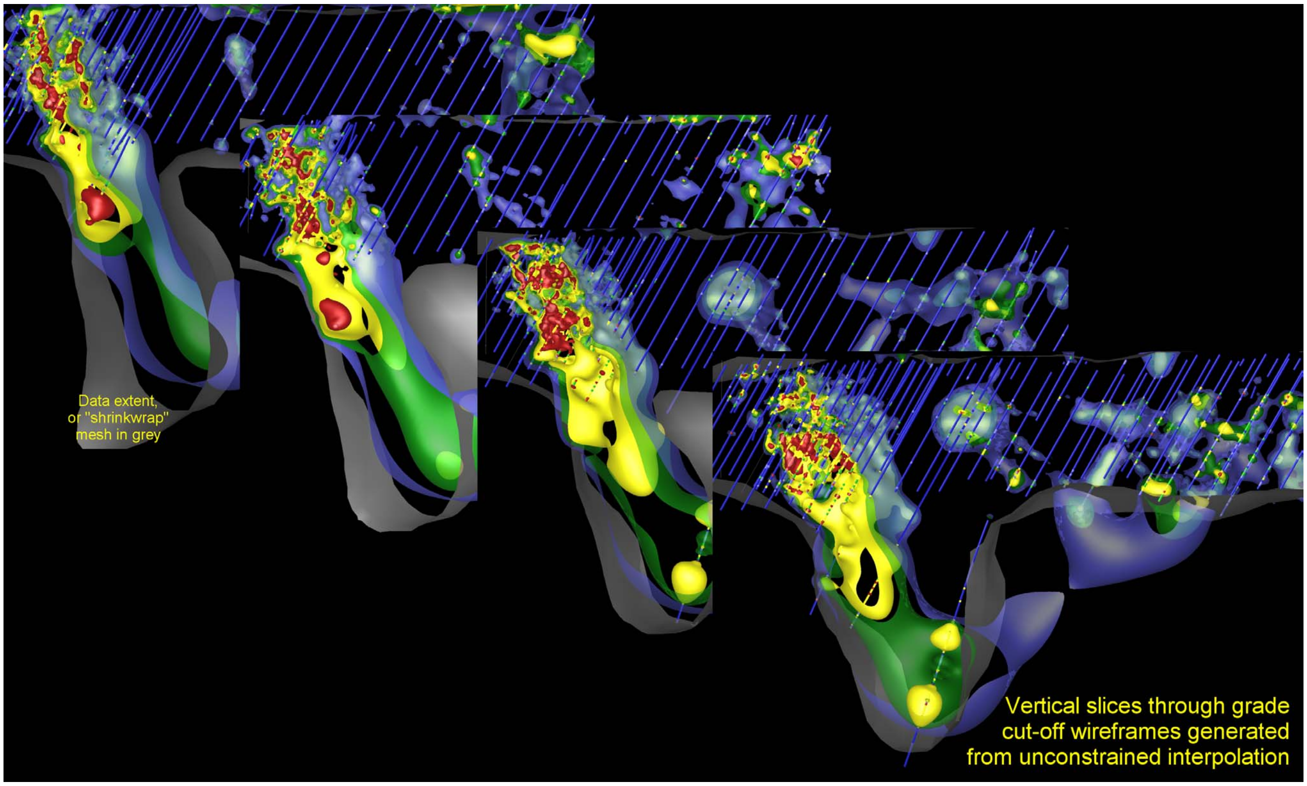


Figure 2. Vertical slices through a grade model constructed directly from 330,000 composited assay values of resource and grade control drilling (STEP 2 of Figure 1). Unconstrained interpolation and grade boundary meshing (STEP 1 in the workflow) allows imaging of subtle geological details. This first processing step can be completed in a matter of hours using a fast form of 3D RBF interpolation. This grade model took 6 hours to process. Geological and structural details seen in the unconstrained interpolation can be then used to construct the geological morphology model used for constrained interpolation (STEPS 3 to 5 of Figure 1)

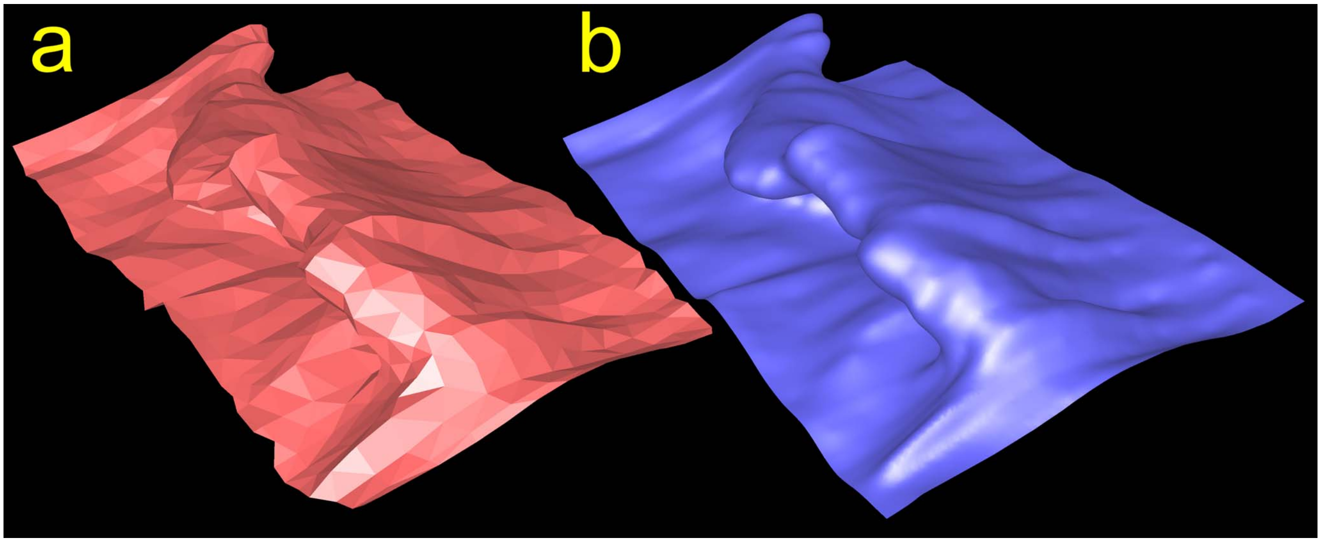


Figure 3. Model of an overturned fold from sectional polylines generated by: a) traditional triangulation with manually digitised tie-lines, and b) high resolution model produced without tie-lines using Leapfrog™. Mesh resolution in the former is fixed to digitised points, whereas models generated with Leapfrog™ can be meshed at any desired resolution.

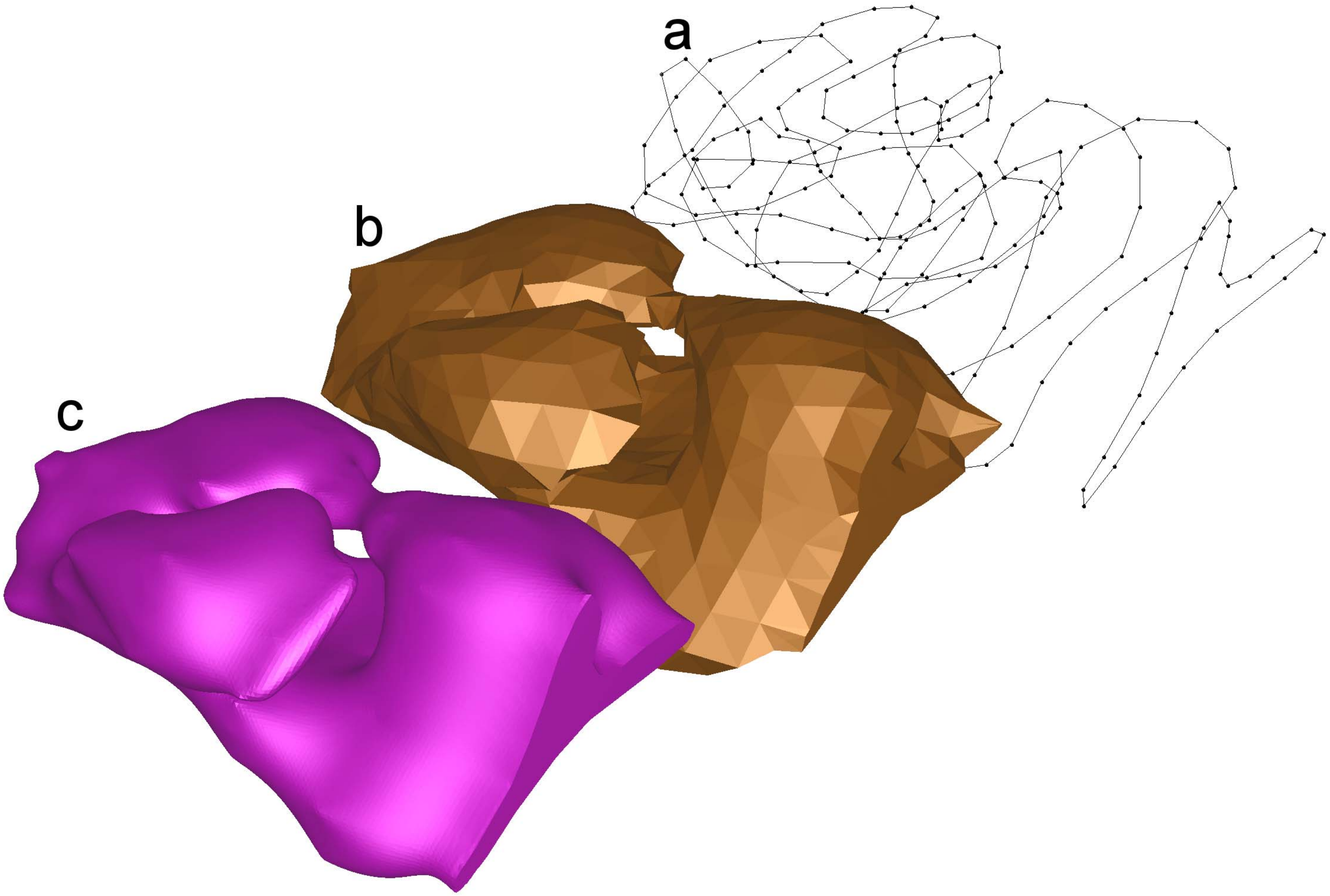


Figure 4. Rapid 3D object construction can be completed without numerous tie-lines between sectional polygons: a) digitised sectional polylines; b) low-resolution, and c) high-resolution mesh model generated with Leapfrog™. The models can be constructed within minutes, and eliminates the need for tie-lines.

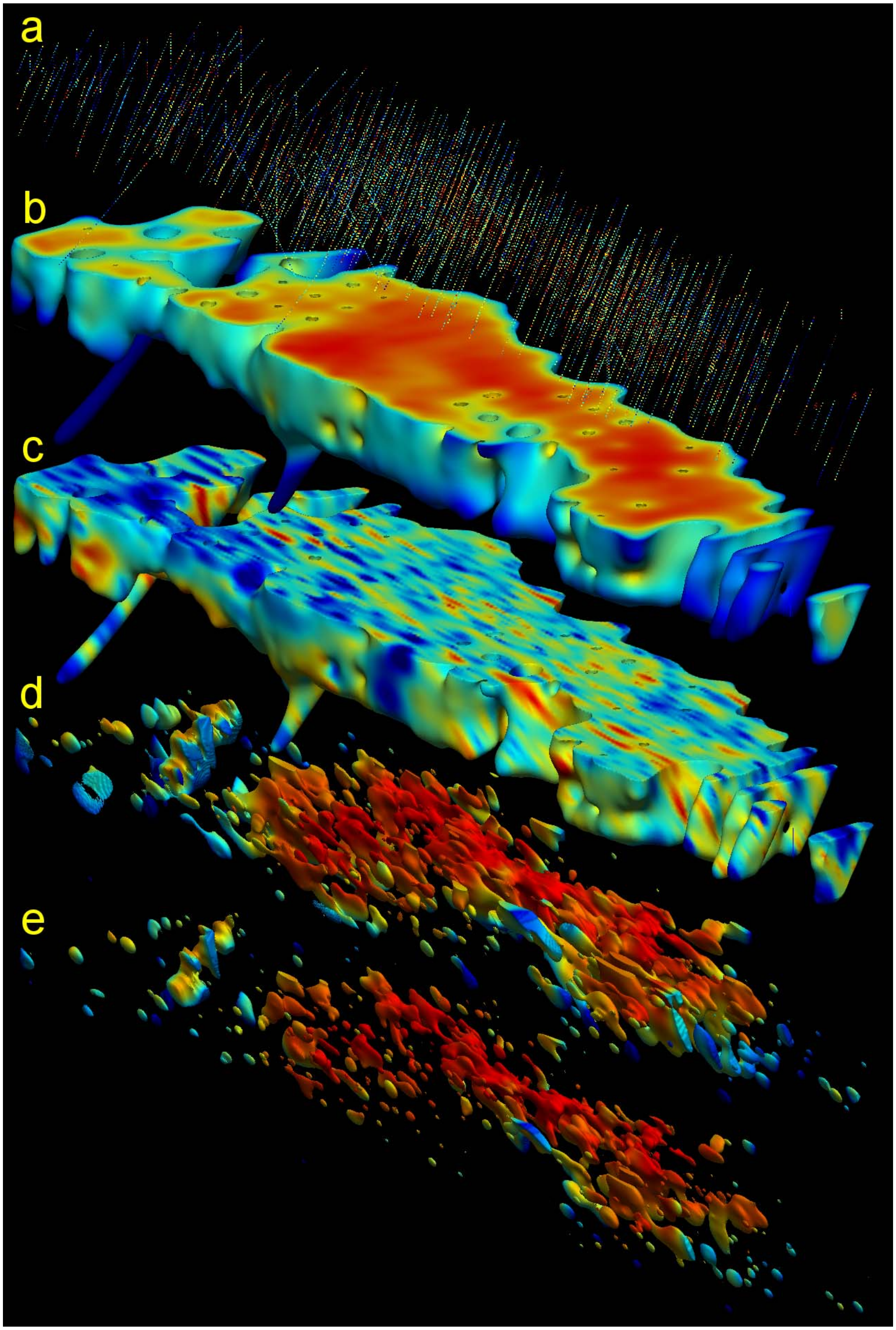


Figure 5. An example of semi-automated grade modelling with Leapfrog™: a) composited assay data coloured with grade; shrinkwrap mesh coloured with b) data density; and c) coloured with grade; d) low- and e) high-value iso-grade mesh coloured with data density. The interpolation was conducted with a range anisotropy obtained from 3D variography. The processing of about 1,200 composite values took about 1.2 hours.

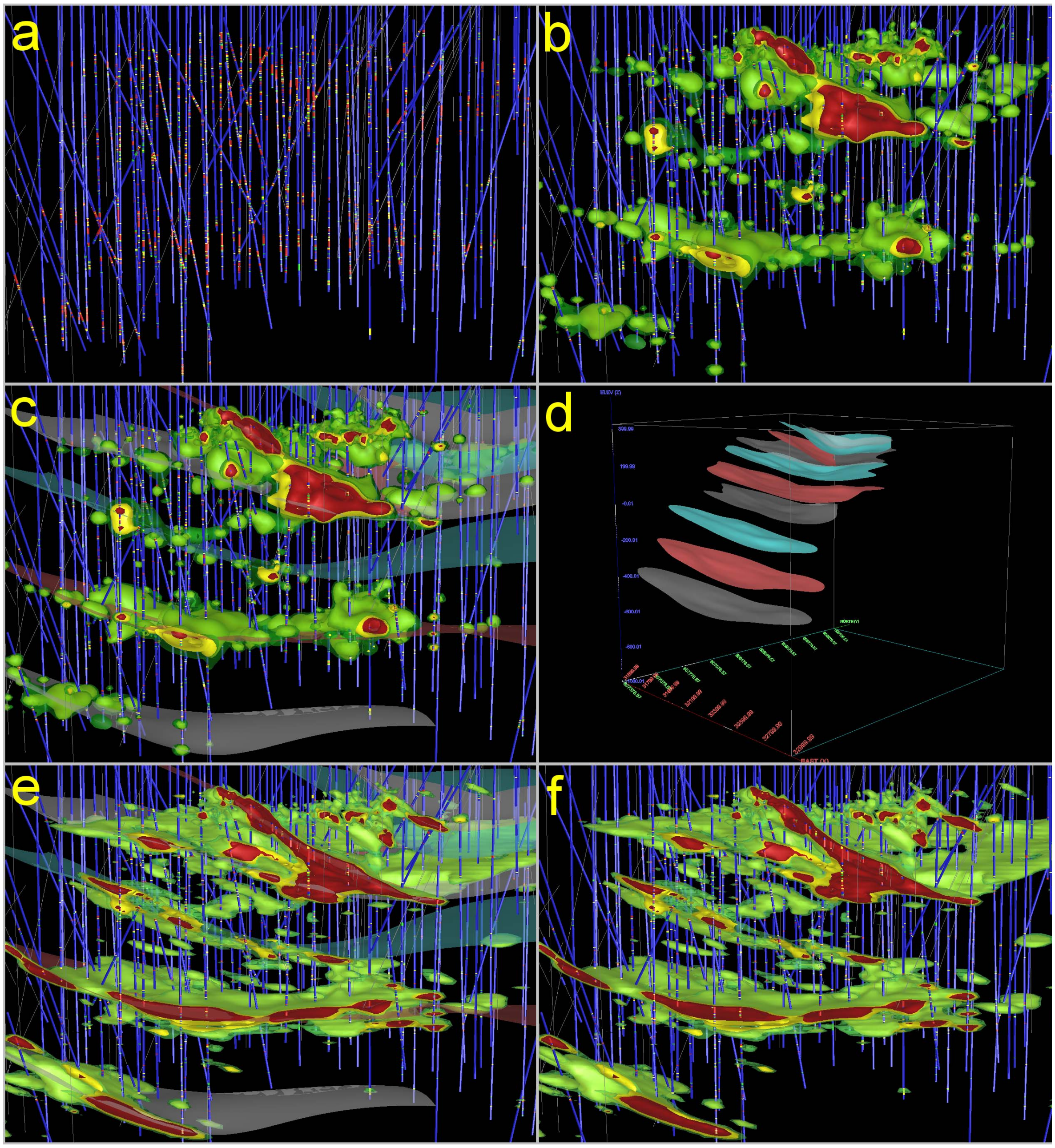


Figure 6. Application of workflow summarised in Figure 1: a) grade composites (STEP 1); b) result of unconstrained interpolation showing three iso-grade meshes (STEP 2); c) interpretation of planar structural controls on mineralisation (STEP 3); d) saved geological morphology model 1, as a result of the interpretation (STEP 4); e) constrained interpolation of grade (STEP 5); f) resulting grade boundary meshes without the interpreted planes. The data consists of ~62,000 5m composites from exploration and grade control data (grade control data not shown for the sake of clarity).

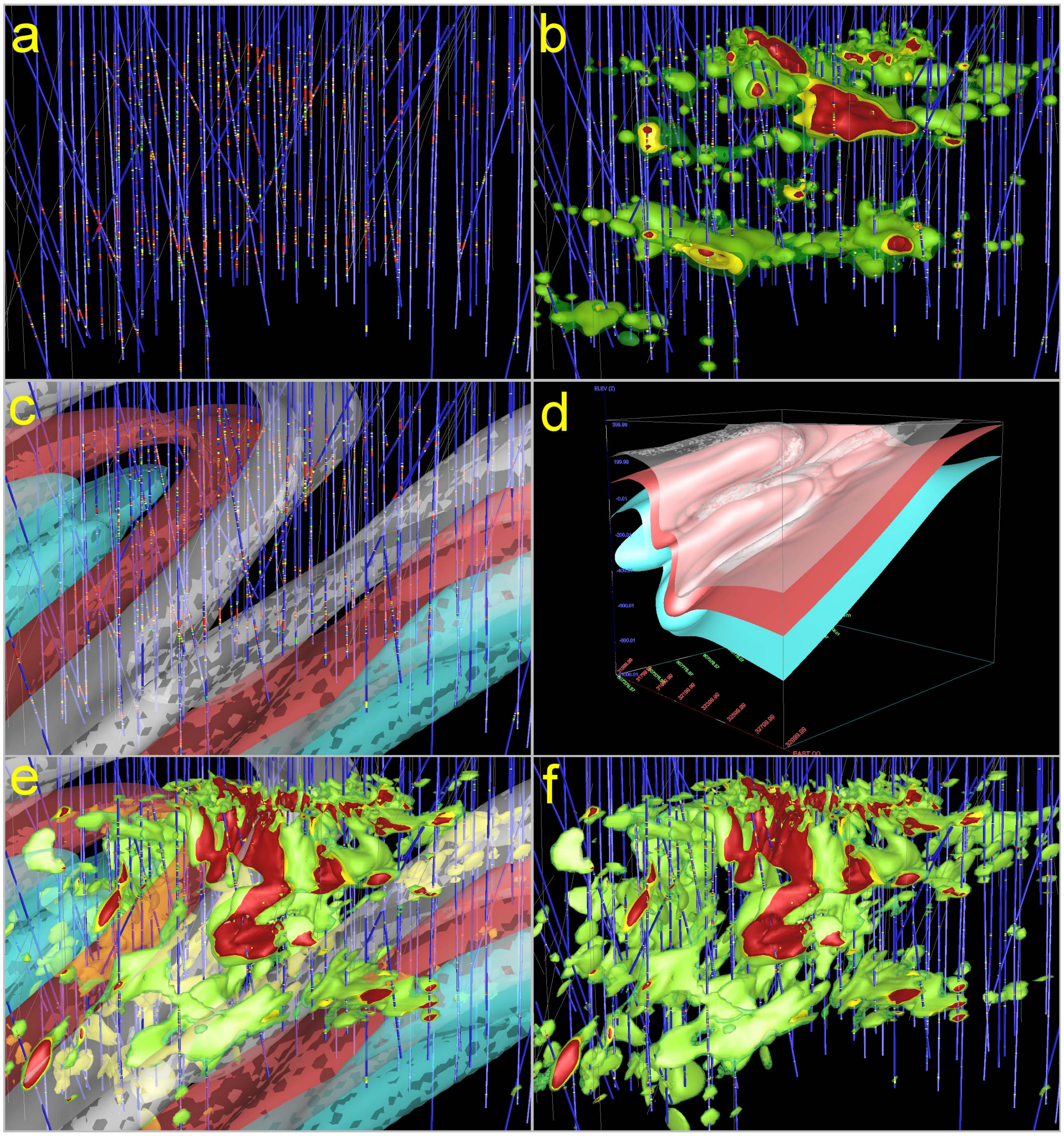
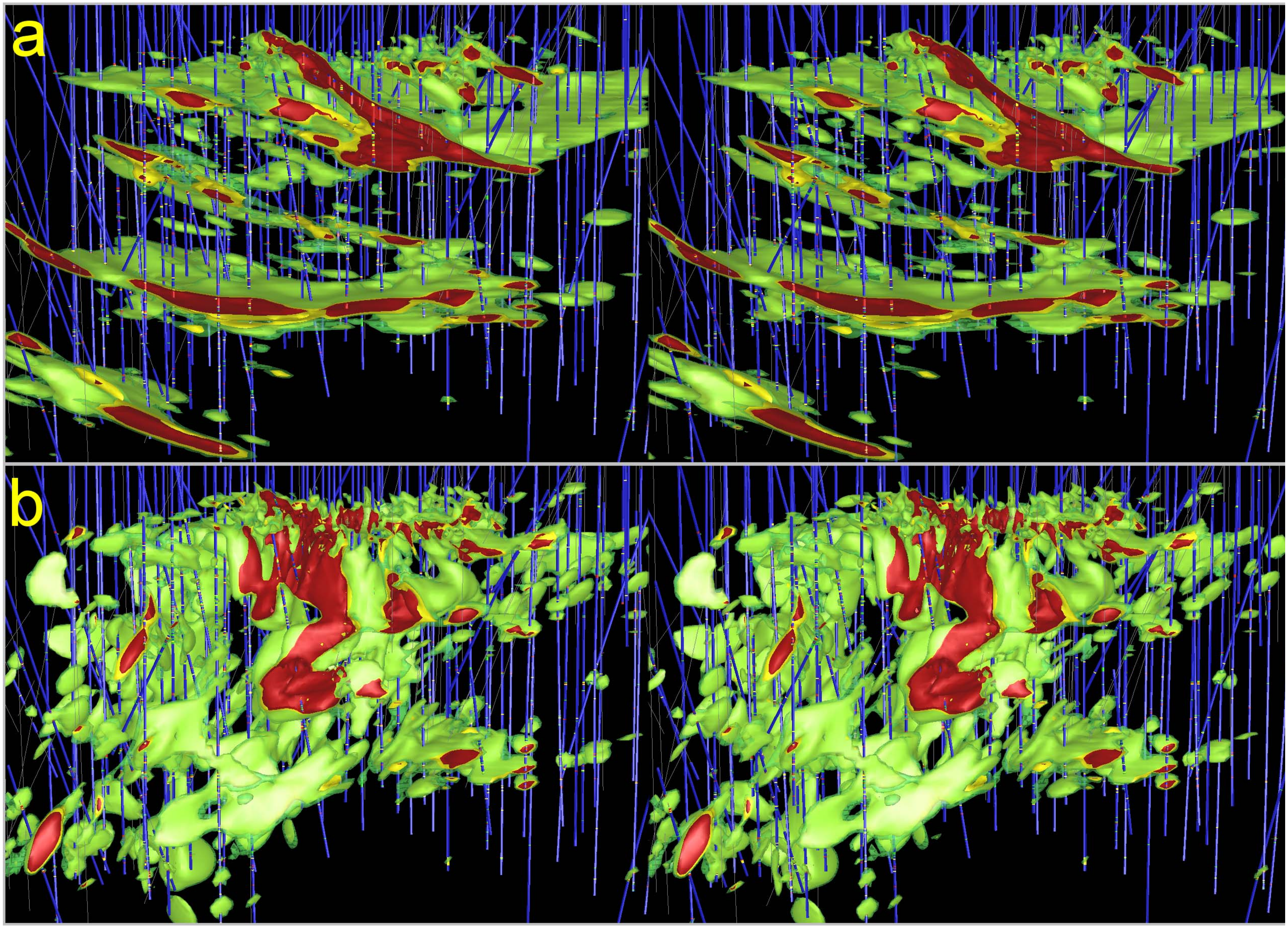


Figure 7. Using a second geological morphology to constrain grade interpolation of the same data shown in Figure 6: a) grade composites (STEP 1); b) result of unconstrained interpolation showing three iso-grade meshes (STEP 2); c) geological morphology model 2; d) saved geological morphology model 2; e) constrained interpolation of grade; f) resulting grade boundary meshes.

Figure 8 (following page). Cross-eyed stereo images of constrained grade meshes generated from a) geological morphology model 1 (Figure 6) and b) geological morphology model 2 (Figure 7). Both sets of meshes are equally valid, as they are conditional to the grade data. That is, both sets of mesh models honour the grade values, but they each honour contrasting geological morphologies defined by the interpreter using Leapfrog™. *Theoretically there are an infinite number of interpretations that can conform to a given grade sampling.*


a
b