Refining 3D Earth models by unifying geological and geophysical information on unstructured meshes

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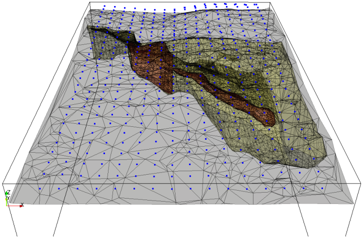
Motivation: The common Earth model

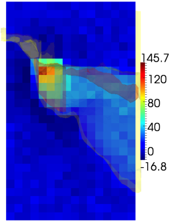
- Earth models used for mineral exploration or other subsurface investigations should be consistent with all available geological and geophysical information
- Geophysical inversion provides the means to unify geological and geophysical data towards the development of a common Earth model

Geophysical inversion

Forward problem



Earth model (e.g. density)

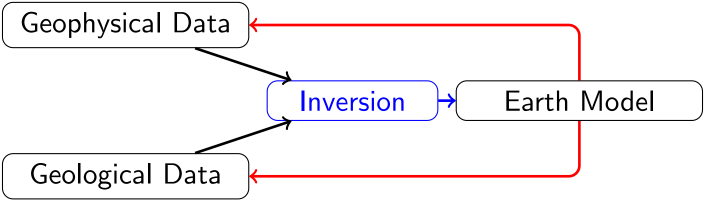


Survey data (e.g. gravity)

Inverse problem

Geophysical inversion

- Incorporation of geological and geophysical data into inversions is always an iterative process

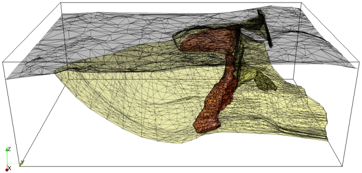


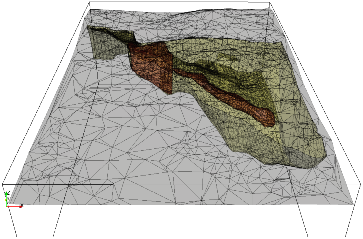
- More information ⇒ reduce non-uniqueness ⇒ higher potential to resolve deeper features

Geological models

3D geological ore deposit models are commonly created during delineation drilling:

- visualization
- calculate volumes of ore reserves
- accuracy is crucial to determine if deposit is economical
- typically comprise wireframe surfaces of connected triangles that represent geological contacts

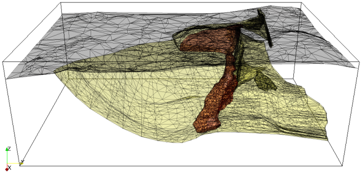


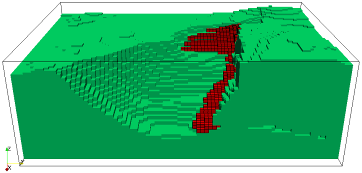


Geophysical models

In contrast, most current 3D geophysical modelling is performed on rectilinear meshes:

- simplifies the development of numerical methods
- incompatible with wireframe geological models:
  - can be impossible to adequately model complicated geology
  - produce pixellated representations





55x82x31=139,810 cells and stair-casing still evident

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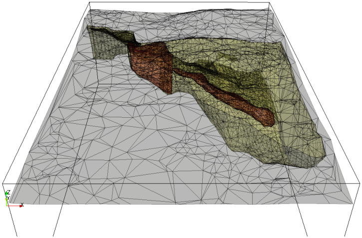

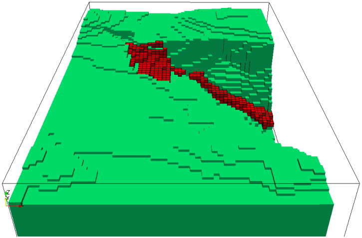

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Why unstructured meshes?

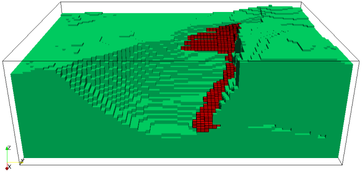
Incompatibility:

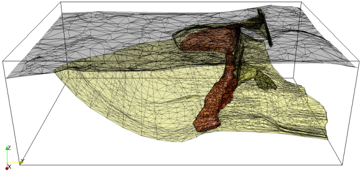
- most current 3D geological Earth models comprise wireframe surfaces (tessellated triangles)
- most current 3D geophysical modelling is performed on rectilinear meshes (rectangular prisms)

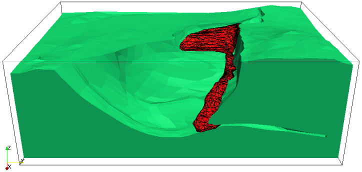
Unstructured meshes

Unstructured meshes provide:

- efficient generation of complicated geometries
- significant reduction in problem size (57,132 vs. 139,810)







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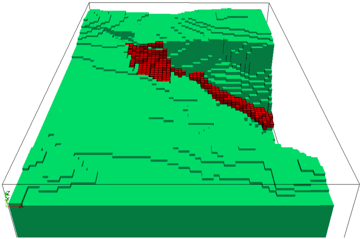
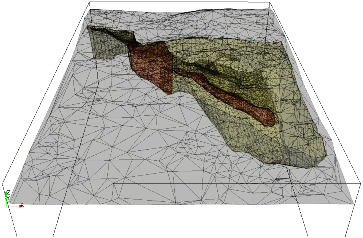
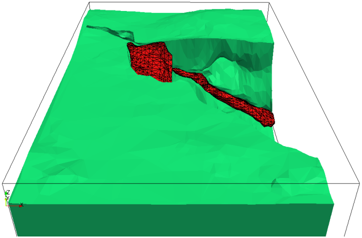






Unstructured meshes

Advantages:

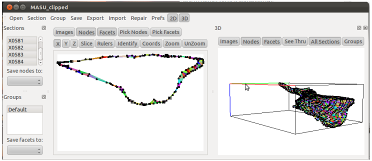
- efficient generation of complicated geometries
- significant reduction in problem size

Challenges:

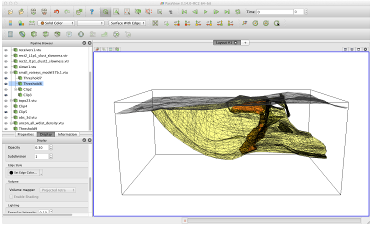
- create, manipulate and visualize Earth models
- mathematics of numerical modelling

Wireframe creation, manipulation and visualization

- Gocad
- FacetModeller
- Blender
- ParaView



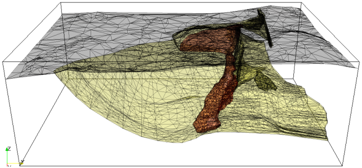
(FacetModeller)

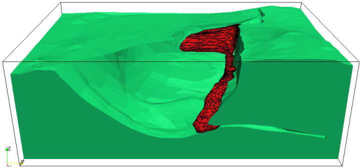


(ParaView)

Volumetric discretization of wireframes

- 2D: Triangle (J. R. Shewchuck)
- 3D: TetGen (H. Si)
- the triangular wireframe surface facets become the faces of tetrahedra in the volumetric model





- geological and geophysical models can share the same modelling mesh; they can be the same model

Forward modelling on unstructured meshes

We have developed modelling methods for various data types:

- gravity (Hormoz Jahandari)
- gravity gradiometry (Cassandra Tycholiz)
- magnetics (Cassandra Tycholiz)
- seismic first-arrivals (Peter Lelièvre)
- geoelectric (Amir Javaheri)
- electromagnetic (Hormoz Jahandari, Masoud Ansari)

Standard deterministic inversion approach

- Objective function

$$\Phi = \Phi_d + \beta \Phi_m$$

- Data misfit

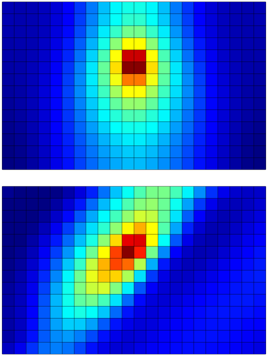
$$\Phi_d = \sum_i \left(\frac{d_i^{pred}(m) - d_i^{obs}}{\sigma_i} \right)^2$$

- Model structure (regularization)

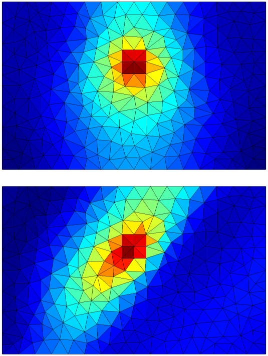
$$\Phi_m = [\text{smallness term}] + [\text{smoothness term}]$$

Regularization

The same regularization is possible on unstructured or rectilinear meshes provided that appropriate matrix operators can be created



regular rectilinear

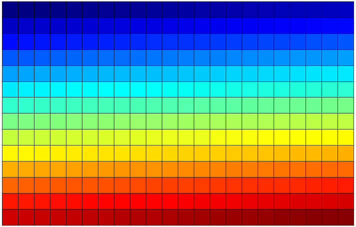


triangular unstructured

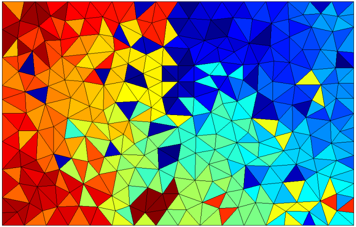
Computational challenges

Algorithms can be designed that exploit mesh structure:

- sparsity structure of spatial matrix operators
- compression of full sensitivity matrices



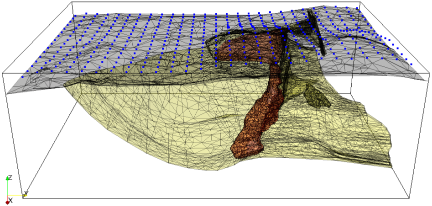
regular rectilinear

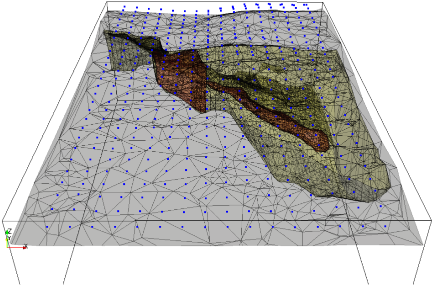


triangular unstructured

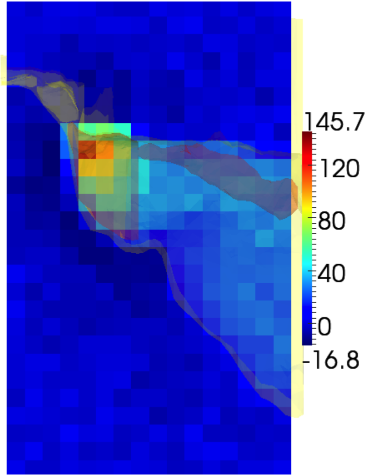
Voisey's Bay example

- nickel-copper-cobalt sulfide deposit
- north-east coast of Labrador, Canada

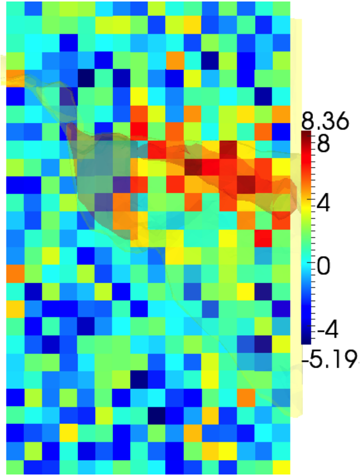




Gravity gradiometry (tensor) data

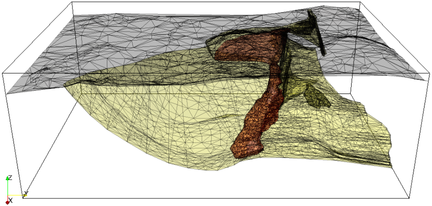


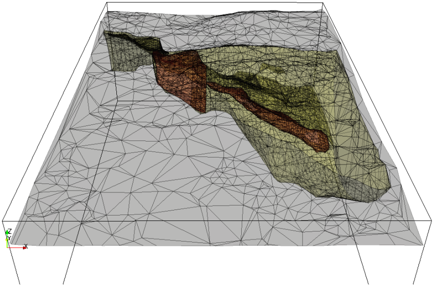
noisy zz-component



noise plus signal from extension

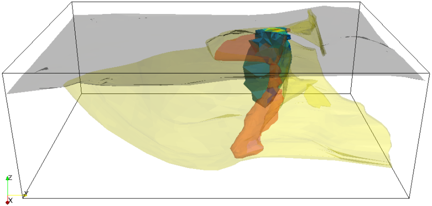
True model

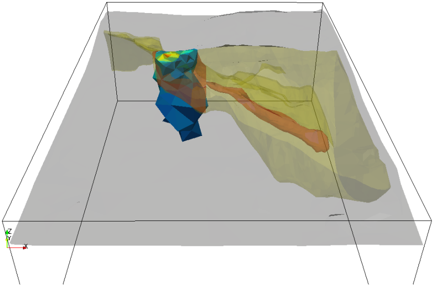




Unconstrained inversion

(gravity gradiometry data only)

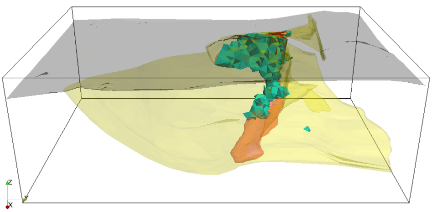


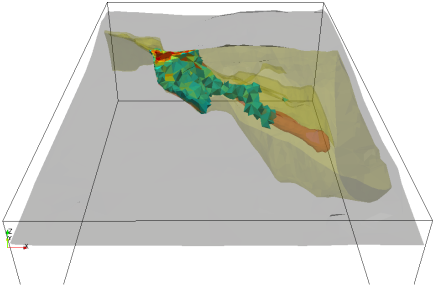


Recovery of shallow sulphide body only

Geologically-constrained inversion

(gneiss-troctolite surface and appropriate bounds)





Indication of extension ⇒ refine geological model; collect downhole data

Conclusion

- most current 3D geological Earth models comprise wireframe surfaces
- in contrast, most current 3D geophysical modelling is performed on rectilinear meshes
- working with unstructured meshes allows for efficient incorporation of complicated *a priori* geometries (forward modelling; constrained inversions)

Acknowledgements

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- Vale