Geomechanics: Predictive Modelling at Ernest Henry

Understanding Structural Controls in Cu and Au localisation in the Mt Isa Inlier

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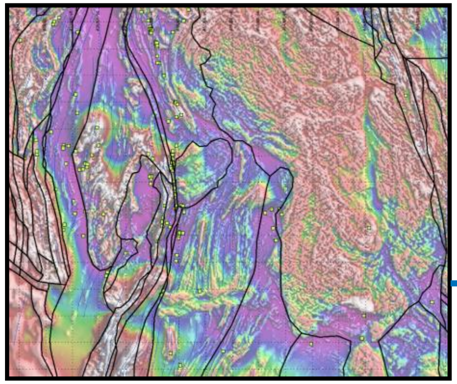
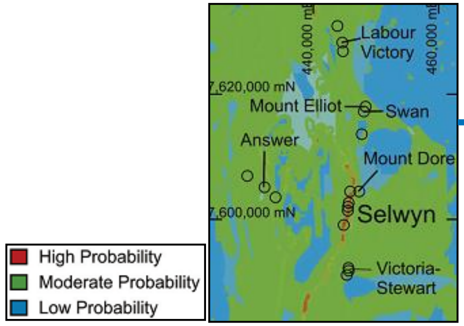
Acknowledgements: Nick Oliver, Mat Brown, Brad Miller, Rhonda O'Sullivan, Trevor Shaw and many others in the Mt Isa District. Special acknowledgement to the GSQ for funding of the 2D regional Mt Isa work.

Geomechanical Enhancement 2D

Exploration Methodology



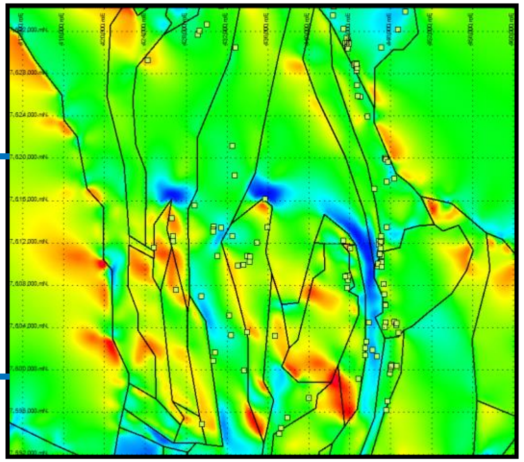


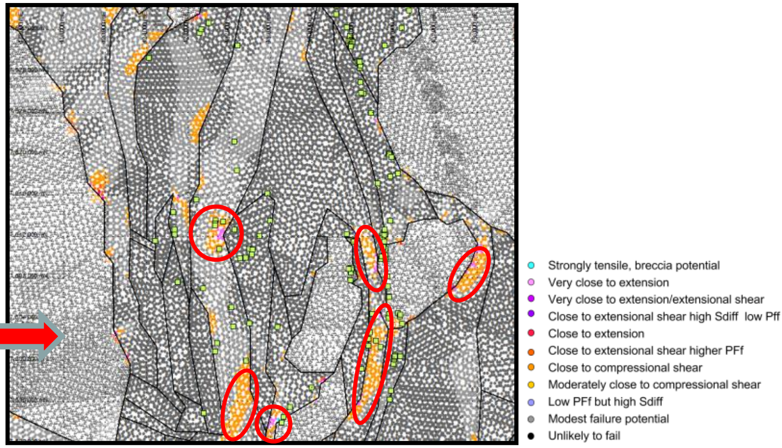
Conventional Methods

- Structural Interpretations from geophysics
- Prospectivity Analysis
- Exploration Continuation?
- Where to Drill

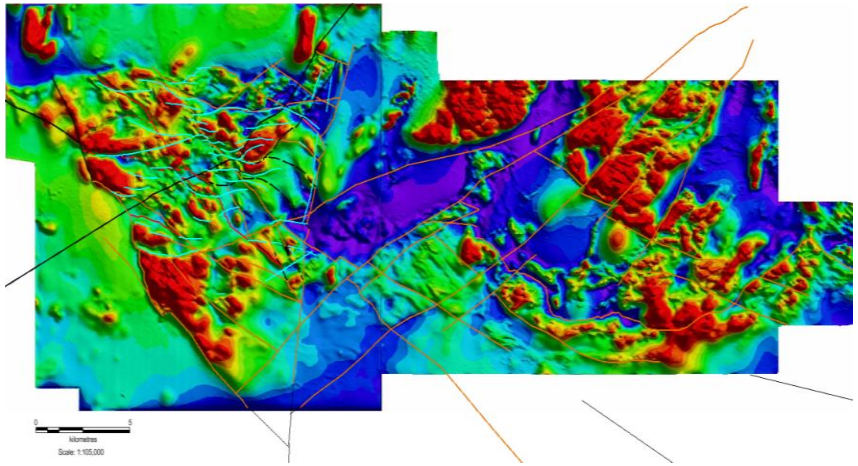
Geomechanical Enhancement

- Geomechanical Analysis of Inferred Faults
- Structural Targets generated from Stress/Strain
- Predictive locations of rock failure and fluid focusing



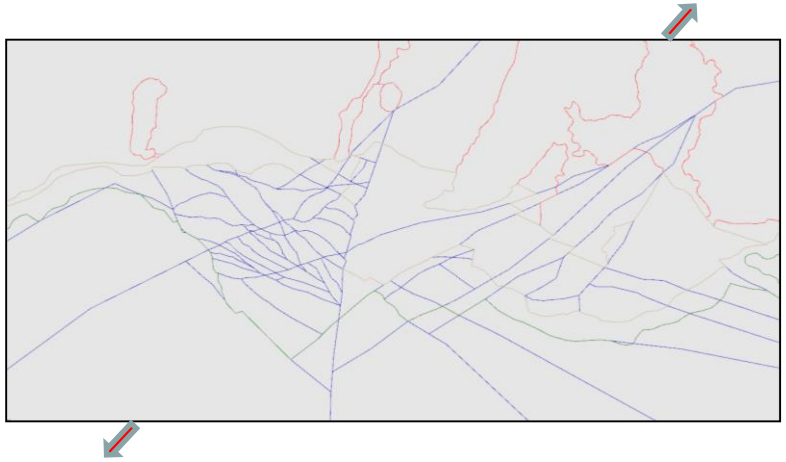


Geomechanical Analysis 2D

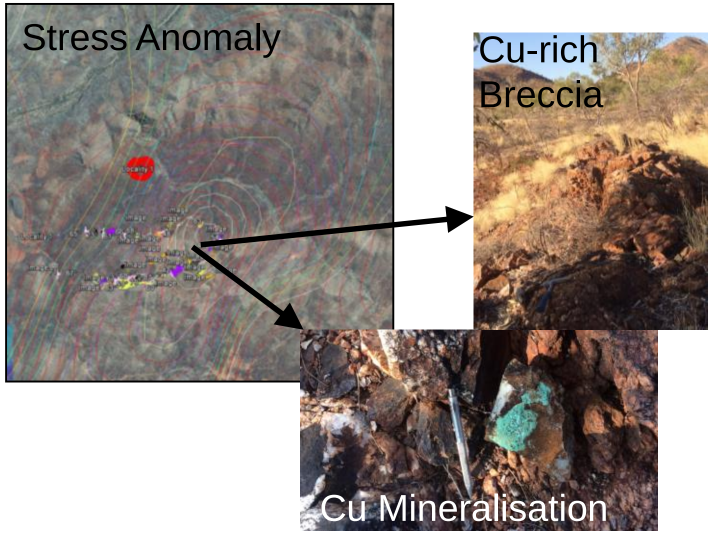


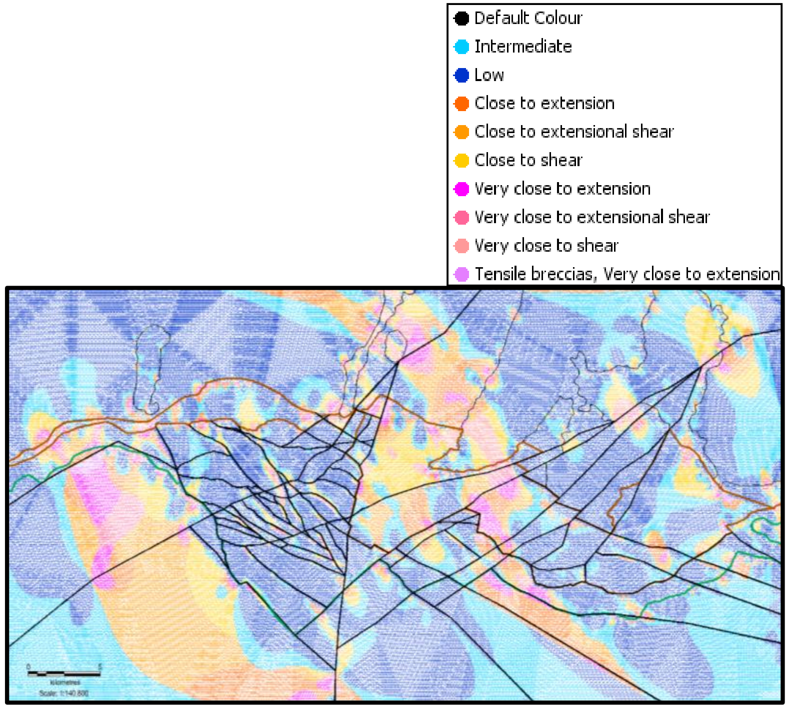
- Regional structural interpretation from geophysical data
- Particularly useful for areas under cover

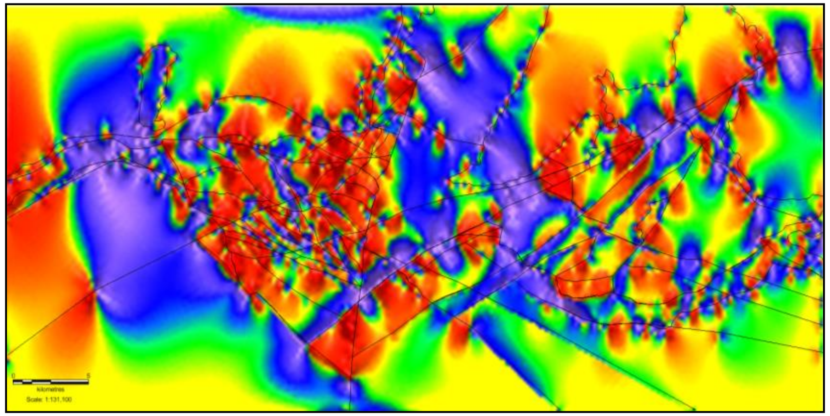
- Conceptual Fault Architecture Model
- Kinematics interpreted from structural evidence
- Sensitivity modelling



Field Validation





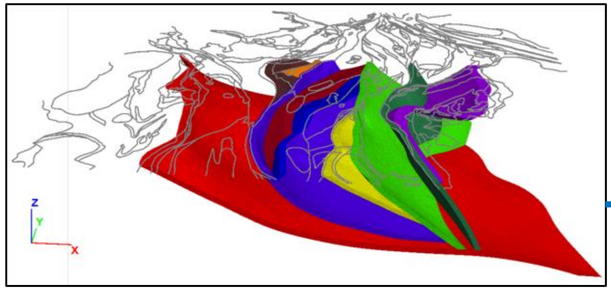


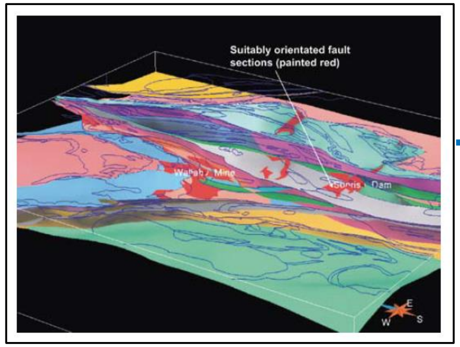
- Geomechanical outputs
- Highlight variables of interest e.g low S3
- Investigate anomalies

- Predictor Maps
- Combines Geomechanical variables

Geomechanical Enhancement 3D

Regional Exploration Methodology





Conventional Methods

- Structural Interpretations from geophysics
- Prospectivity Analysis
- Exploration Continuation?
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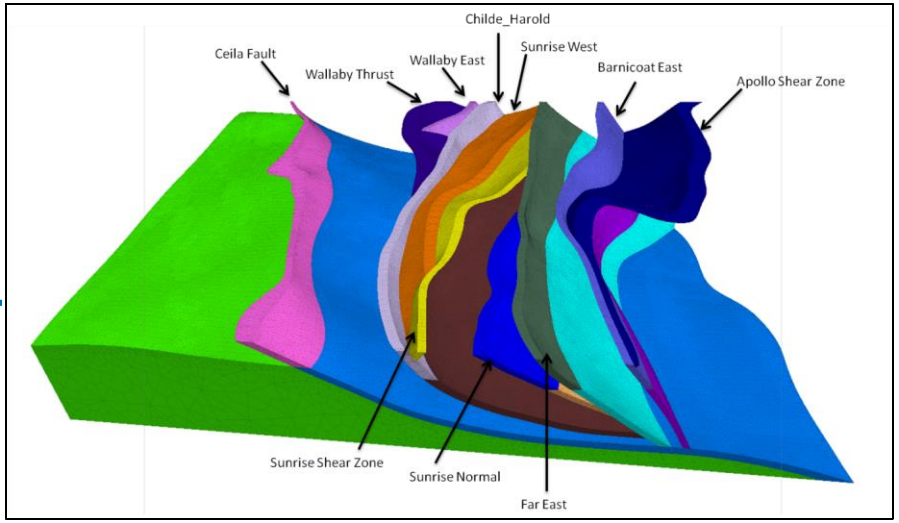
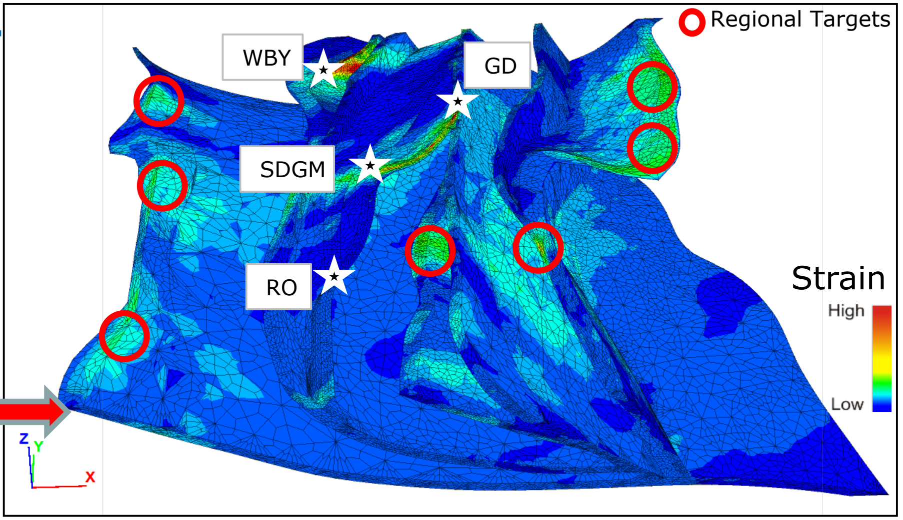
Geomechanical Enhancement

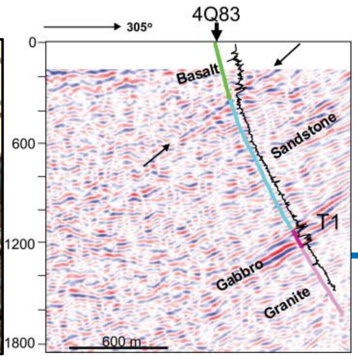
- Geomechanical Analysis of Inferred Faults
- Structural Targets generated from Stress/Strain
- Predictive locations of rock failure and fluid focusing

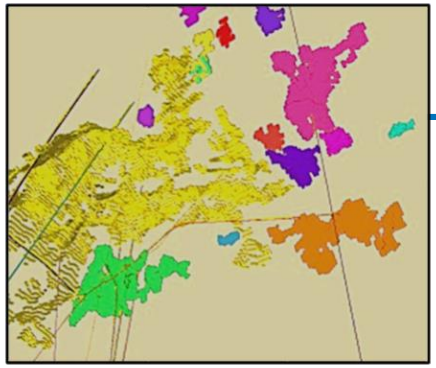




Geomechanical Enhancement 3D

Mine-Scale Exploration Methodology



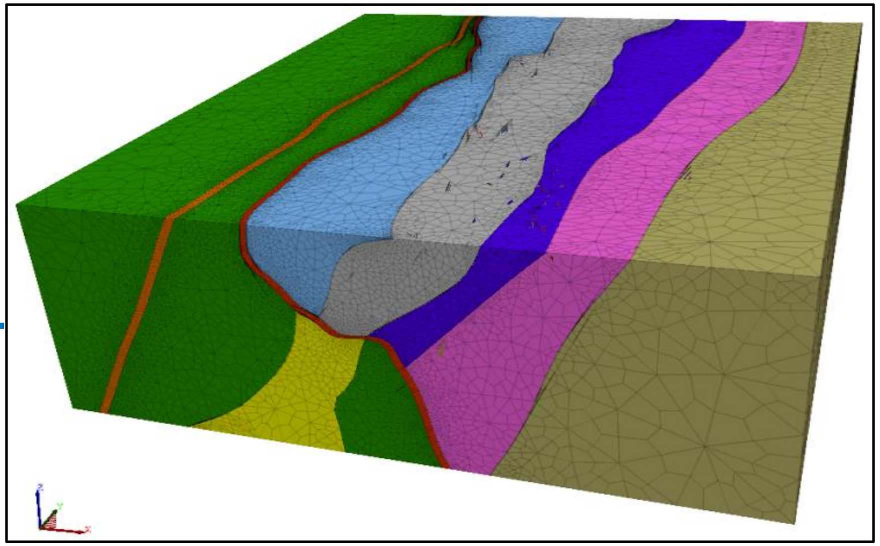


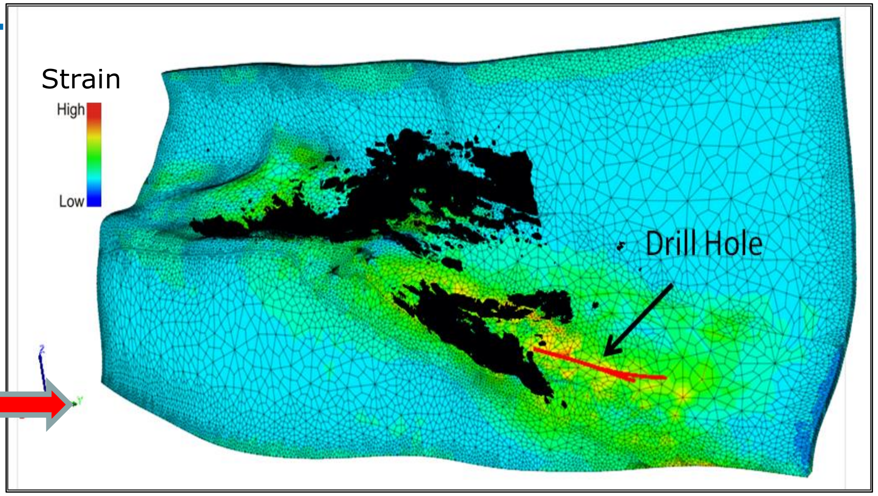
Conventional Methods

- Structural Interpretations from geophysics, mapping and drill core
- Structure, Geochemistry and known lodes
- Follow mineralised trends. What happens when they terminate?
- Where to Drill

Geomechanical Enhancement

- Geomechanical Analysis of Deposit Architecture
- Structural Targets generated from Stress/Strain
- Predictive locations of rock failure and fluid focusing

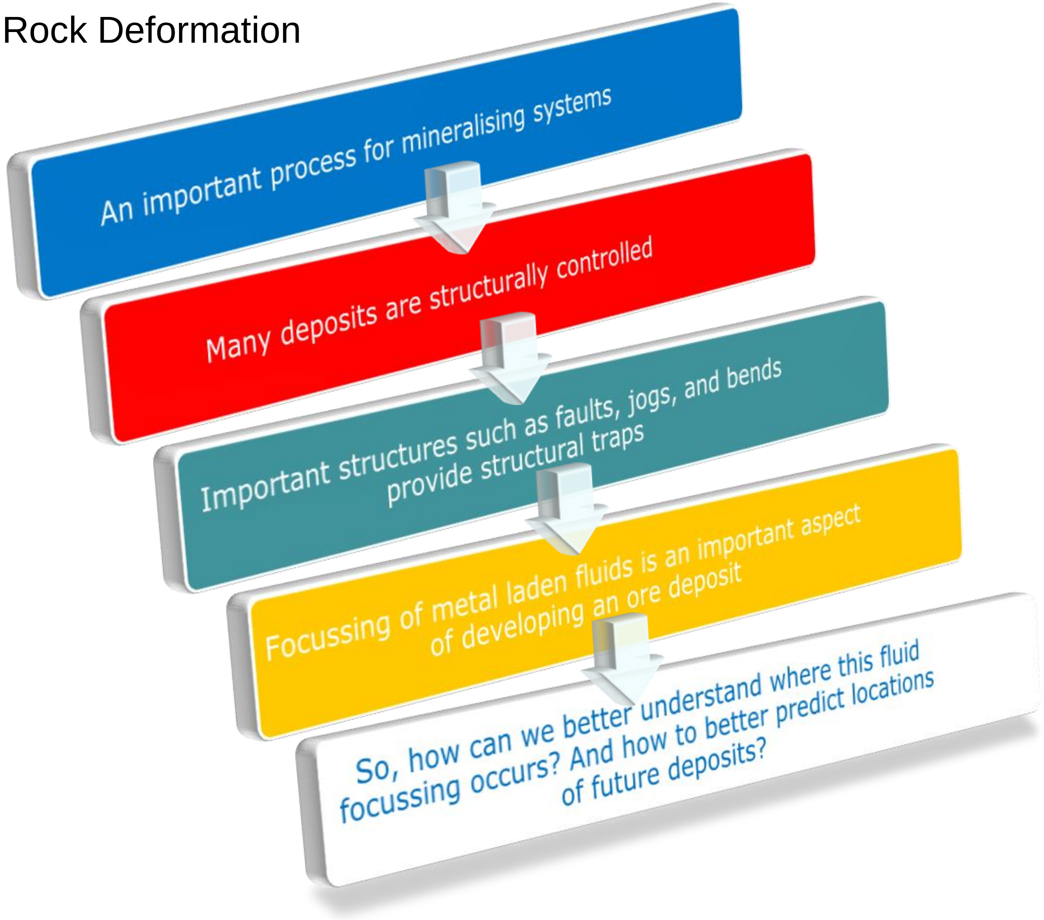




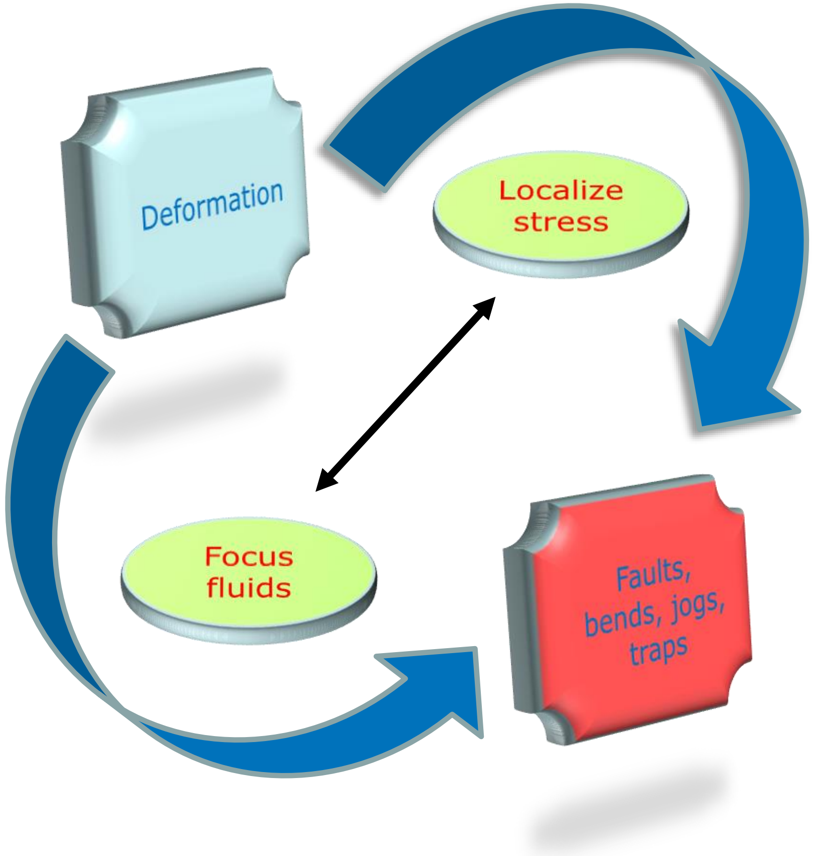
Geomechanics: Some Basic Theory

- Localising Mineralisation – The Law of Effective Stress

Rock Deformation



Deformation is generally coupled with fluid
e.g. **"Law of effective stress"**

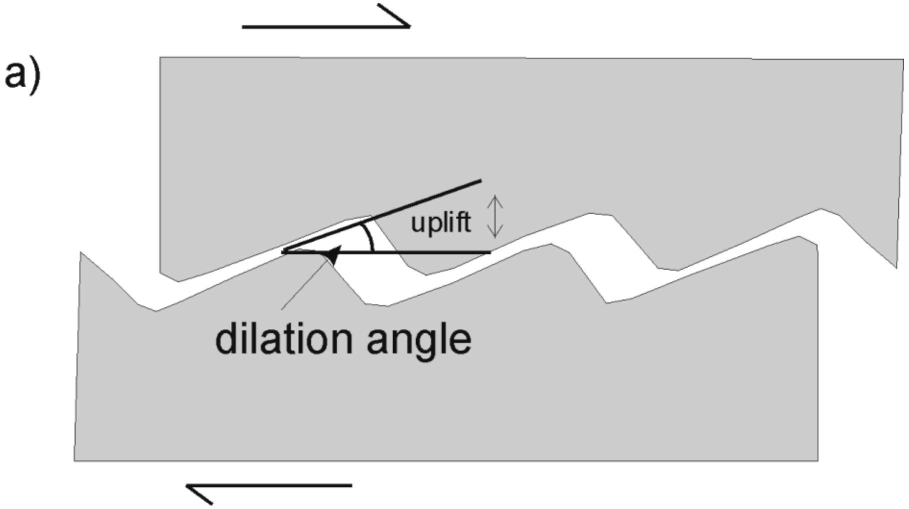


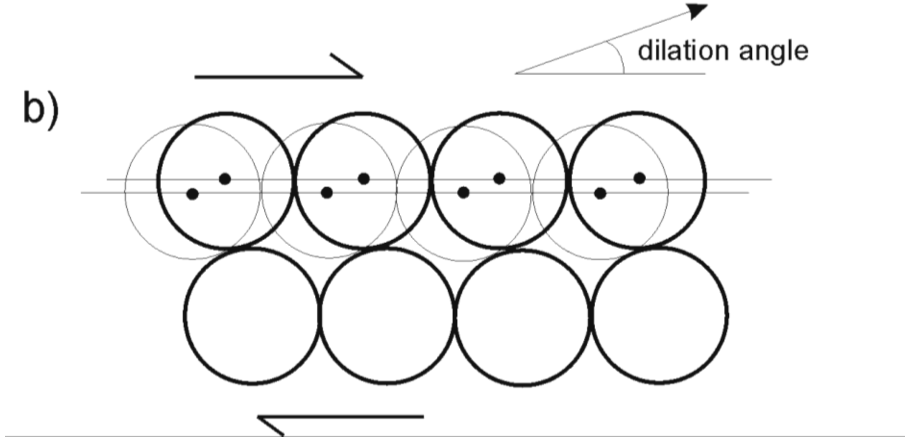
Geomechanics: Some Basic Theory

- Coupled Processes – Dilatancy and Fluid Flow
- Porosity v Permeability

Dilation Concept:

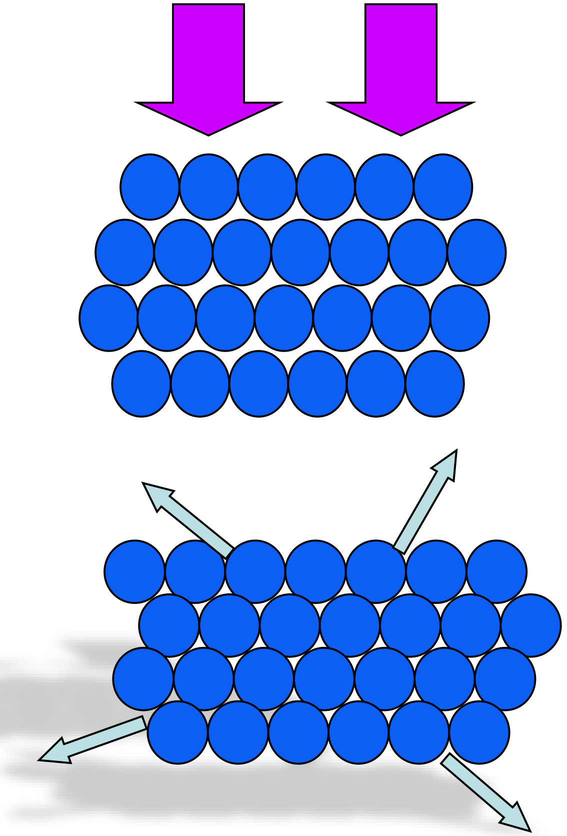
- During shear in Mohr-Coulomb material volume change is induced
- Dilatancy=“inelastic dilatation relative to the shear strain”
- Results in deformation induced fluid flow (major important driver)



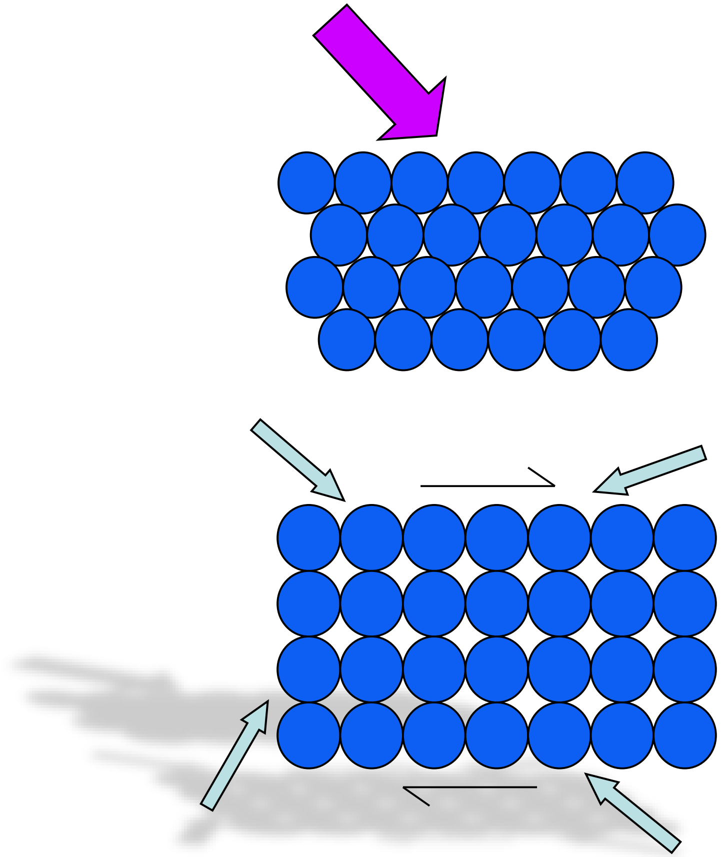


Geomechanics: Some Basic Theory

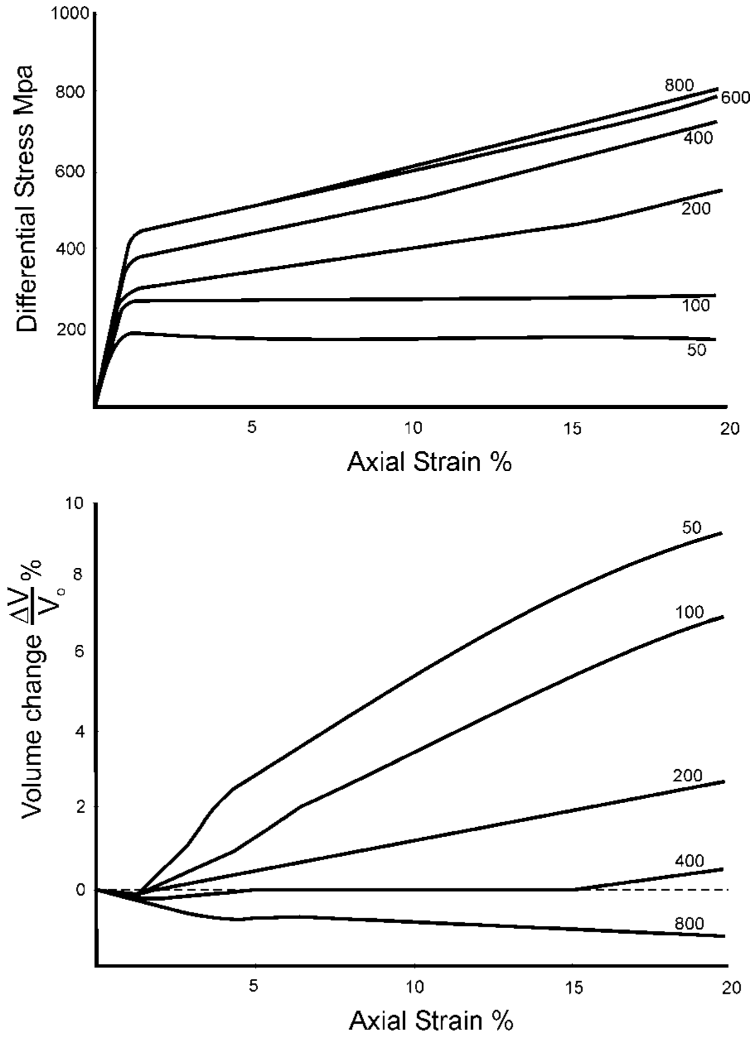
Elastic and Plastic response to deformation and associated fluid flow



Poro-elasticity: fluid pressure increases, fluid moves away from stressed regions



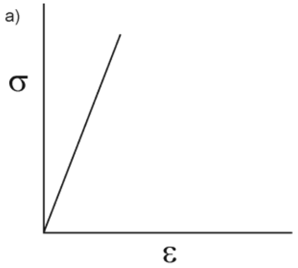
Poro-plasticity or dilation: fluid pressure decreases, fluid moves towards regions of high shear stress

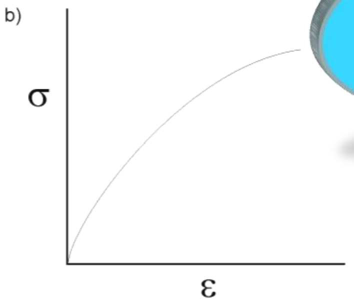


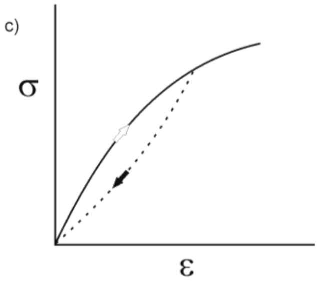
Edmond & Paterson (1972)

Geomechanics: Some Basic Theory

- Material Behaviour







Deformation

Elastic

Generally linear stress/strain

Hookes Law
Young's Modulus
Poissons Ratio

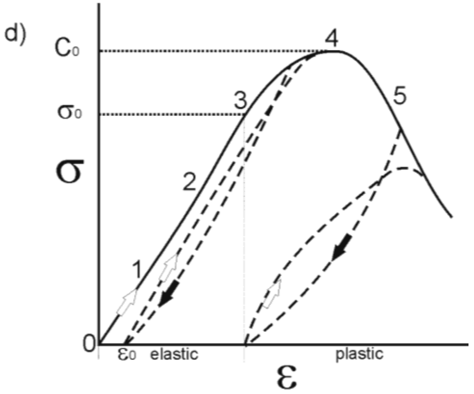
Material resumes original state

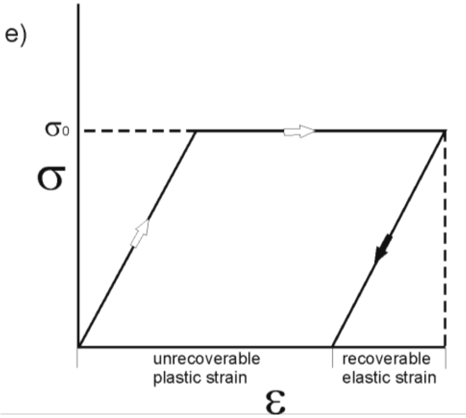
Plastic

Non-linear stress/strain

Yield Function
Flow Rule
Friction and
Dilation angles

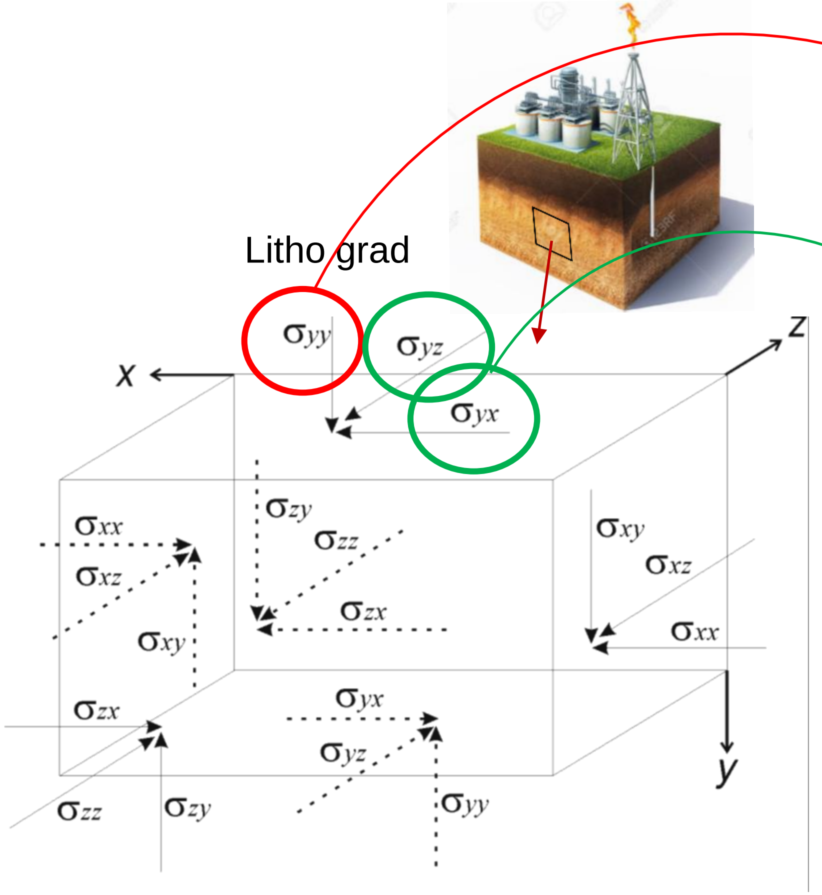
Unrecoverable deformation occurs



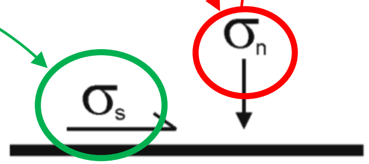


Geomechanics: Some Basic Theory

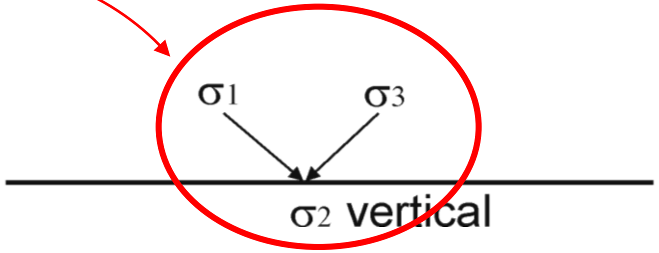
- Structural controls on mineralisation – we need to understand the partitioning of stress and strain
- Stress-Strain relationship is important for localising deformation and fluids
- Lets look at stresses acting on the top surface of a 3-dimensional block



3-dimensional stress components acting on a volume of rock



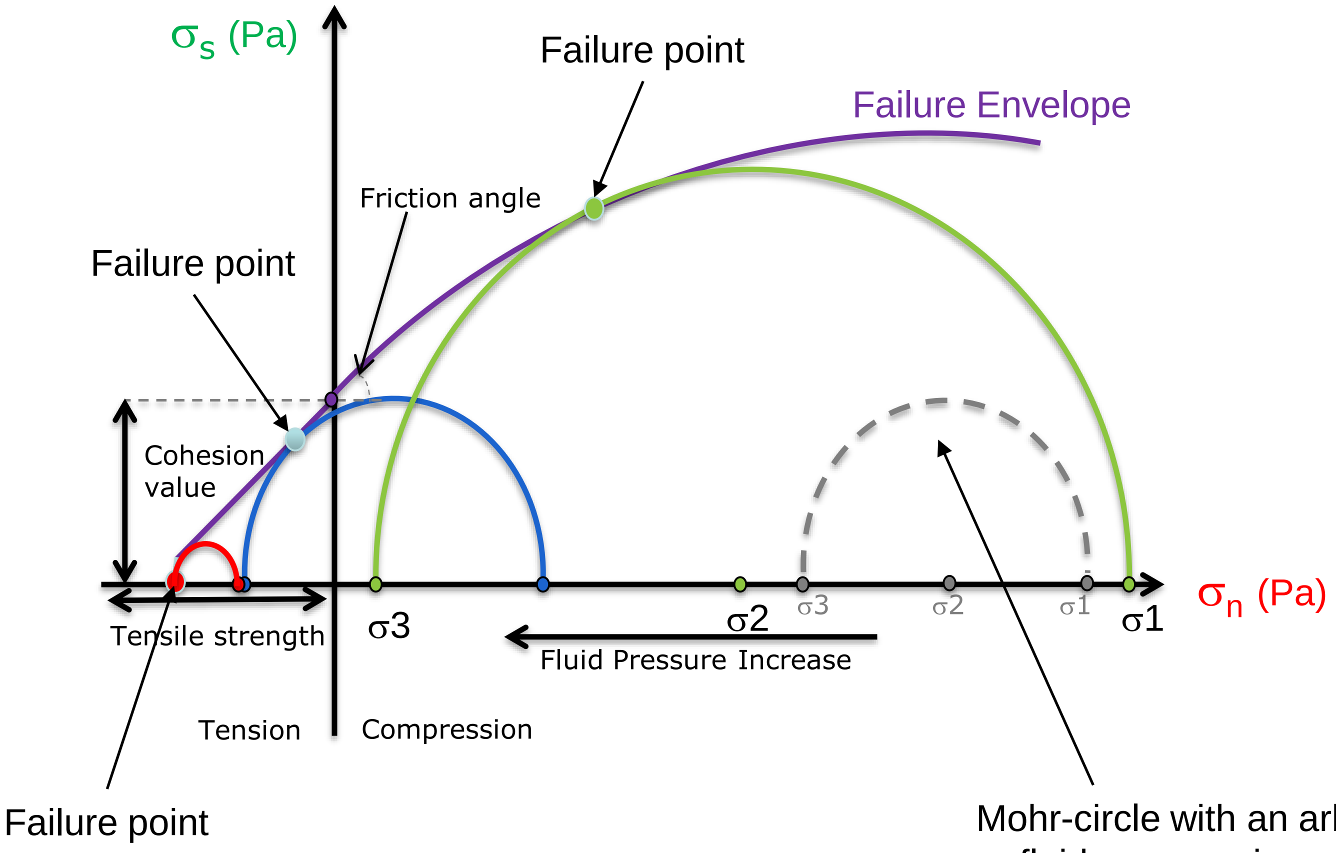
Simplified stress components acting on a plane (normal stress –red, and shear stress - green)



Normal Stress upon a plane, resolved into Cartesian co-ordinates of maximum, mean and minimum stress

Geomechanics: Some Basic Theory

- Mohr Circle diagrams are a great way to visualise stress relationships and failure modes
- Stress-Strain relationship is important for localising deformation and fluids



Mohr-circle with an arbitrary starting value of stress in the system prior to deformation or fluid pressure increase (example starting condition in a rock volume)

2-ways to fail material:

1) Increase diameter of Mohr-Circle (effectively increasing differential stress (σ1-σ3) until circle touches failure envelope (e.g. grey dashed circle to green circle)
2) Increase fluid pressure to shift whole circle along normal stress axis towards failure envelope (e.g. grey dashed circle to blue circle)

Given specific criteria e.g. rock properties, failure criteria, fluid pressures, we can deduce when a rock will fail in either

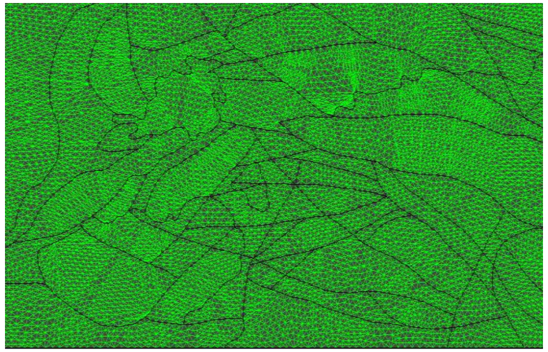
a) Compressional shear
b) Extensional shear
c) Extension

Geomechanical Applications

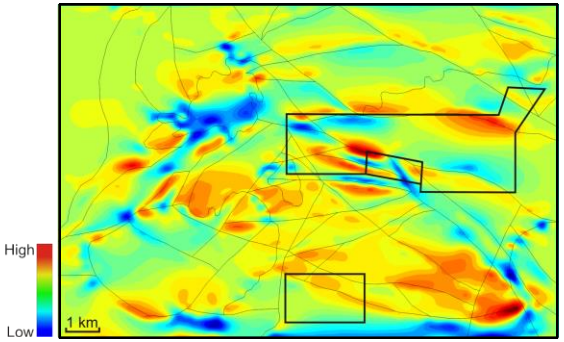
- So, **HOW** do we simulate the processes taking place in the crust during deformation events
- Geomechanical Modelling incorporates the physics/maths behind the processes to describe the material behaviour

2D Discrete Element Modelling

Conceptual Geological Model indicating fault architecture and lithological boundaries

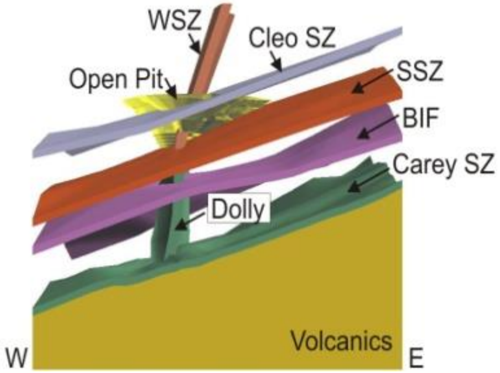


2D triangulated mesh to represent the geology

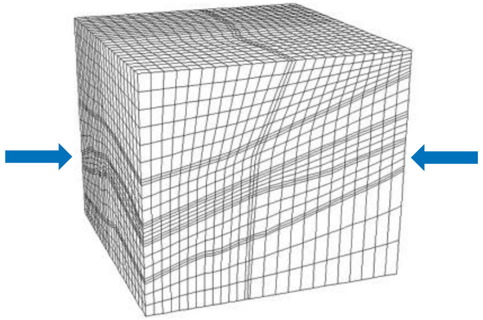


Example of model results from applied stress conditions. We can clearly define areas of stress anomalies as a function of fault block movement

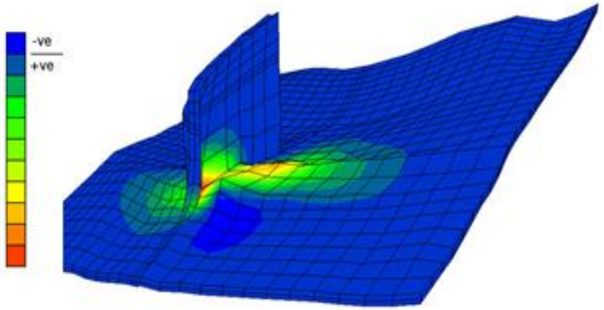
3D Finite Element Analysis



Conceptual Geological Model from 3D Geology Information



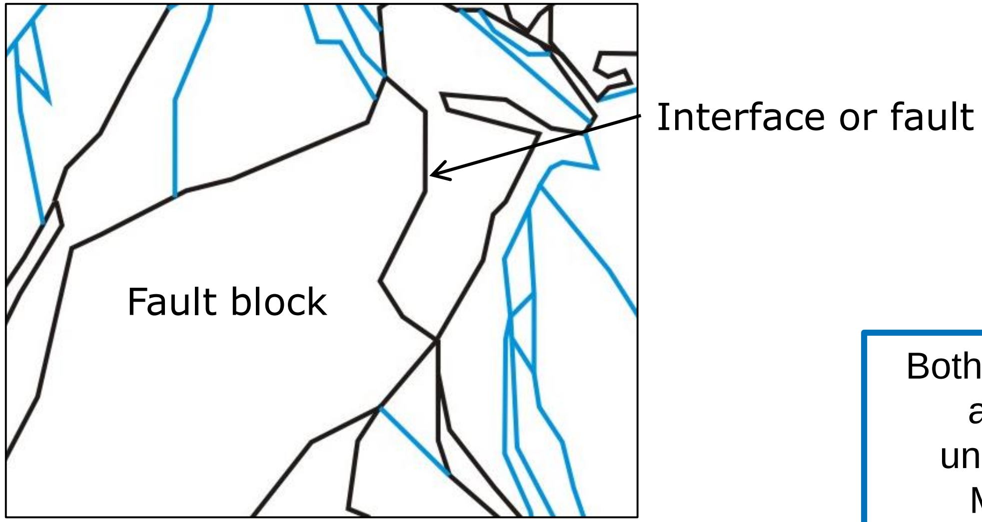
3D hexahedral mesh to represent the geology



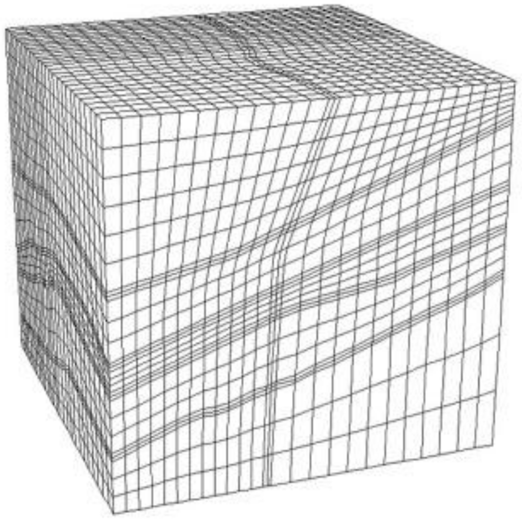
Example of model results from applied deformation. We can clearly define areas of stress anomalies as a function of mesh deformation and stress partitioning.

Geomechanical Applications

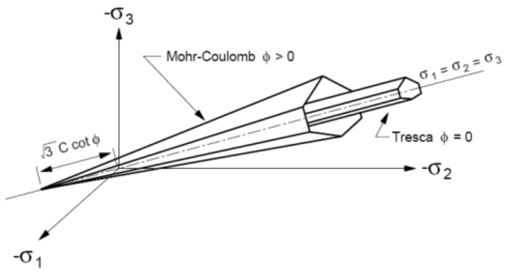
2D Discrete Element Modelling

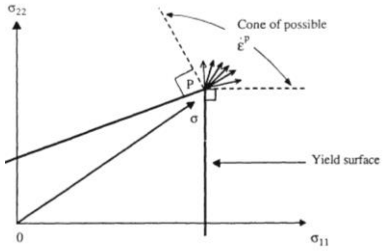


3D Finite Element Analysis



Both Modelling Techniques are governed by an underlying Constitutive Model/Relationship





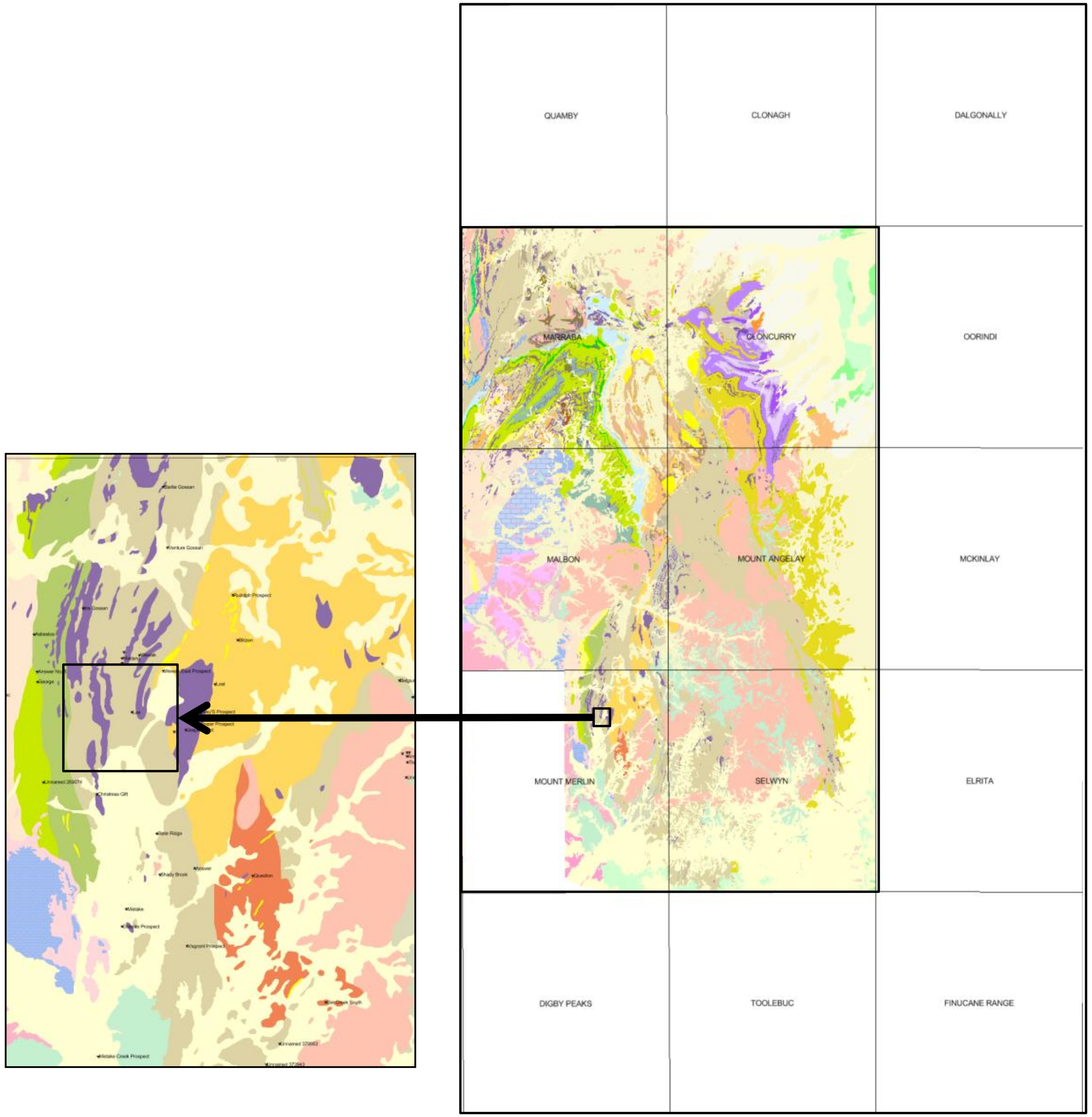
- Discrete Process
- Considers rock material (fault blocks) and interfaces (faults)
- Fluid pressure is maintained in rock and fault interfaces, which has an effect on stress transfer

- Continuum Process
- Deformation is continuous to a pre-determined bulk strain
- Faults are treated as non-discrete entities
- Porous media flow is possible

Case Study – DEM Mt Isa Inlier

- Scale is important! – What's the question?
- Structurally controlled mineralisation
- Fault controlled system with competency contrasts
- Meta Sediments and intrusives
- Aim: to identify the most favourable areas of deformation loci

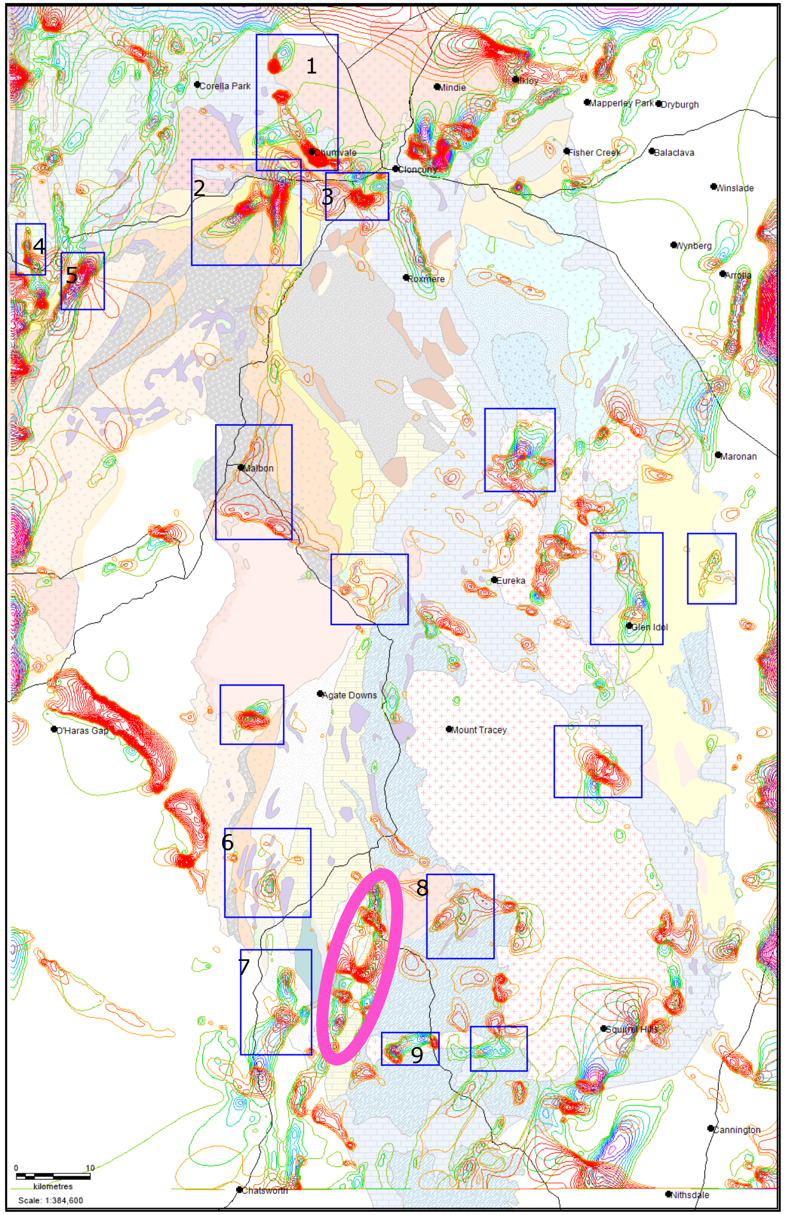
- Three scales of interest:
- Large Scale Regional Modelling (~43,000 km^2) 15x100k map sheets
- Medium Scale Regional Modelling (~ 17,000 km^2) 6 x 100k map sheets
- Small Scale Local Modelling (between 0-25 km^2)



Case Study – DEM Mt Isa Inlier

- Regional Scale for Tenement Selection
- A desktop exercise was undertaken to ascertain the most prospective areas for ground truthing based upon several criteria, namely:

1. Geomechanical suitability (low minimum principal stress and/or high differential stress)
2. Favourable geology based on fault architecture and competency contrasts
3. Geophysical signatures
4. Geochemical signatures (or lack of geochemical data)
5. Tenement Access and physical locality

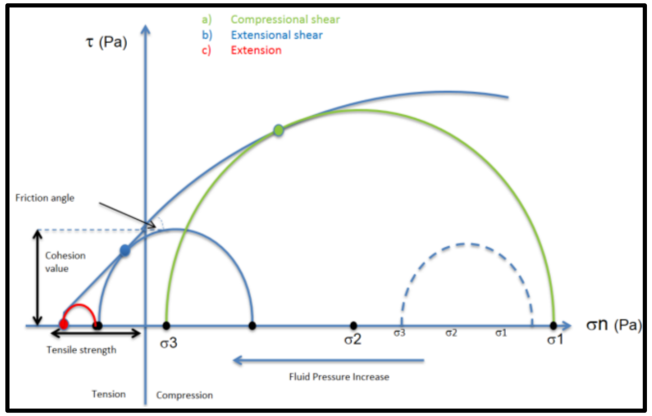


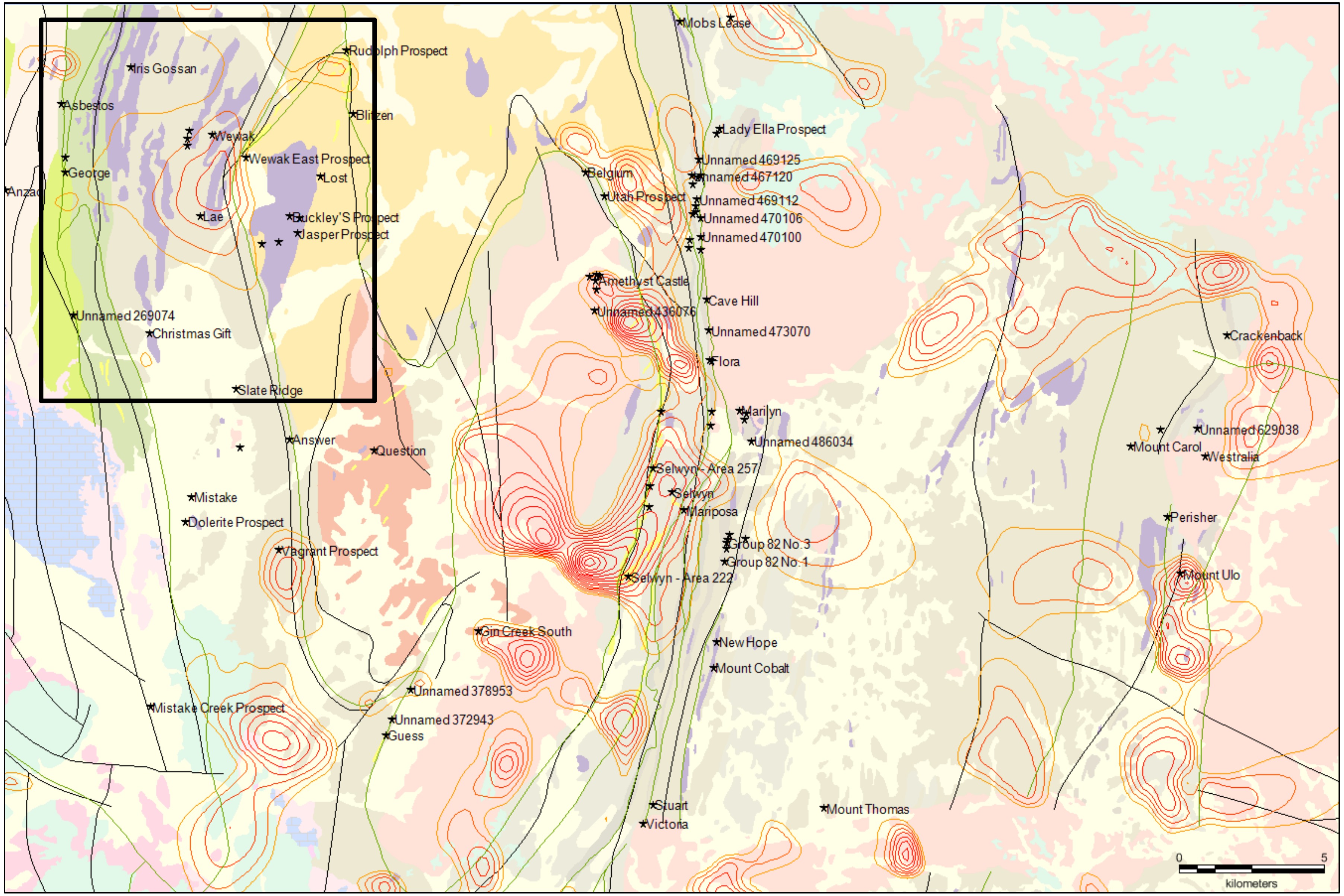
1. Ironclad
2. Kingfisher
3. Magpie
4. Elaine Dorothy
5. Brown Eye
6. Wewak
7. Mistake
8. Mort
9. Yellow Waterhole

Case Study – DEM Mt Isa Inlier

Selwyn Area

- **Contours**
  - Fluid Pressures required for failure (PfF)
  - Differential Stress (Δσ)

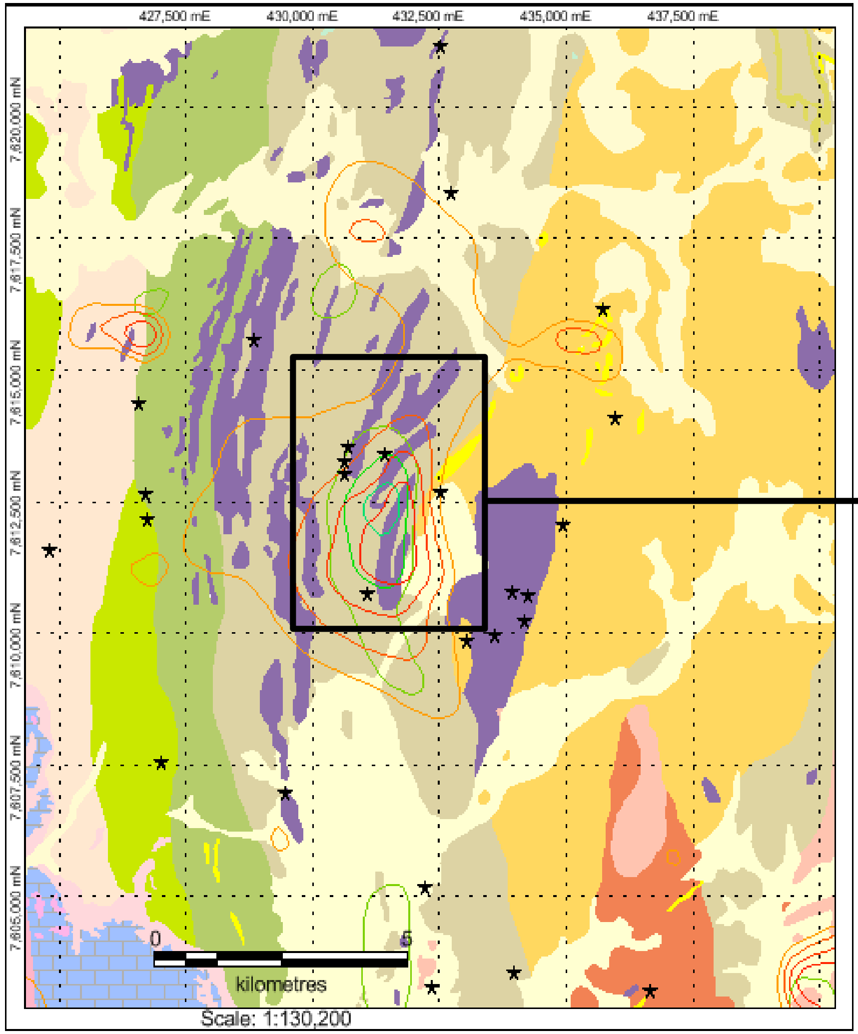


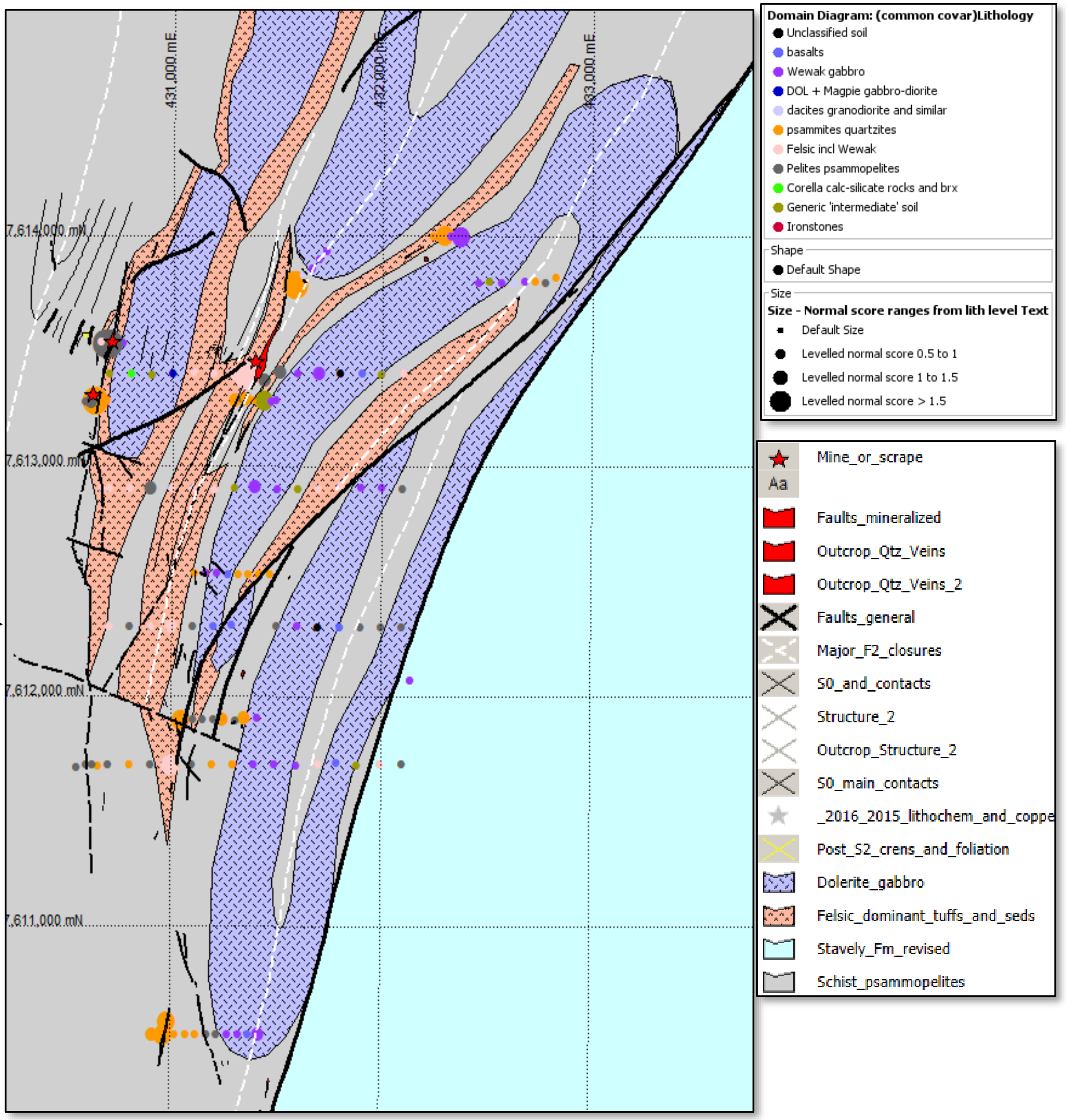


Case Study – DEM Mt Isa Inlier

Wewak Area

- Regional Low Minimum Principal stress and high differential stress overlapping anomalism



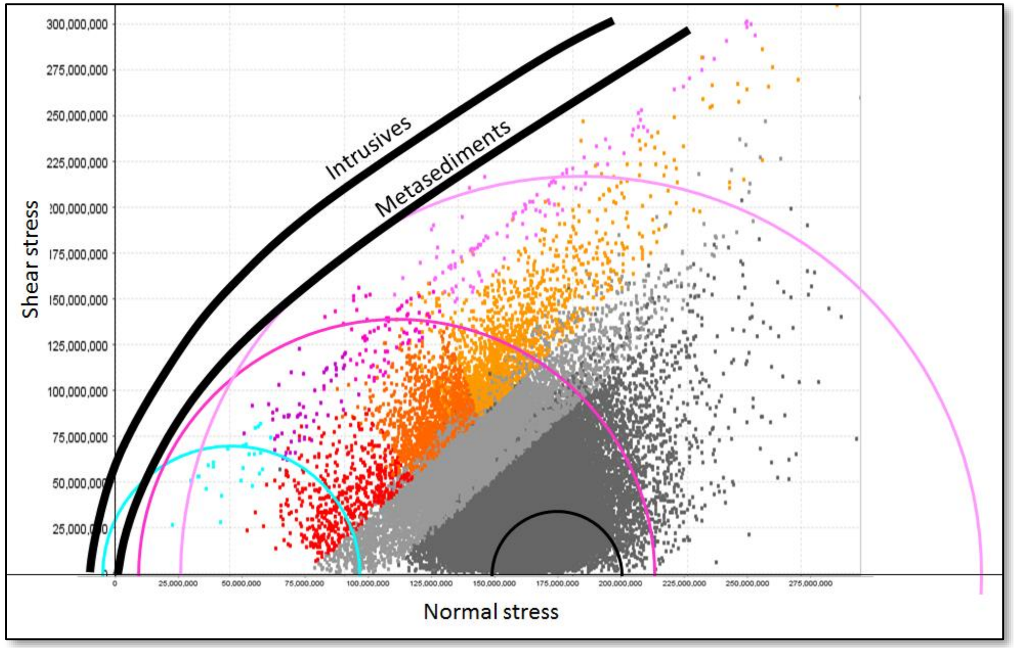


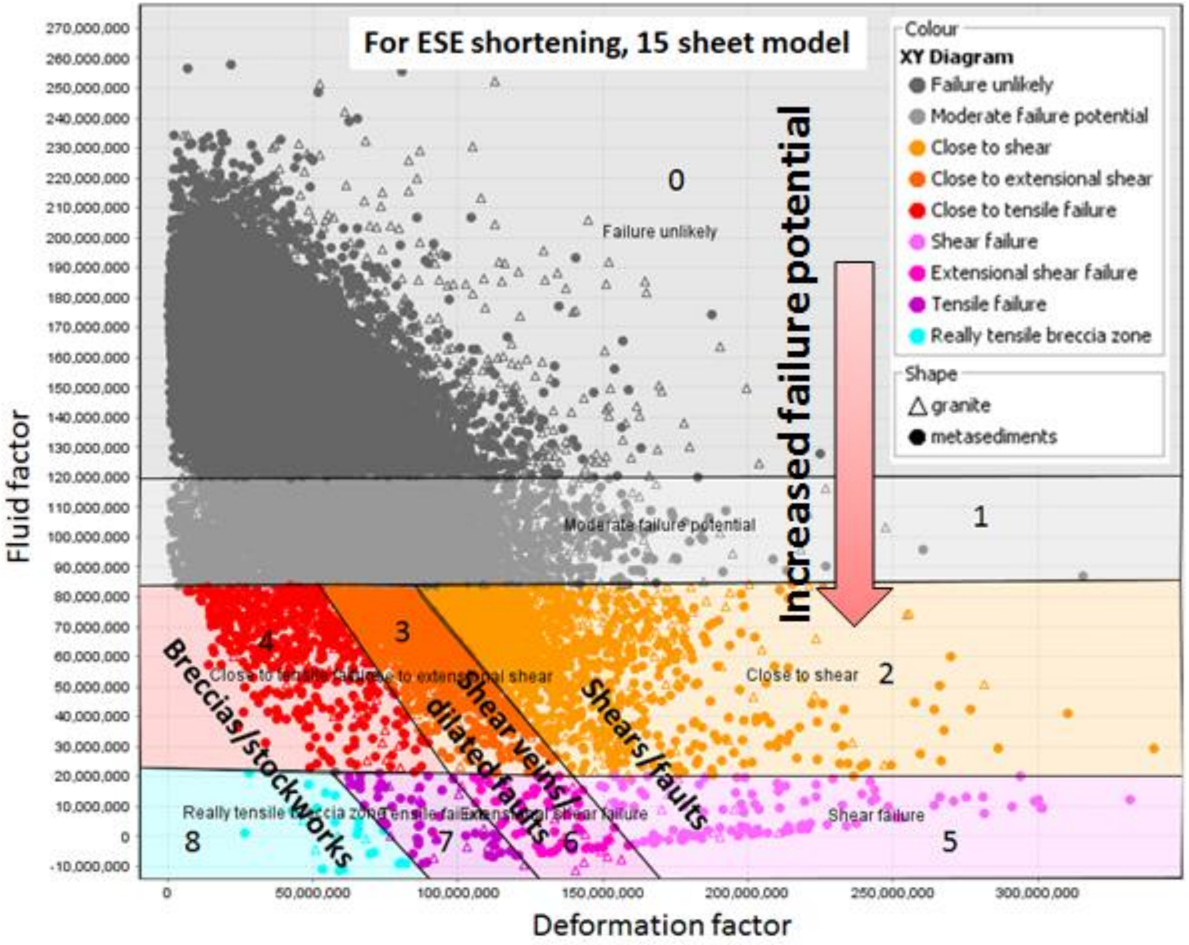
Case Study – DEM Mt Isa Inlier

Wewak Area

Predictor MAPS

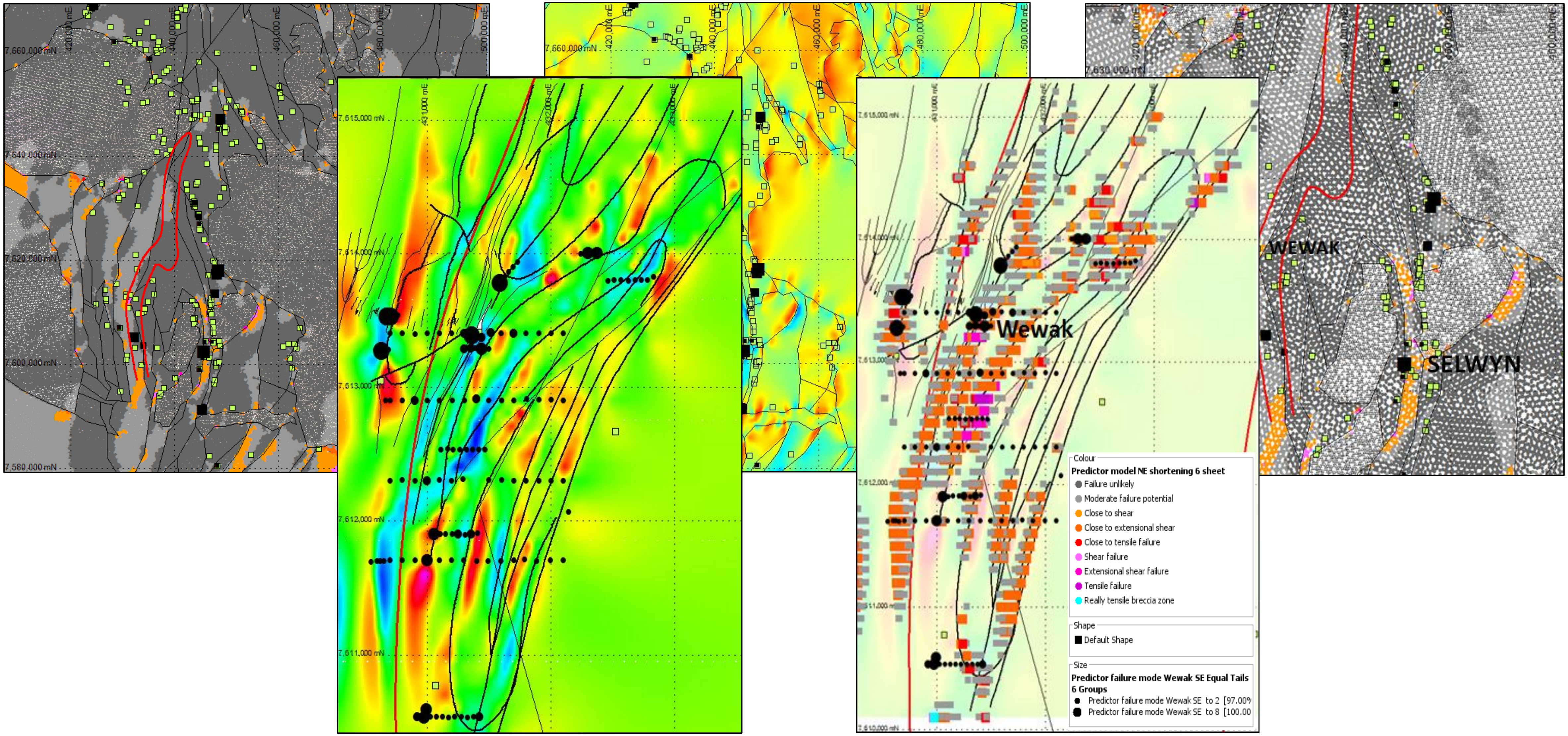
Predictor maps are essentially grid point maps of every zone within the geomechanical model, which describes its stress state as a point in Mohr space or "failure space". When these points are plotted as a 'deformation factor' versus a 'fluid factor' as described above, we can deduce the most likely cause of failure as a result of a stress or fluid pressure change at each discrete point within the model





Case Study – DEM Mt Isa Inlier

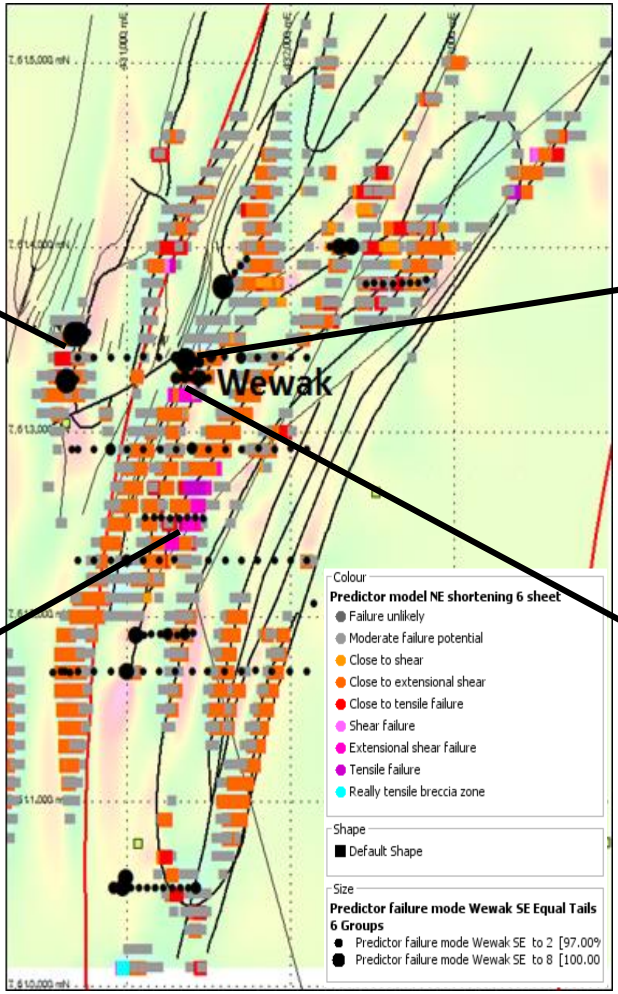
Wewak Area



Case Study – DEM Mt Isa Inlier

Wewak Area

Old Cu workings



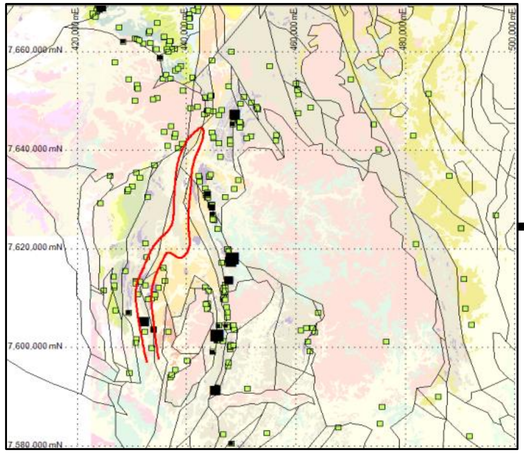
Shear failure, Cu mineralisation

Shear failure, ferruginous material

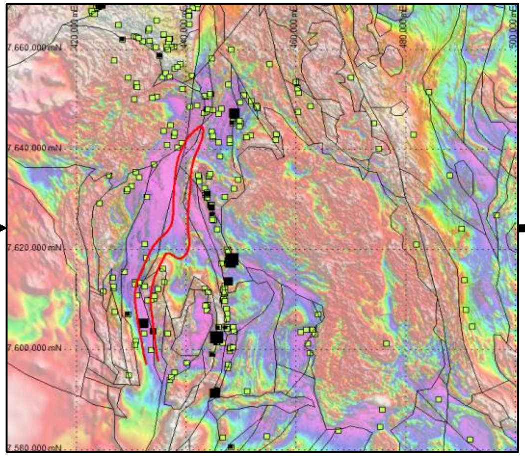
Shear failure and associated tensile veining, Cu mineralisation

Prospectivity Analysis

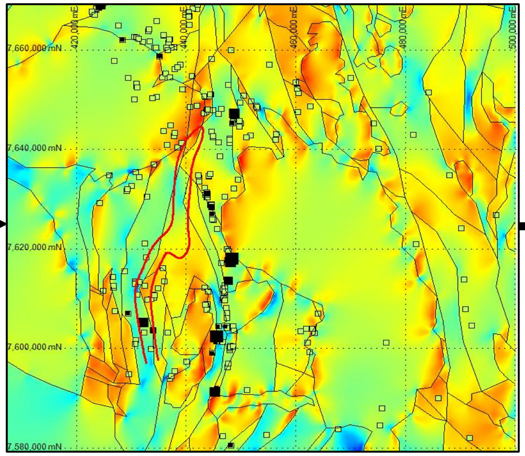
Regional-Scale Prospectivity



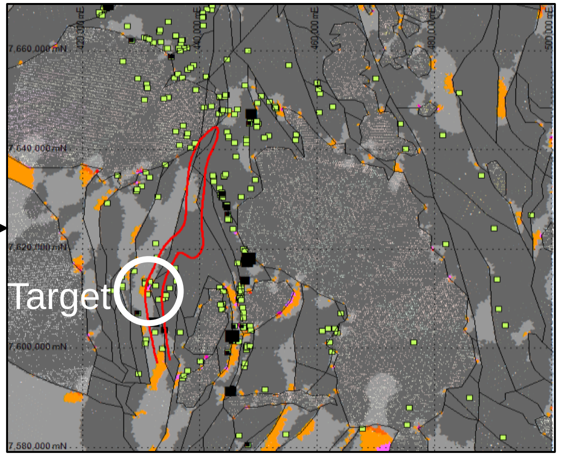
- Incorporating all Geological Datasets



- Remote Sensed Data Interpretation

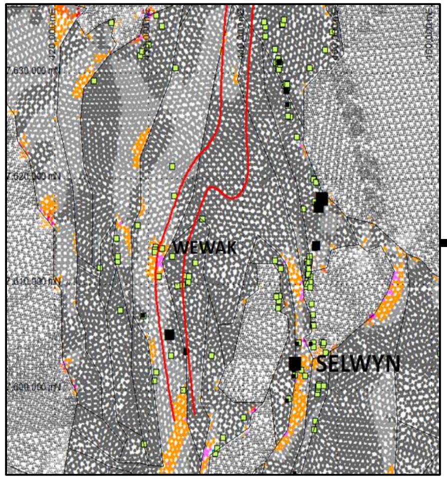


- Geomechanics

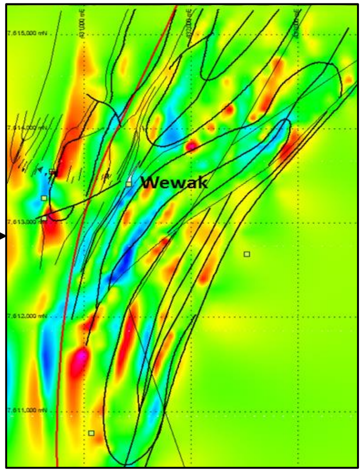


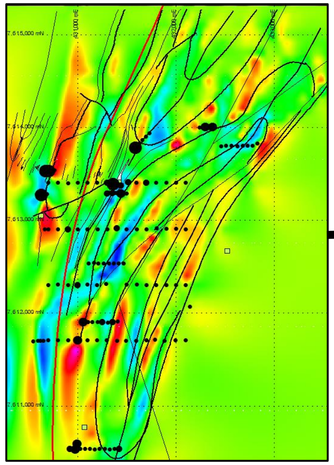
- Predictor Maps

Local-Scale Structural Targets

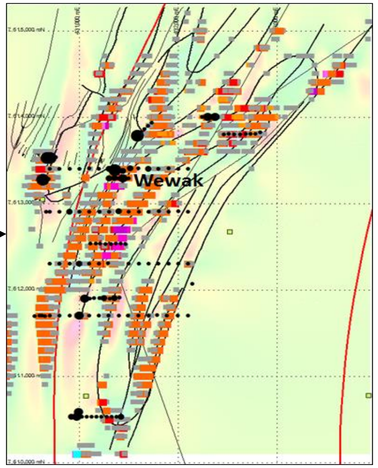


- Predictor targets identified





- Local-scale targets identified by geomechanics match with metal anomalism in soils



- Predictor data and Cu = 1st Order targets

Case Study – Mt Isa Cu

Introduction

- Located adjacent to the City of Mt Isa, Qld Australia. Originally founded in 1942 and one of the world's largest underground operations
- Lies within the Western Fold Belt (WFB) of the Mt Isa Inlier, which comprises a series of Paleoproterozoic to Mesoproterozoic Superbasins
- The Mt Isa Copper Deposit sits almost entirely within the Urquhart Shale sediments of the Isa Superbasin
- Voluminous granitic intrusions with the Mt Isa Cu deposit sitting east of the Mt Isa Fault, adjacent to the Sybella Batholith
- The deposit sits along the Paroo Fault, spatial association with Pb-Zn mineralisation
- Protracted history of deformation during the Isan Orogeny (~1590 Ma to 1500 Ma)
- D_2 (east-west compression), D_3 (northeast-southwest compression), and D_4 (southeast-northwest compression)
- Timing of copper mineralisation still debated but related to the main deformation phases D_2 to D_4

MOUNT ISA MINES
A GLENCORE COMPANY

Case Study – Mt Isa Cu

Introduction

- The main project aim was to better understand the geomechanical response of the Mt Isa system to deformation events linked to mineralisation and focused on two main areas:

1. Structural analysis and review of the Mt Isa Copper Deposit. Construction of a 3D conceptual model.
2. Finite Element Analysis (FEA) – Fully coupled geomechanical modelling and fluid flow analysis.

Key Questions

1. What are the important structural features that control mineralisation?
2. What deformation event provides the best correlation with mineralisation?
3. Can we predict additional mineralised zones?

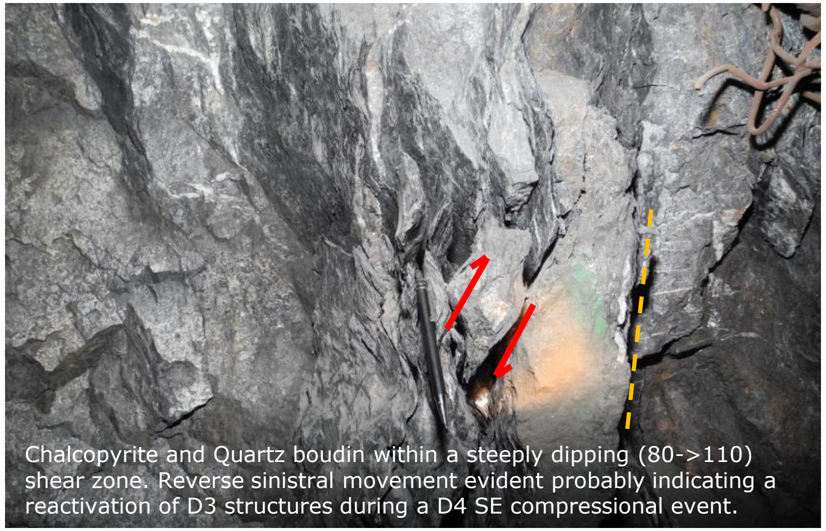
Case Study – Mt Isa Cu

Structural Review

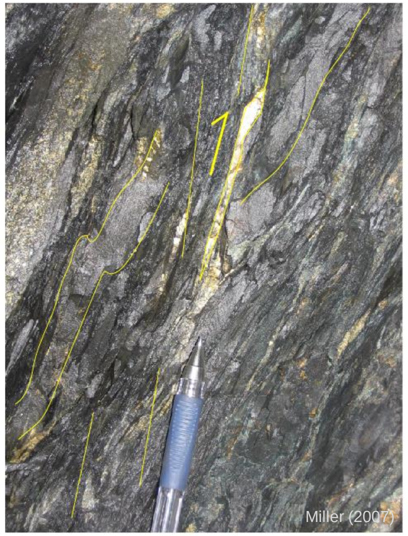
- Regional to local-scale deformation events
- Use evidence from field observations and relationships within the mine sequence to ascertain max principal stress directions

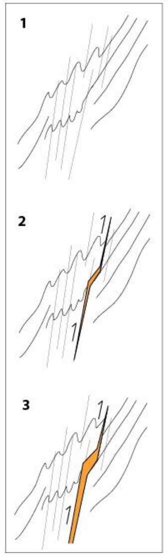
Event	Tectonics	Age
Basin Formation		
Leichhardt	ENE-WSW Rifting	1800 - 1740 Ma
Calvert	N-S Rift-drift	1730 - 1670 Ma
Isa	Sag	1640 - 1595 Ma
Basin Inversion		
D1	N-S thrusting	1640 Ma
D2	E-W Compression	1595 Ma
D3	ENE-WSW to NE-SW Compression	1550 Ma
D4	ESE-WNW Compression	1530 Ma

Local-scale relationships



Chalcopyrite and Quartz boudin within a steeply dipping (80->110) shear zone. Reverse sinistral movement evident probably indicating a reactivation of D3 structures during a D4 SE compressional event.





Vein bedding relationships also indicative of reverse sinistral movement

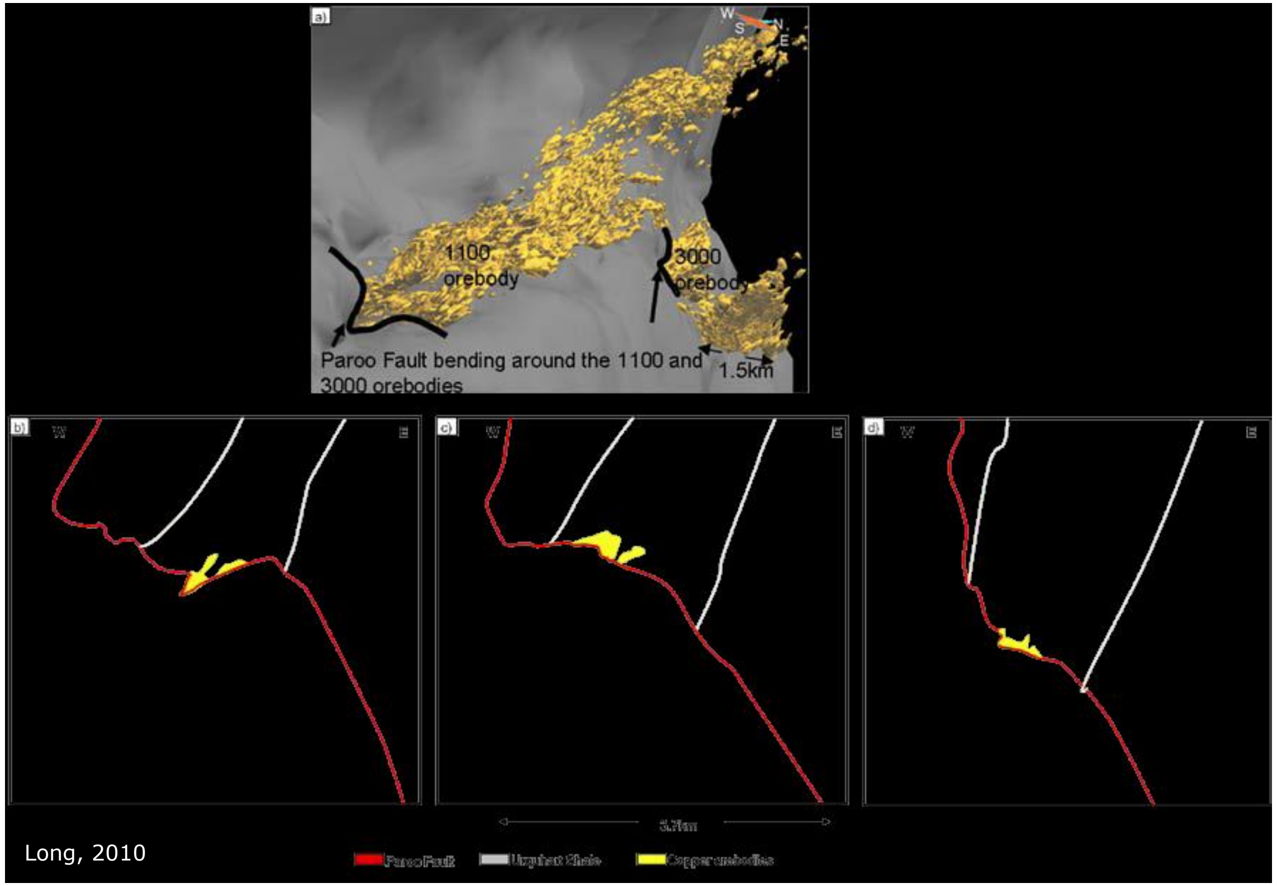
Case Study – Mt Isa Cu

Structural Review

- Recent work by Long, 2010 has suggested that mineralisation was pre-to-syn D_2 based on the observations of the Paroo Fault inflections wrapping or folding around Cu mineralisation.

Is it possible to form mineralised zones in and around inflections on the Paroo fault with post D_2 timing?

Essentially, is the fault surface an important consideration in localising strain and focussing fluids?



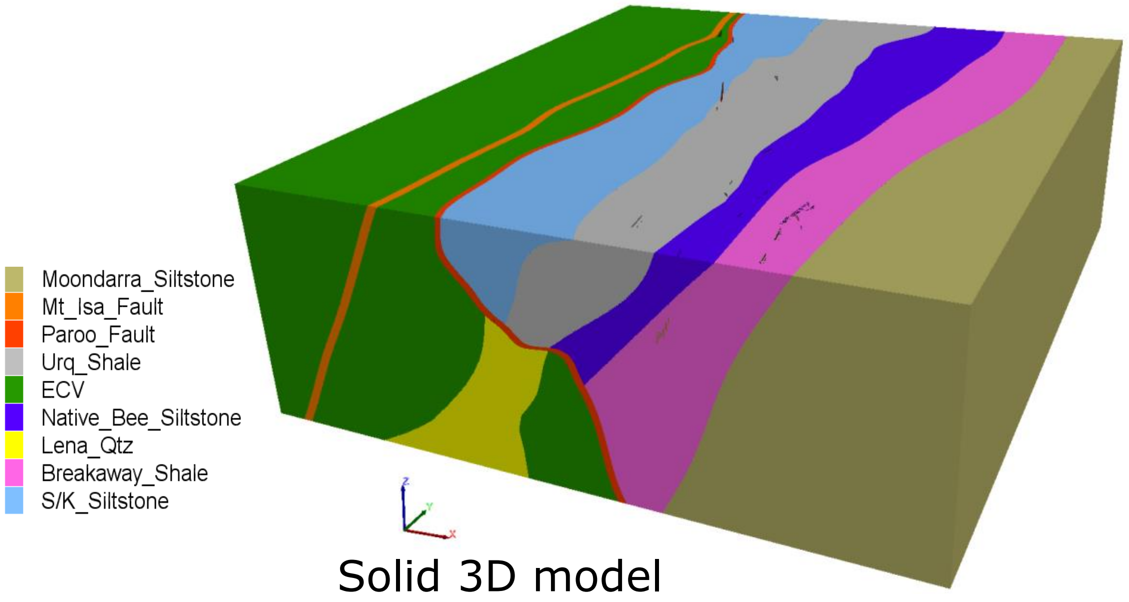
Long, 2010

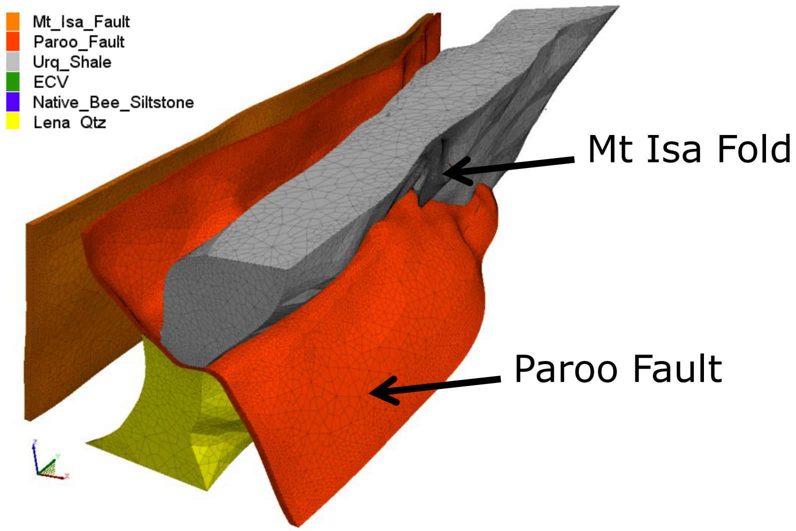
What is the geomechanical response of the Paroo fault during D3 and D4 deformation events?

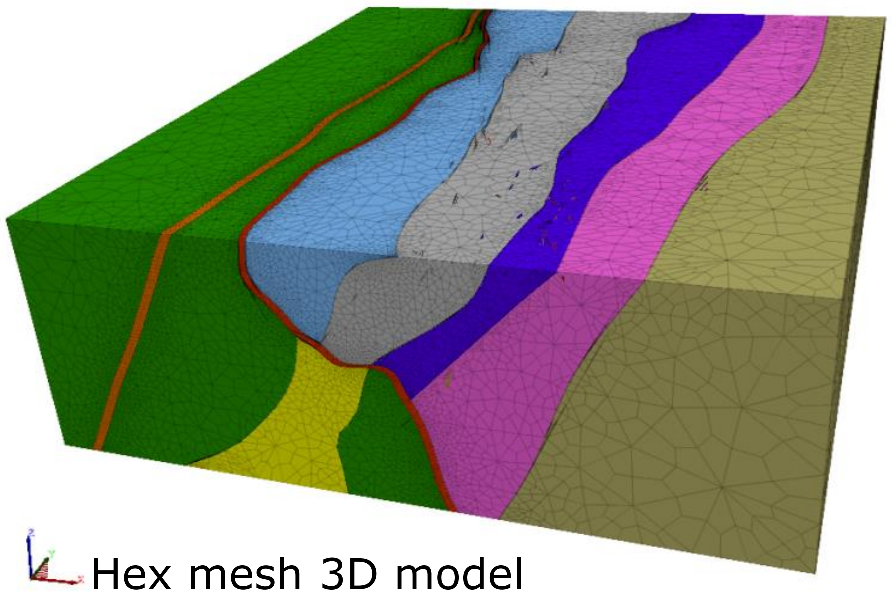
Case Study – Mt Isa Cu

Conceptual Model

- A 3D conceptual model (7 km x 8 km x 2.5 km) included the Mt Isa and Paroo Faults and the Mt Isa Fold which allowed us to look at the influence of this structure on strain localisation and fluid focusing
- Boundary conditions were commensurate with the deformation events
- Depth of mineralisation and vertical pressures were considered to be around 6 km or 150 MPa
- Model 1 – NE compression (simulating the latter stages of D3)
- Model 2 – SE compression (simulating the D4 post main mineralisation stage event e.g. Miller, 2007; McLellan & Oliver, 2008)

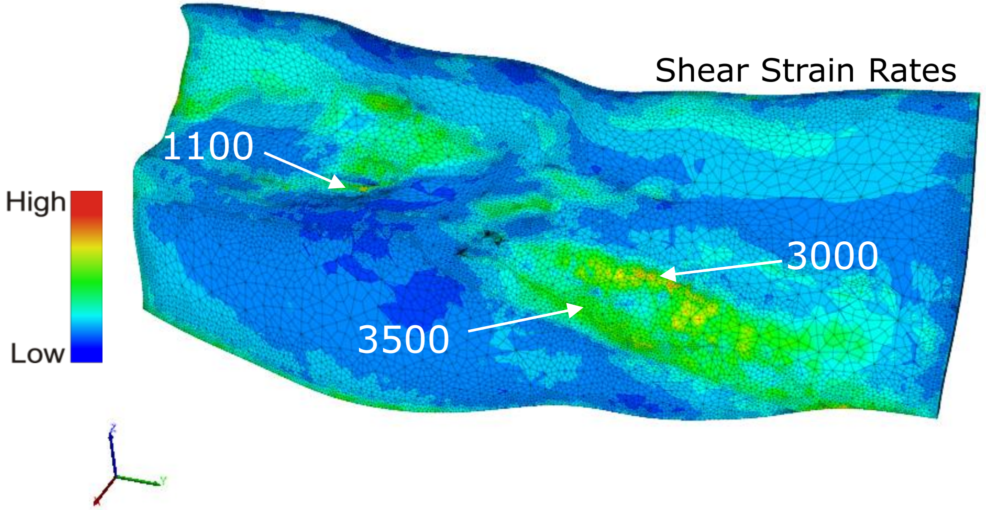


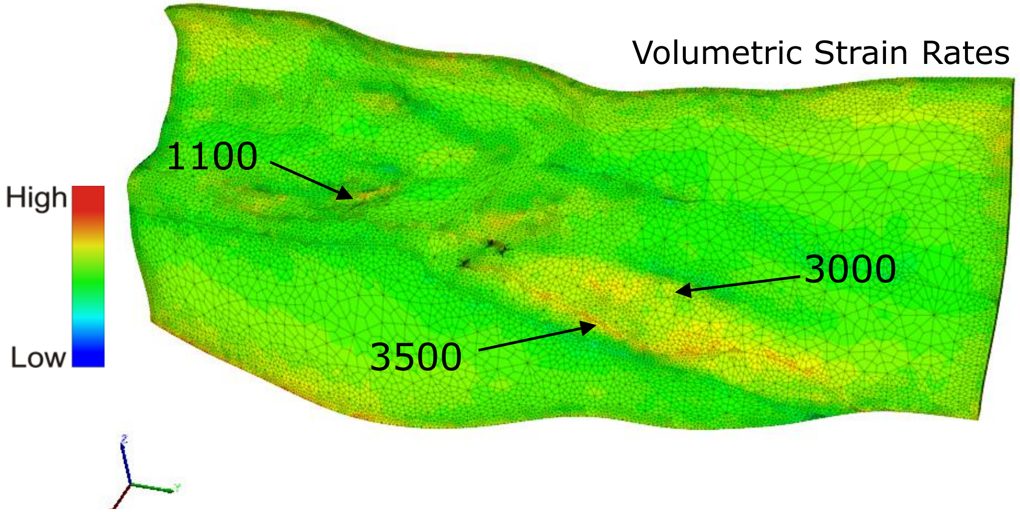


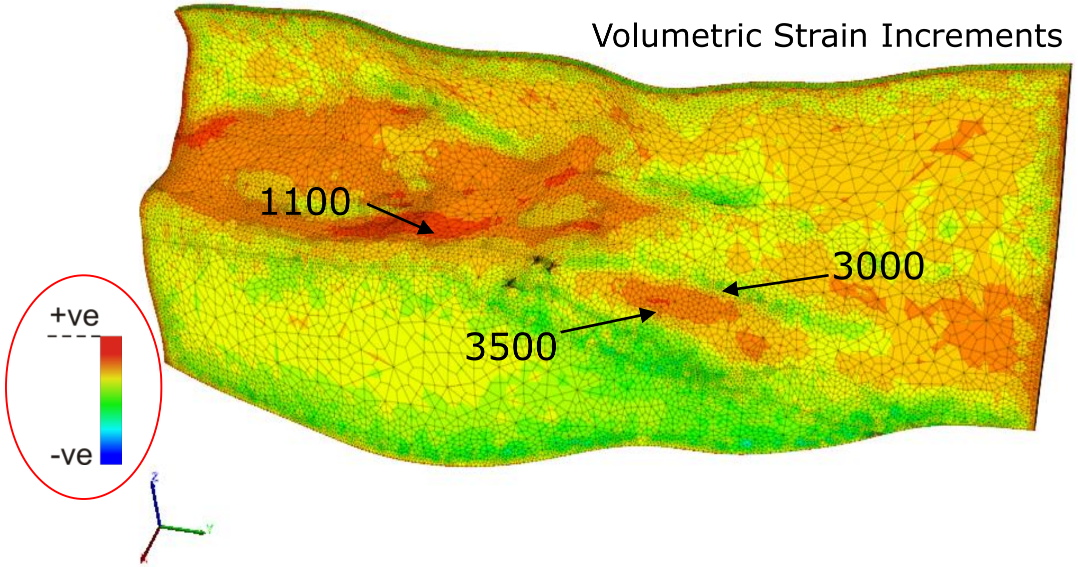


Case Study – Mt Isa Cu

Results – NE compression (EARLY STAGES)



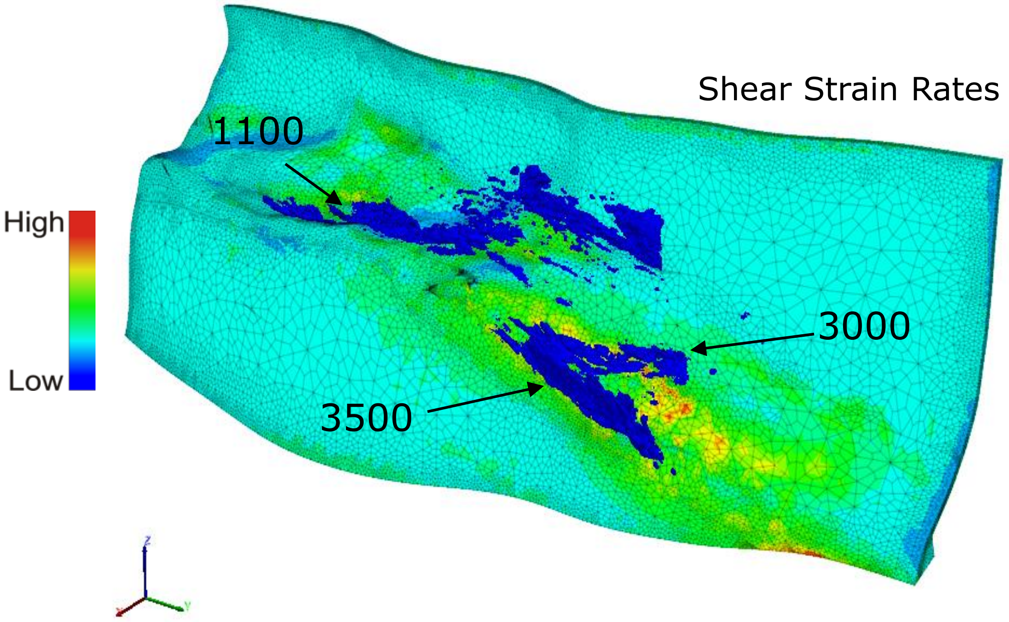


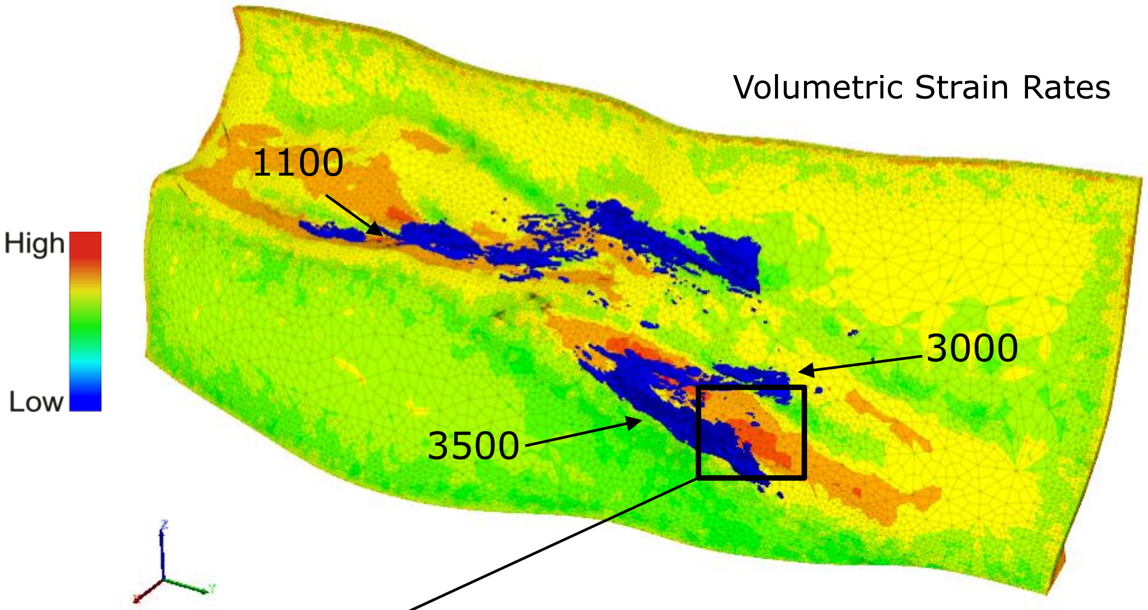


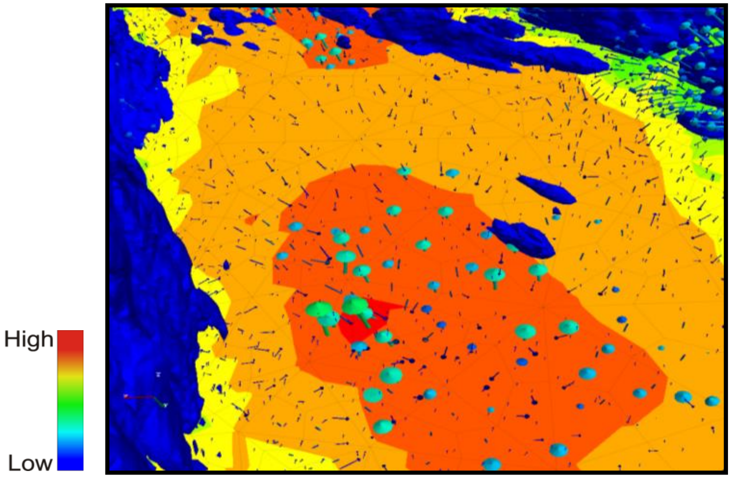
At early stages of the D_3 deformation sequence the main areas on the PFS that are beginning to accommodate the strain are clearly evident. Maximum values of shear strain rates are focused in three main areas that correspond well to the known mineralisation of the 1100, 3000 and 3500 Orebodies.

Case Study – Mt Isa Cu

Results – NE compression (MID STAGES)







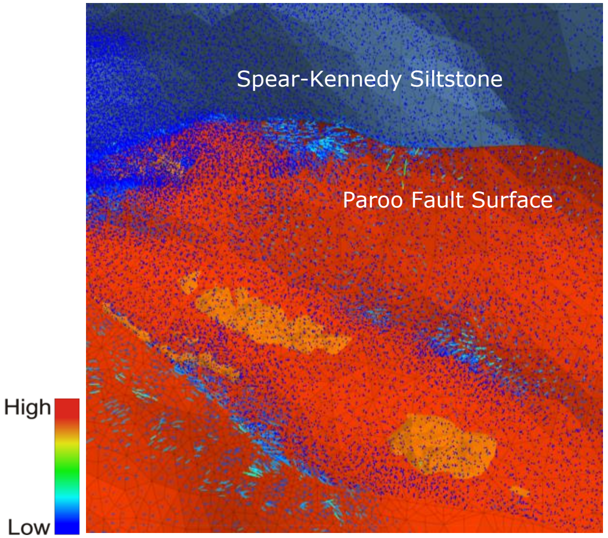
Volumetric strain rates and Darcy fluid flow vectors

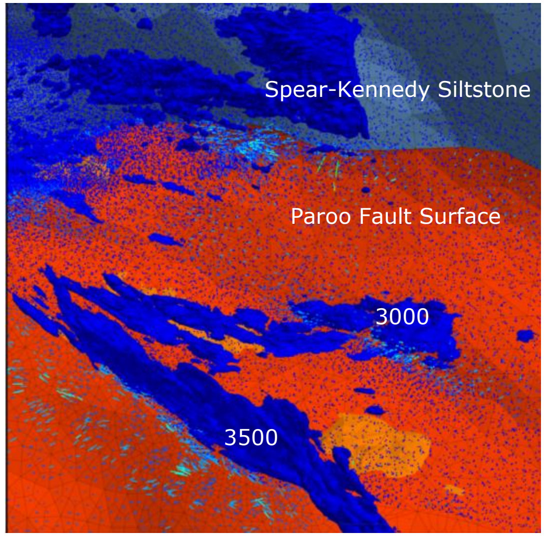
During mid stages of the D_3 deformation sequence there is a distinct continuation of areas accommodating strain with areas of maximum dilation focusing highest fluid fluxes.

Case Study – Mt Isa Cu

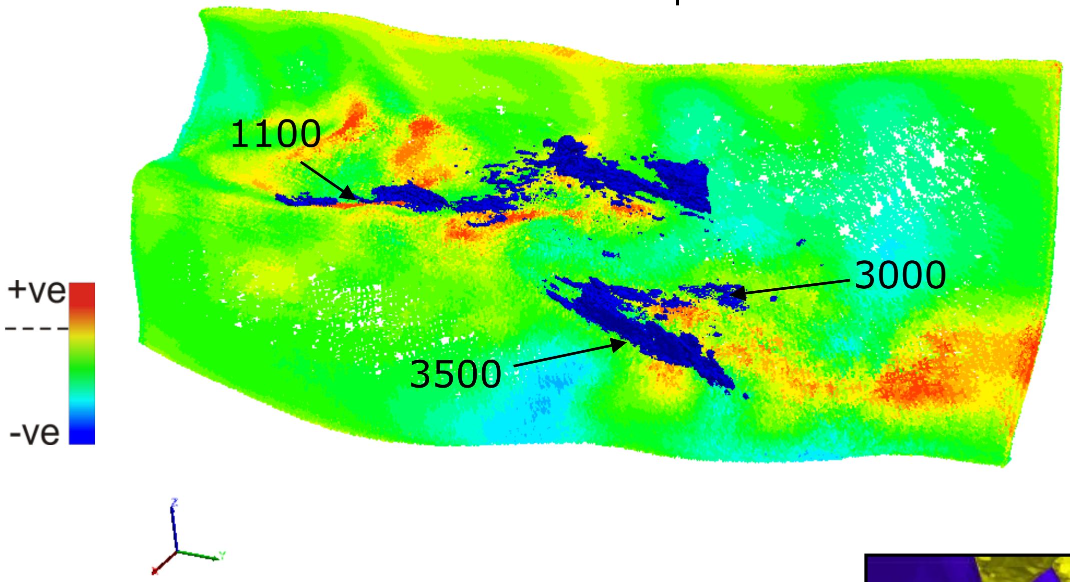
Results – NE compression (LATE STAGES)

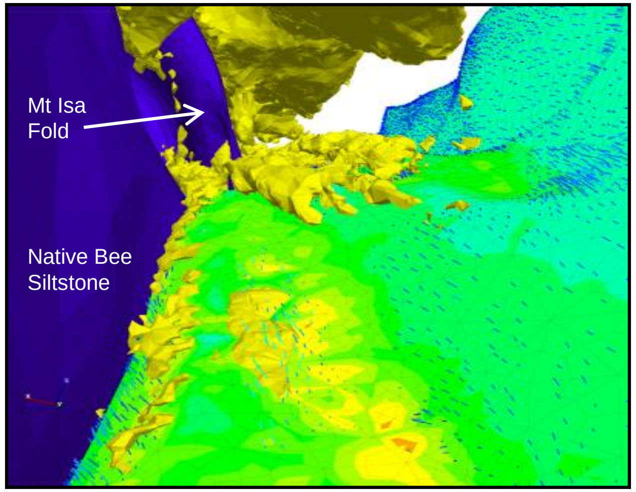
+ve Volumetric Strain Increment Isosurfaces





XY Principal Stress Tensors

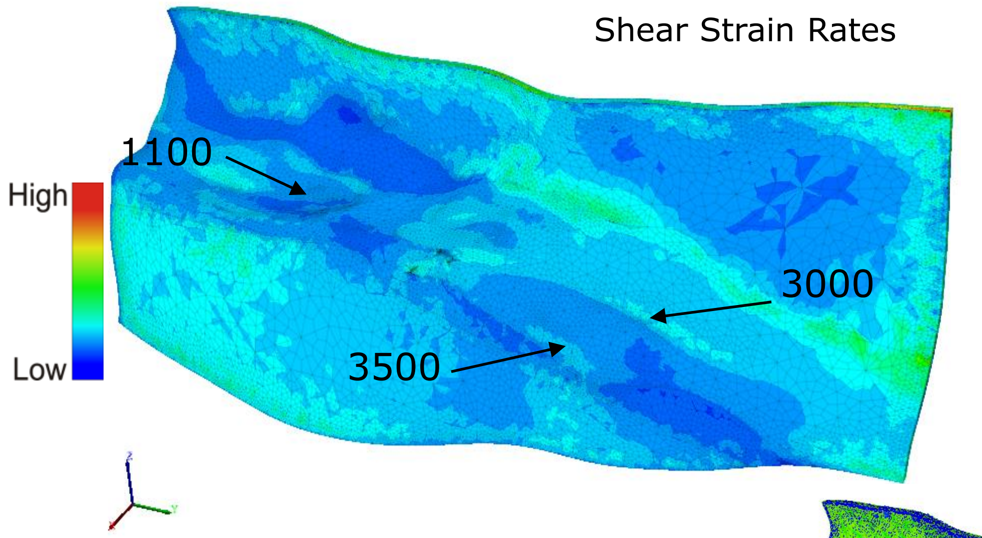


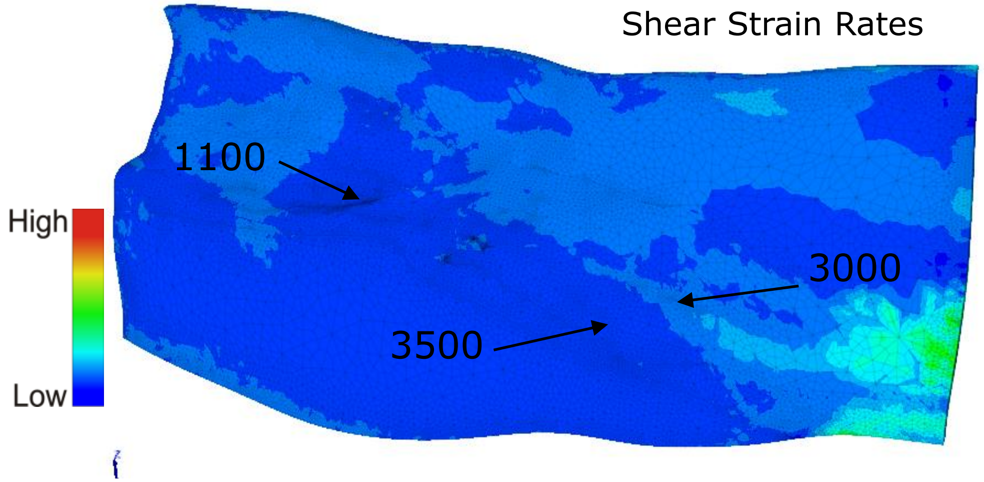


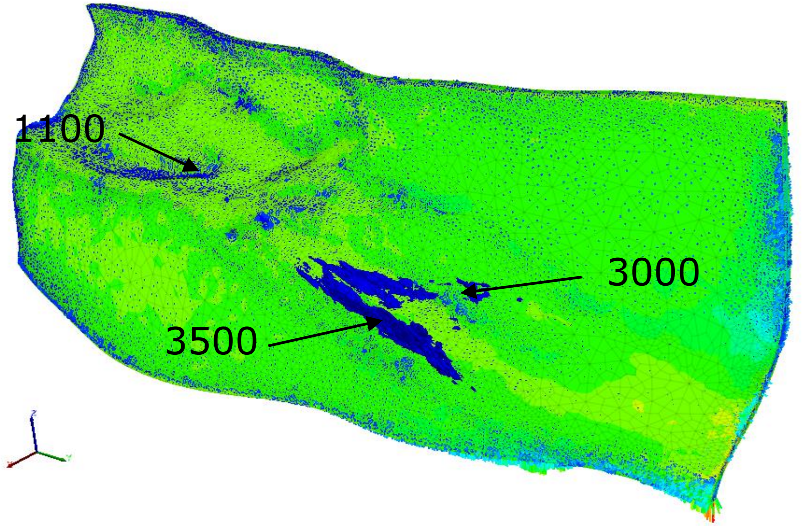
During late stages of the D3 deformation sequence there is a continuation of areas accommodating strain, and areas indicating high fluid focusing correlate well with known mineralisation.

Case Study – Mt Isa Cu

Results – SE compression







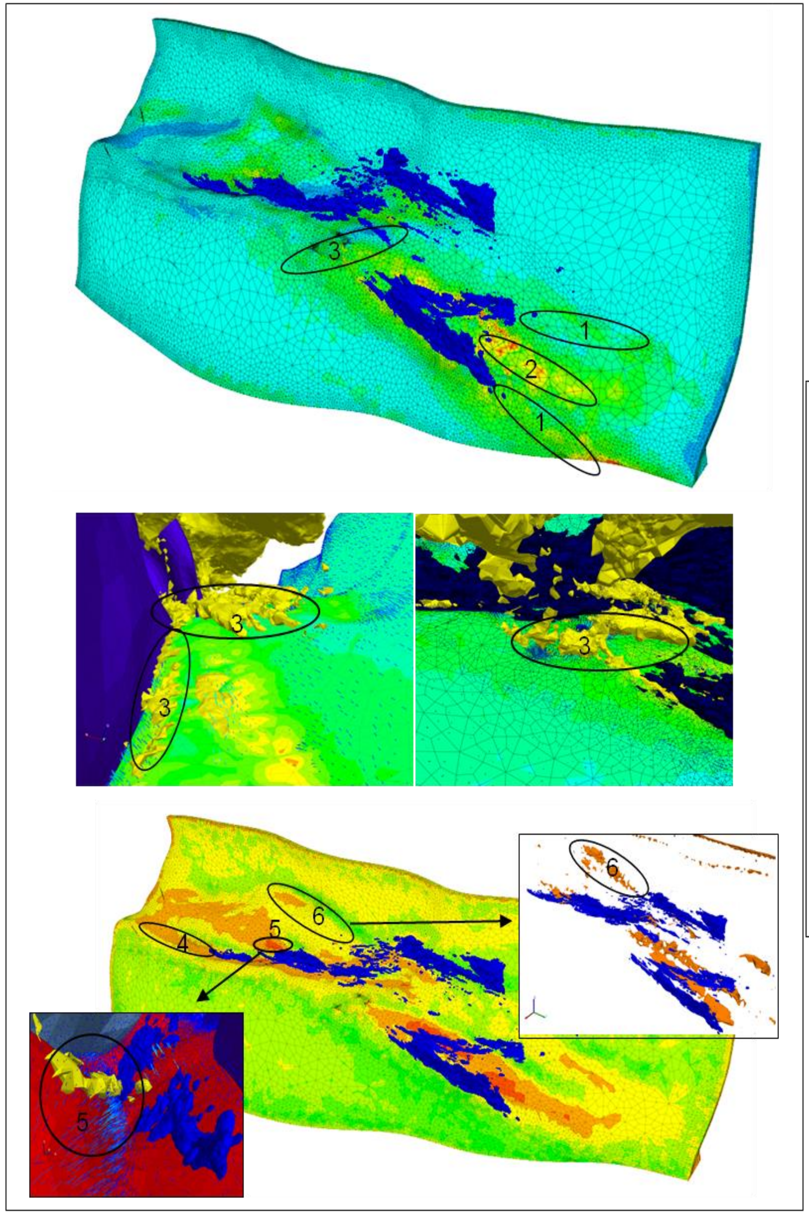
This model displays less of a correlation to the known orebodies than the previous model. The majority of the shear strain during this event is partitioned onto the shallow dipping northern end of the Paroo Fault Surface. This has the potential to highlight orientations of Cu remobilisation during D_4.

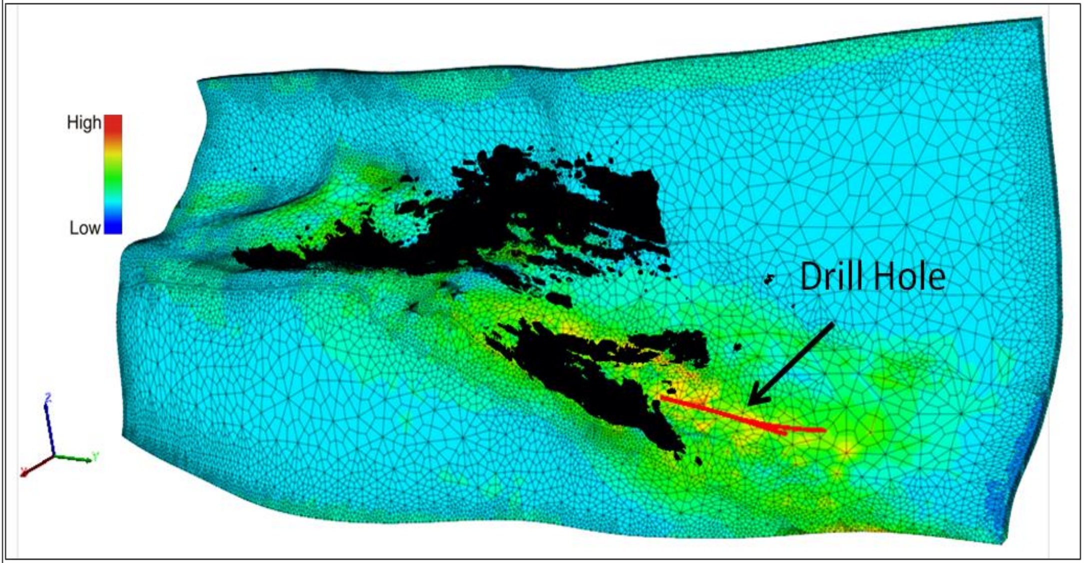
Case Study – Mt Isa Cu

Predictive Targeting

Some Key Criteria:

- Dilation (positive volumetric strain)
- Shear stress and shear strain (high values)
- Fluid flow (maximum values of fluid flow)
- Principal stress (low minimum principal stress or extensional shear stress)





Current drilling targets based on geomechanical results has shown encouraging results

Case Study – Mt Isa Cu

Conclusions

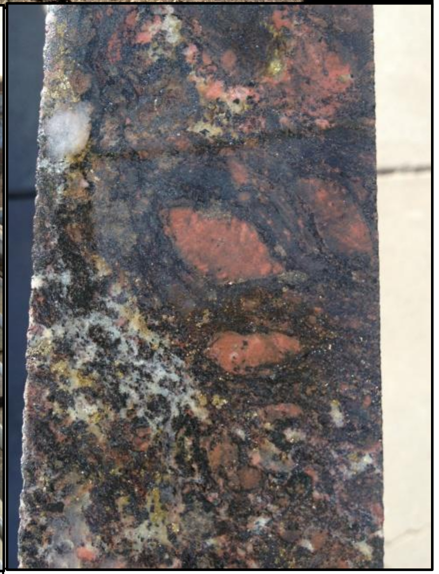
- Modelling of the Mount Isa copper deposit has highlighted that the D_3 NE-SW compressional deformation event has been critical in the distribution of the most structurally favourable zones for shear strain localisation, dilation and focussed fluid flow
- Mineralisation need not be a result of early D_2 folding of the Paroo Fault, but indeed can be localised around early inflections at later stages of the deformation history, unlike the conclusions of Long (2010)
- Employment of innovative techniques such as 3D geomechanical modelling coupled with good structural geology and geological planning has provided a valuable outcome for both the exploration and resource geology team
- Having this critical understanding of how the deformation events relate to both structures and geomechanical response has enabled the MICO team to:

a) gain a greater understanding of the system
b) prioritise drilling campaigns in a more cost effective manner
c) return successful and promising assay results with planned drilling intersections
d) increase the potential for discovery of mineralisation extensions and extend the current life of mine

ERNEST HENRY
A GLENCORE COMPANY

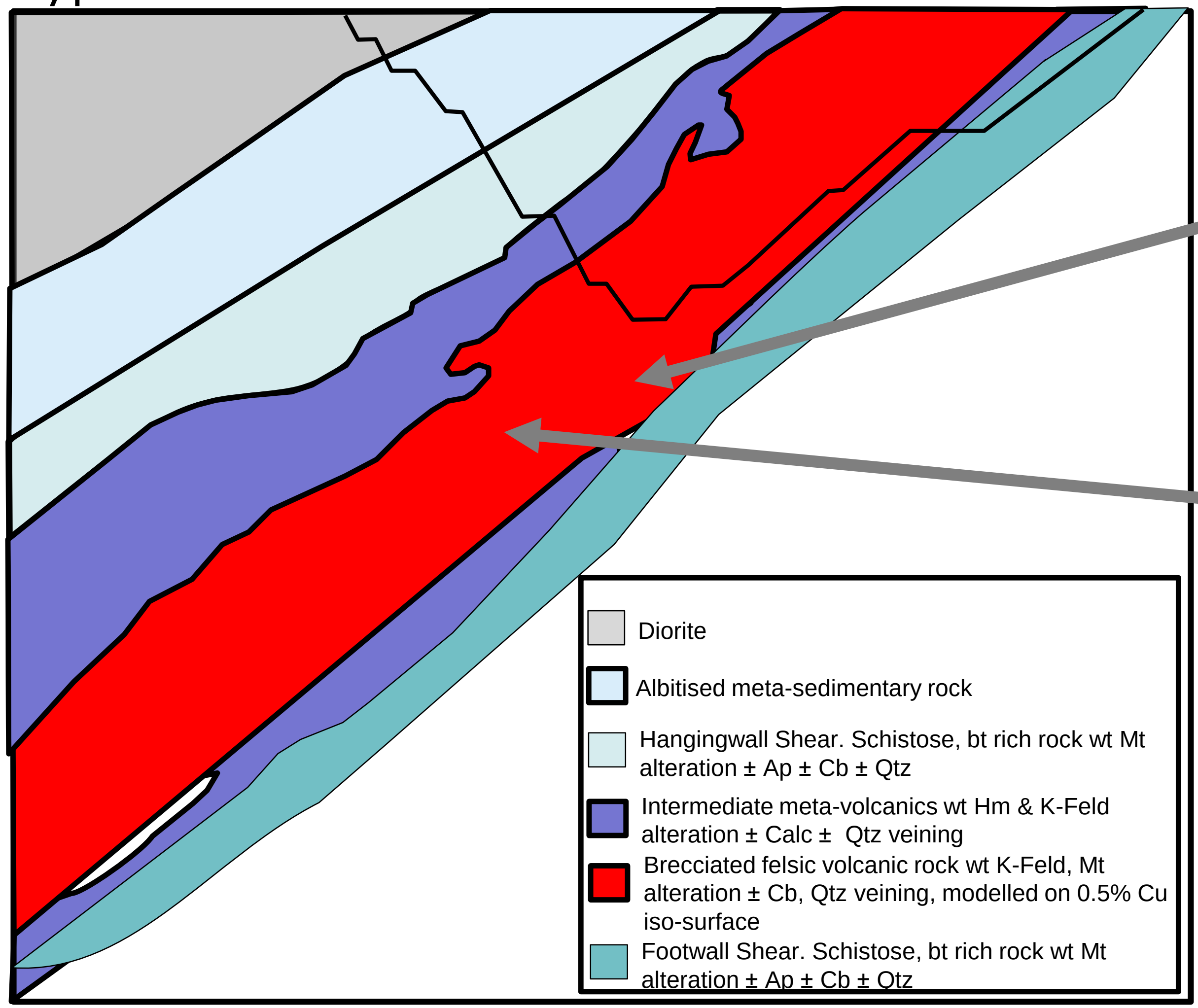
Ernest Henry Cu-Au Deposit

- Essentially a large mineralised breccia system
- Open pit transition to underground 2016
- 2016 Resource of 87.1Mt @ 1.18% Cu, 0.6- g/t Au
- Sits within a deformed sequence of Proterozoic metavolcanic and minor metasedimentary rocks
- Surrounded by intrusive granitoids and a large diorite body
- Covered by up to 60 m of Phanerozoic sediments

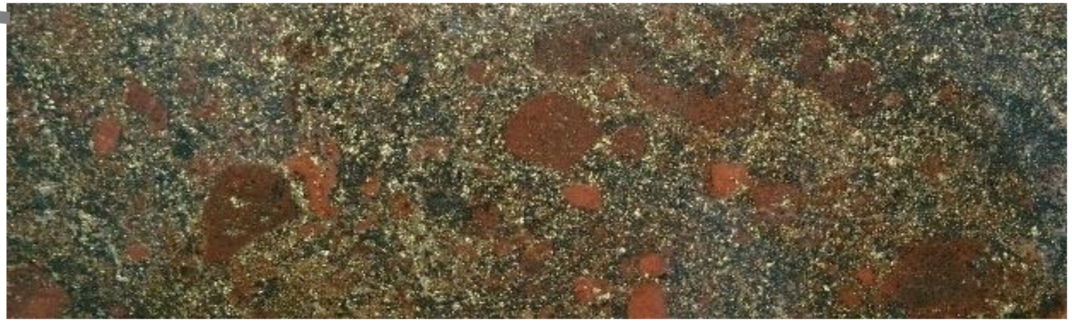


- No surficial geological indicators related to either breccia or mineralisation
- Discovery based on structural geology and geophysics
- Breccia displays mixed breccia types from clast to matrix supported and monomictic to polymictic compositions
- It also displays variations of high to low energy environments (physical to chemical milling)

Typical schematic cross section



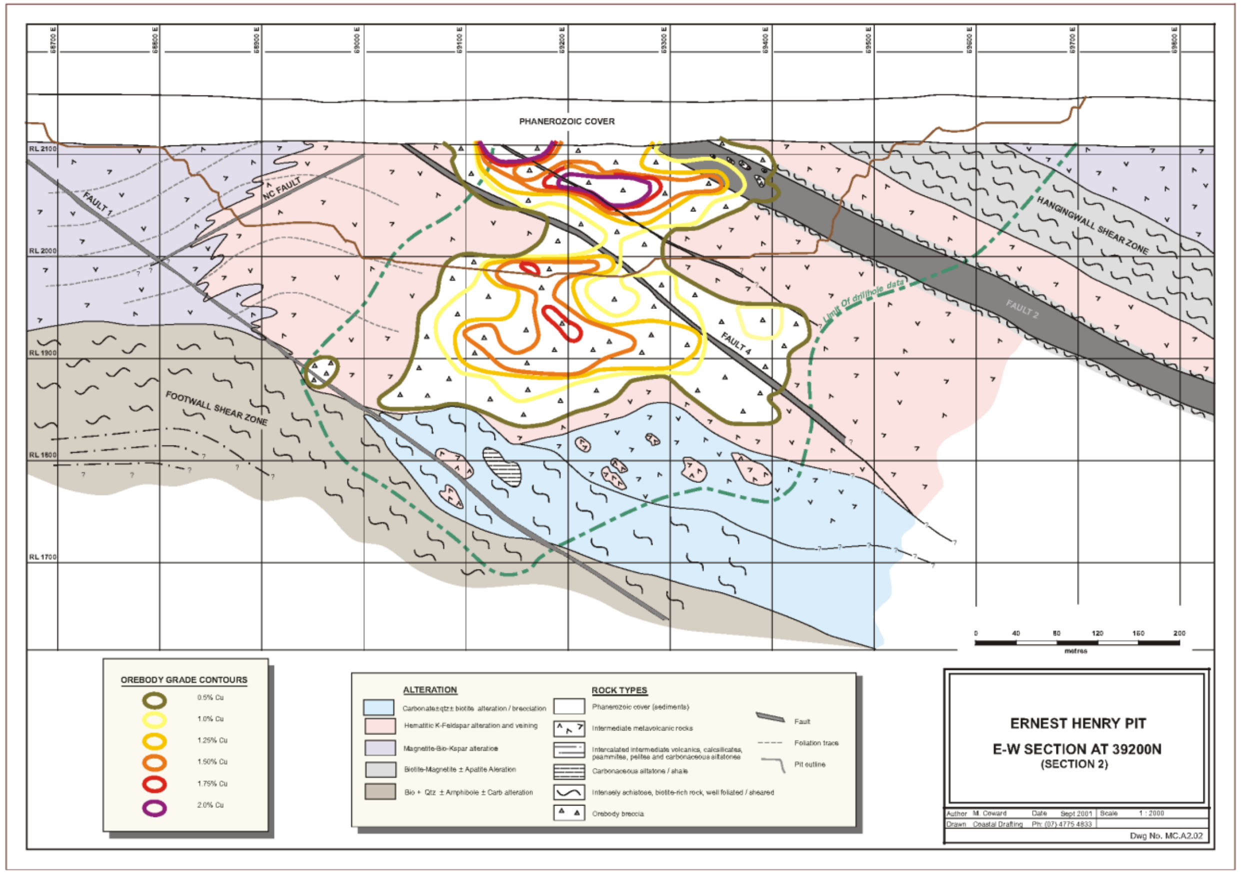
Clast supported brecciated felsic volcanic rock with matrix chalcopyrite mineralisation, bearing 0.5% to 1% Cu.

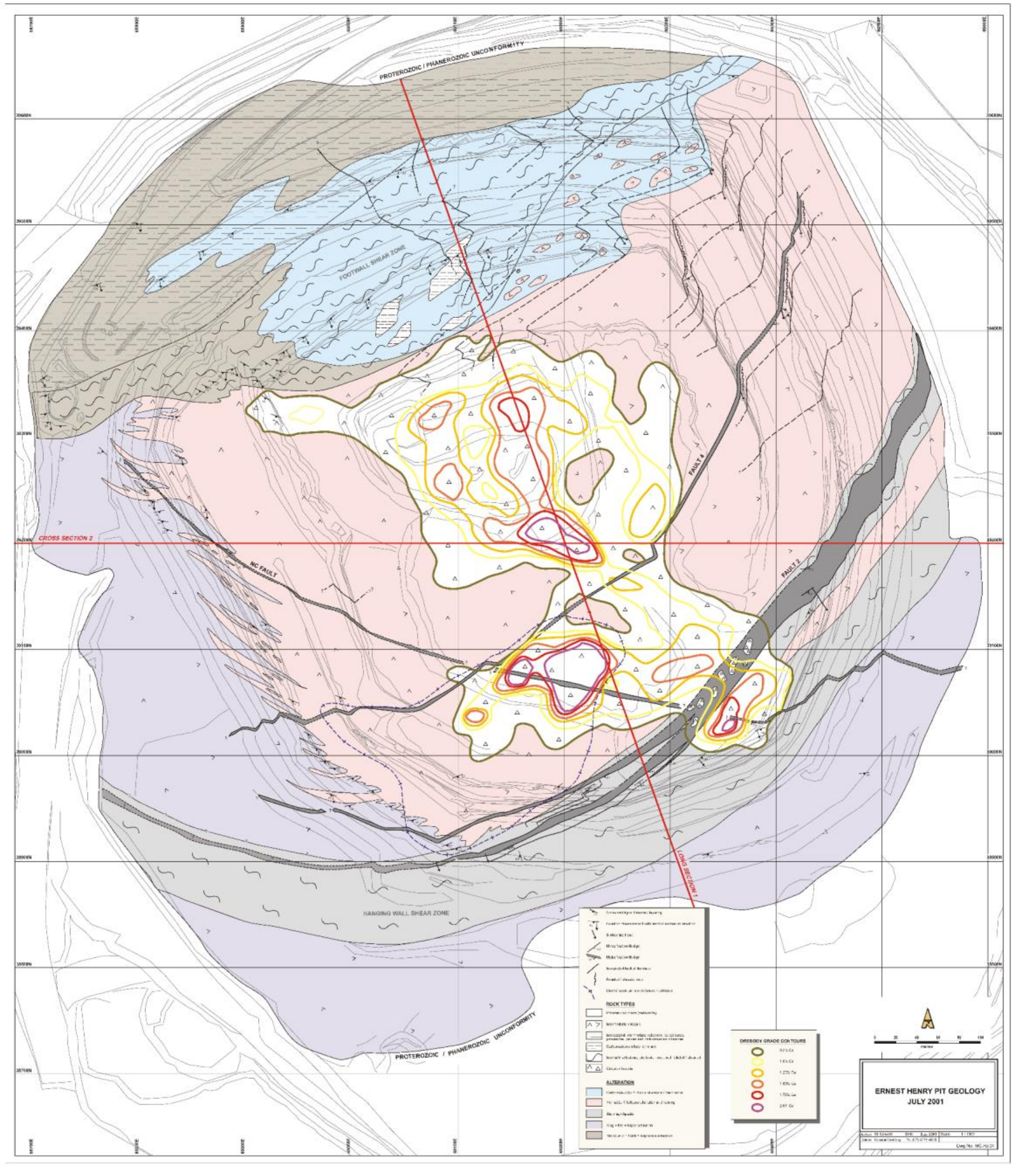


Matrix supported brecciated felsic volcanic rock with chalcopyrite, pyrite, magnetite mineralisation, bearing +1% Cu

Case Study – EHM

Structural Review

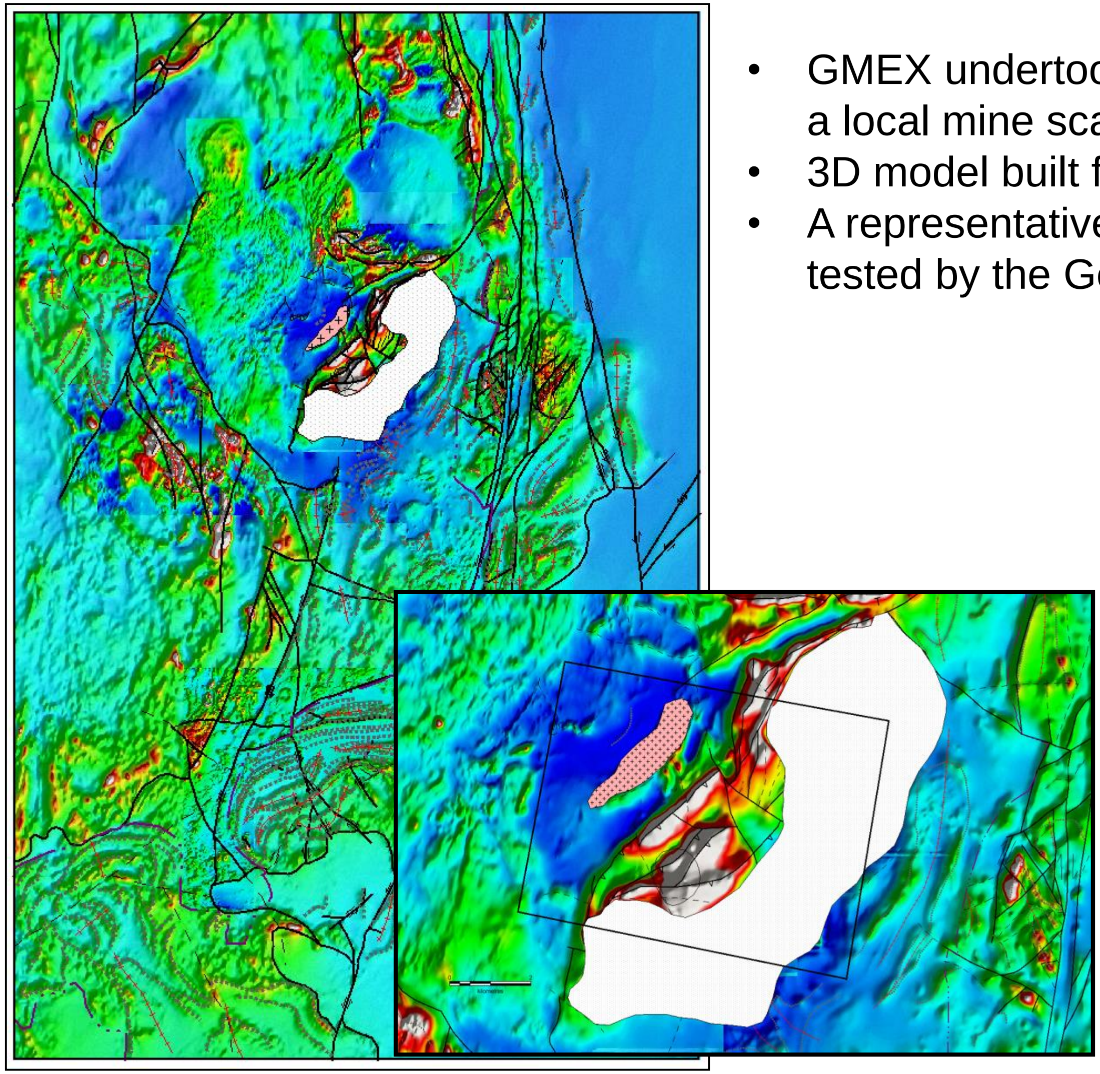




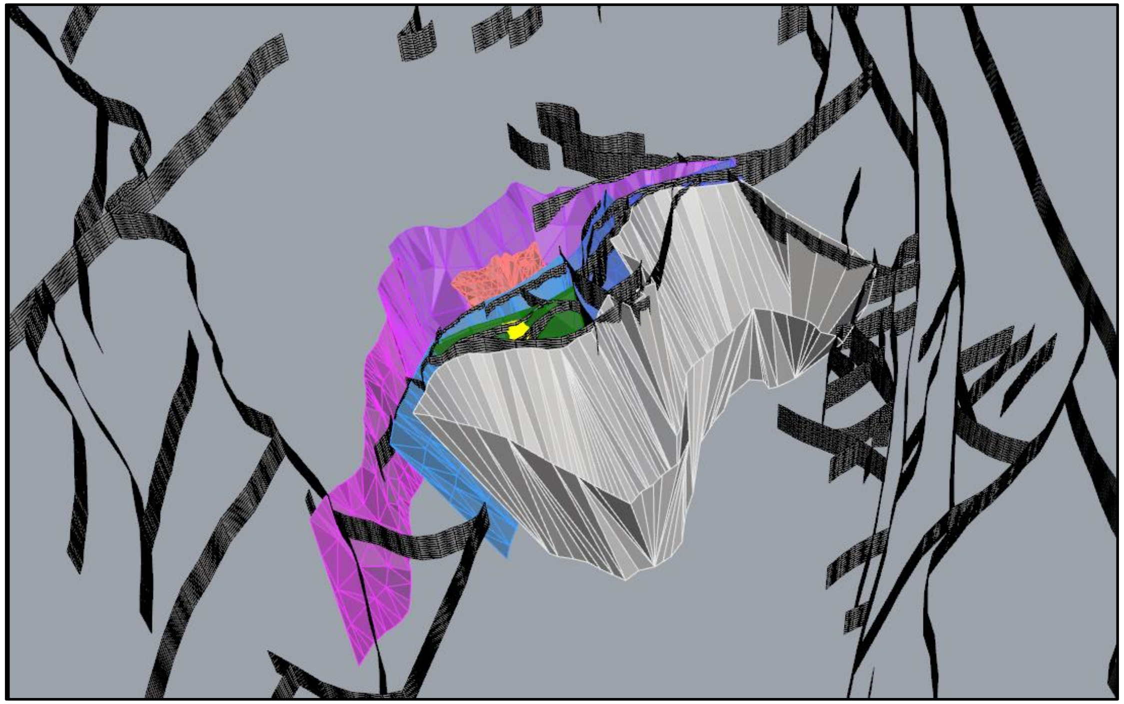
M Coward, 2001

Case Study – EHM

Structural Review



- GMEX undertook a regional interpretation of new geophysical data, then on a local mine scale and matched with known drilling data
- 3D model built from the assimilation of data
- A representative 3D volume was then chosen as the conceptual model to be tested by the Geomechanics



Case Study – EHM

Structural Review

Previous Mine Exploration Methodologies

- EHM Discovery - Regional interpretation of geophysics identified magnetic anomalies and interesting structural architecture which led to drilling and ultimately discovery
- Prior to Geomechanical modelling:
  - Targeting magnetic anomalies using regional airborne surveys
  - Multiple large-scale regional induced polarization surveys
  - Minor amounts surficial geochemistry
- Limited Success

Depth limitations due to infrastructure so Geomechanical Modelling employed to assist with near mine exploration

Case Study – EHM

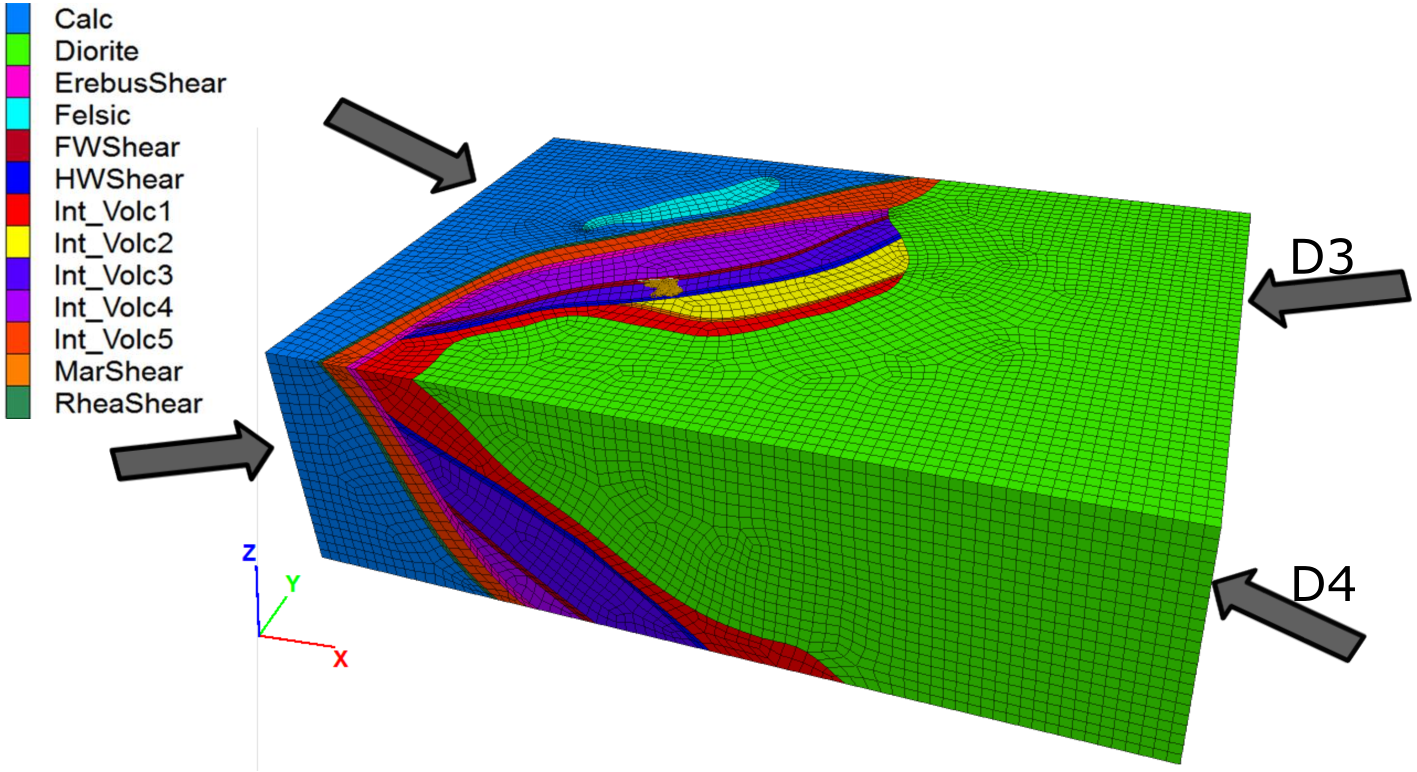
Structural Review

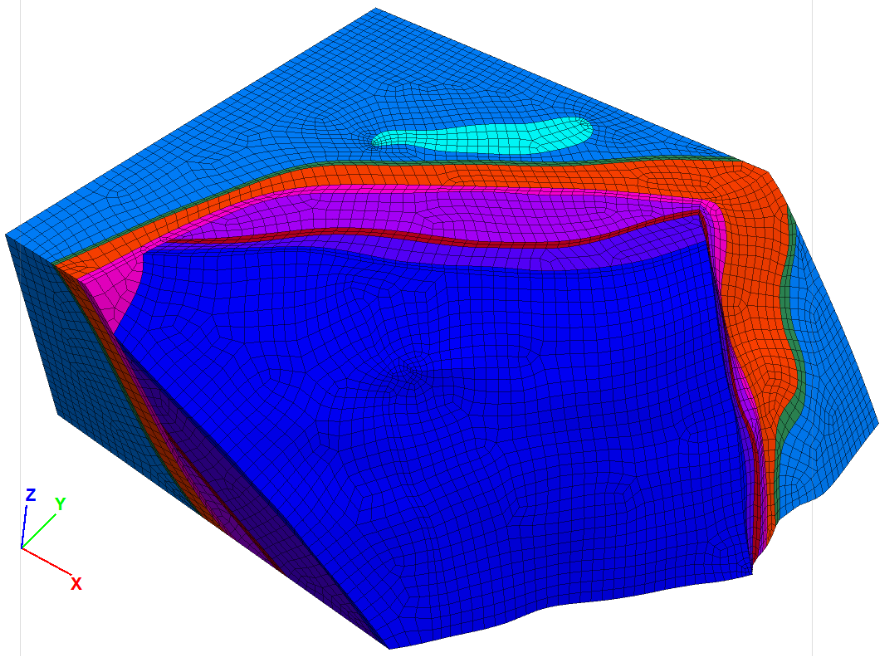
- Regional deformation events relatively well known
- Local scale evidence of regional events
- Slickensides confirming reverse movement on the FW SZ
- Late normal movement also noted on the interlens shear (post mineralization)
- Two deformation vents to be considered are the D3 and D4 events

Event	Tectonics	Age
Basin Formation		
Leichhardt	ENE-WSW Rifting	1800 - 1740 Ma
Calvert	N-S Rift-drift	1730 - 1670 Ma
Isa	Sag	1640 - 1595 Ma
Basin Inversion		
D1	N-S thrusting	1640 Ma
D2	E-W Compression	1595 Ma
D3	ENE-WSW to NE-SW Compression	1550 Ma
D4	ESE-WNW Compression	1530 Ma

Case Study – EHM

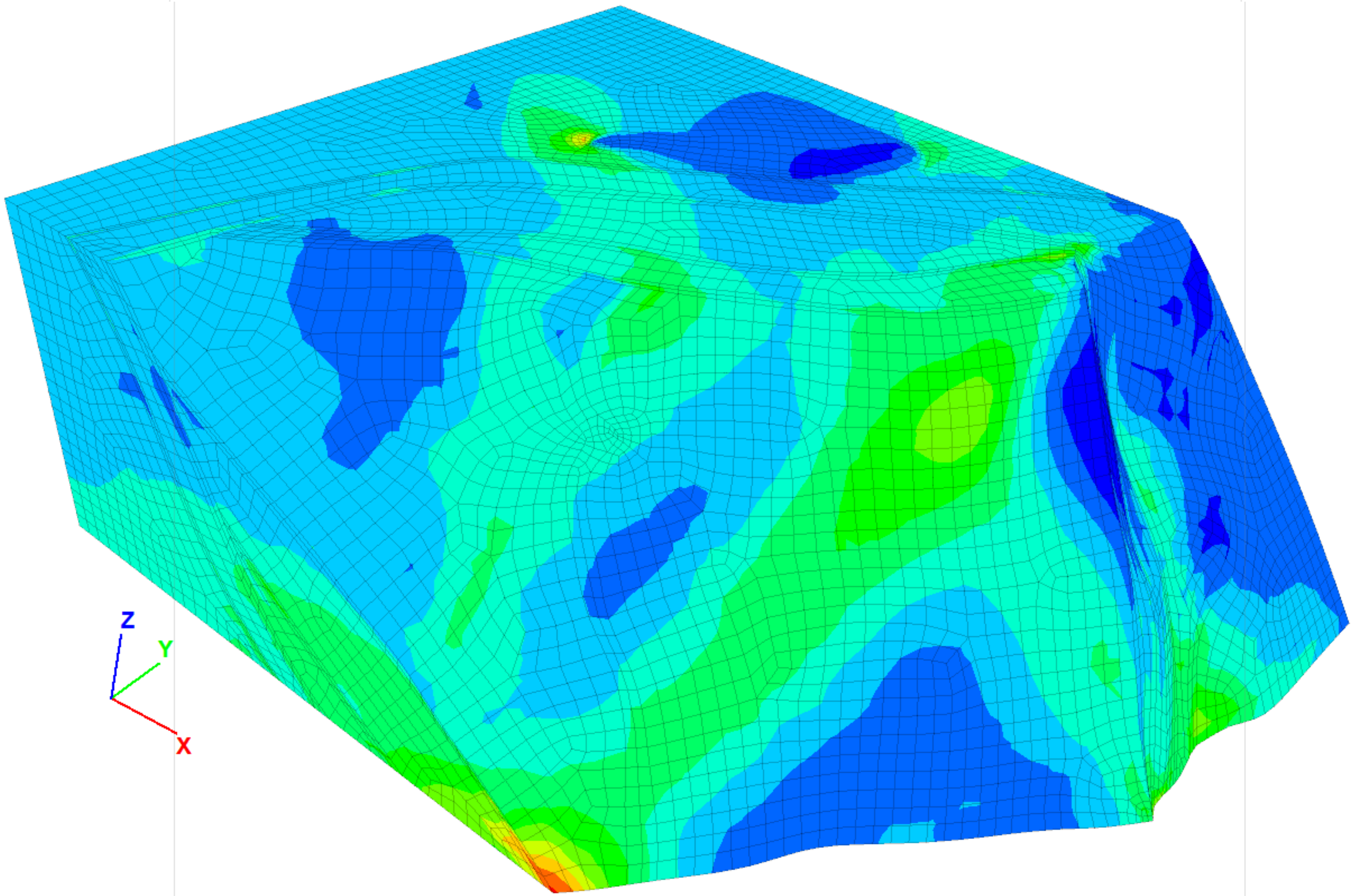
Conceptual Models





Case Study – EHM

Results: D3 (EARLY STAGES)



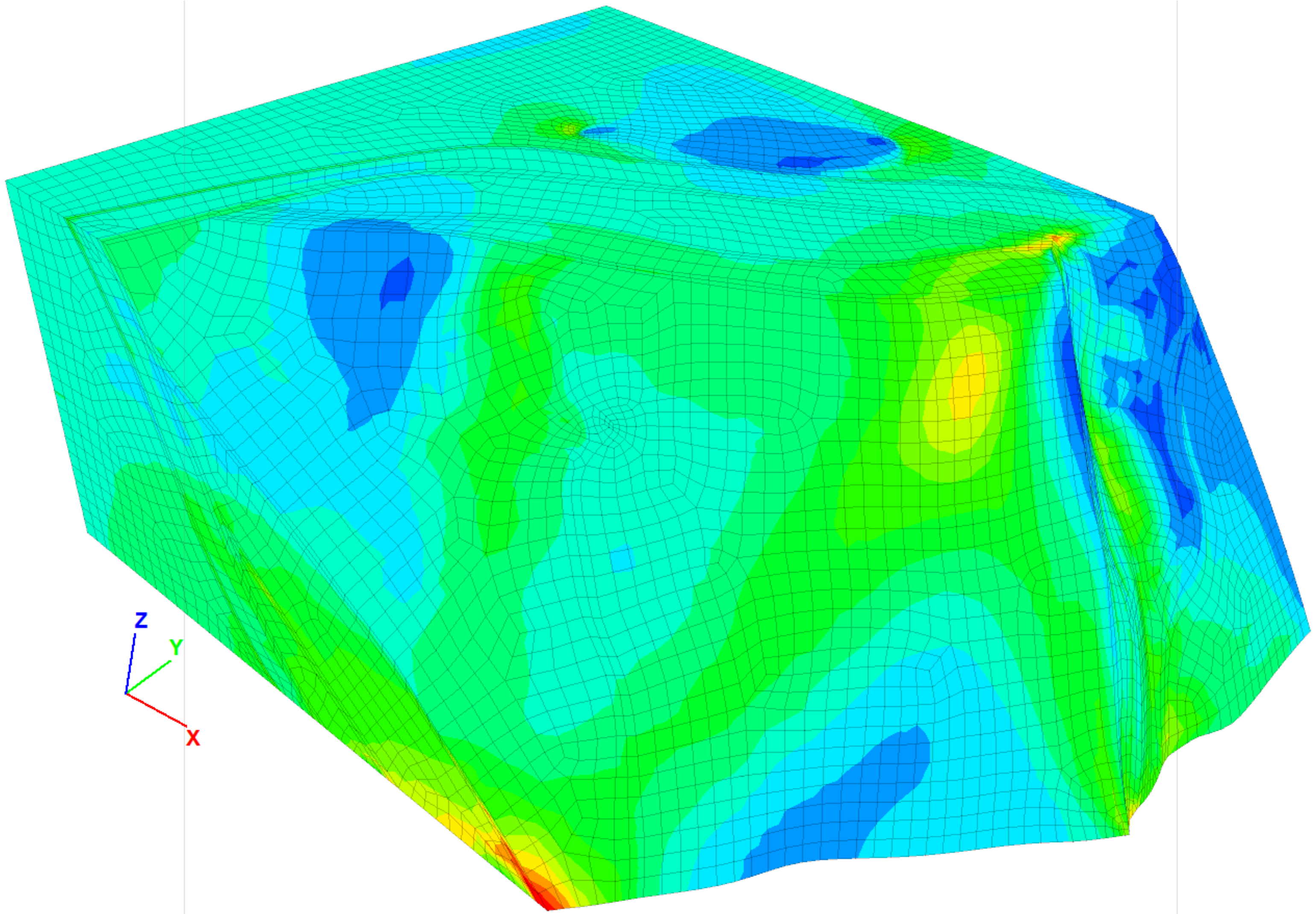
Max Shear Strain Rate

High

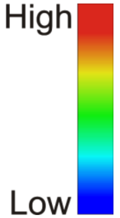
Low

Case Study – EHM

Results: D3 (LATE STAGES)

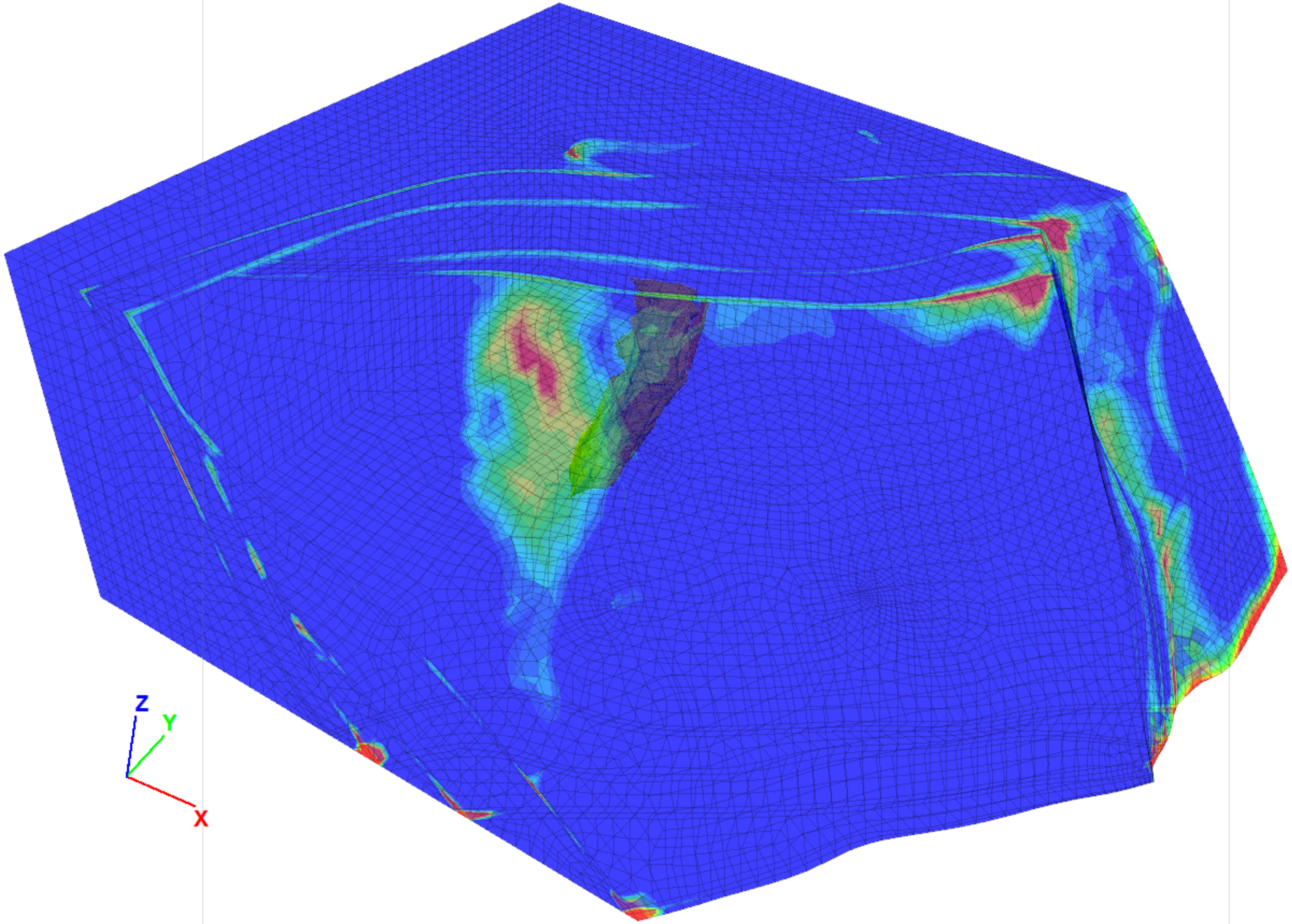


Max Shear Strain Incr



Case Study – EHM

Results: D3 (LATE STAGES)



Volumetric Strain Incr.
Dilation

High

Low

Case Study – EHM

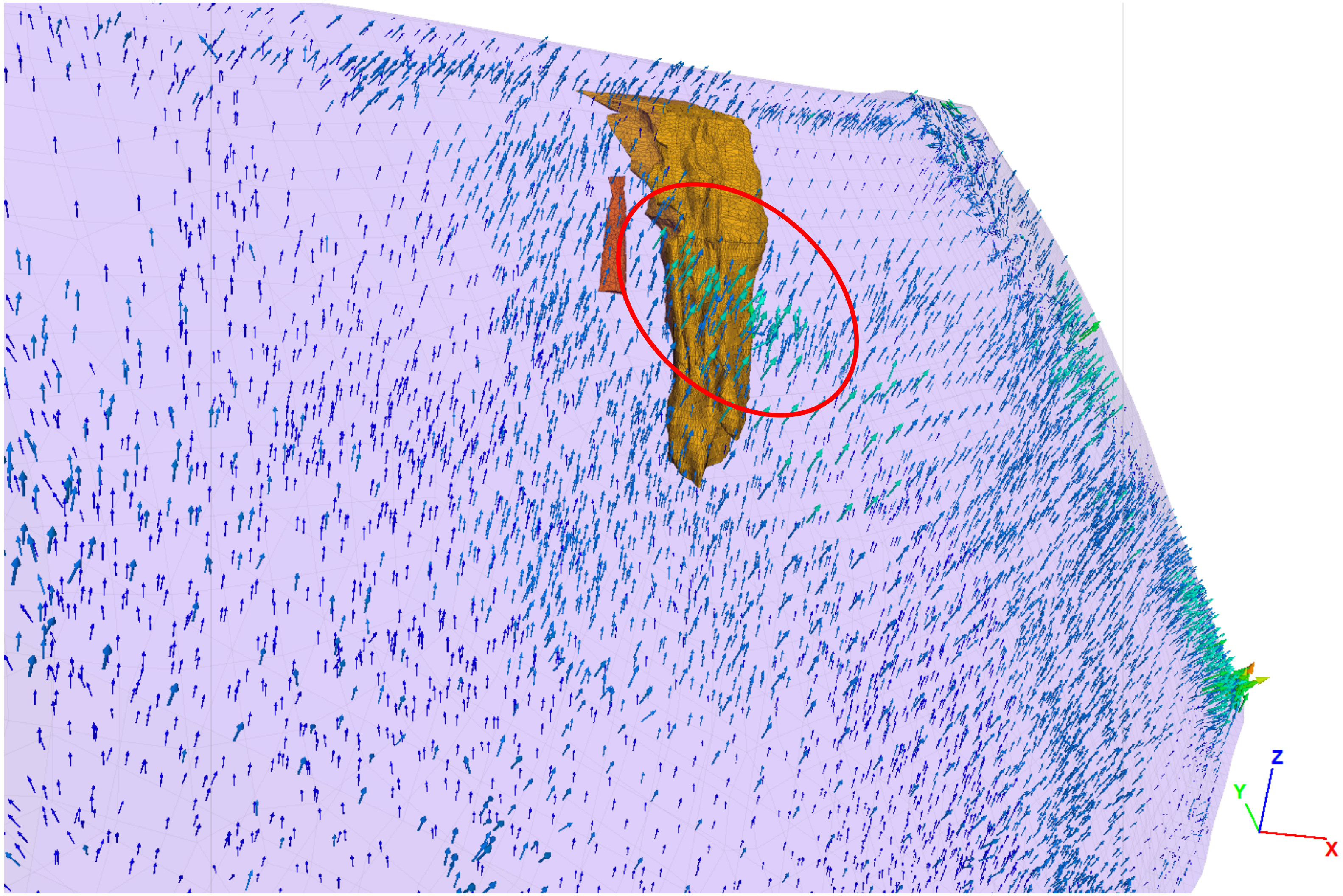
Results: D3 (LATE STAGES)

(Within the volcaniclastics)

Fluid Flow

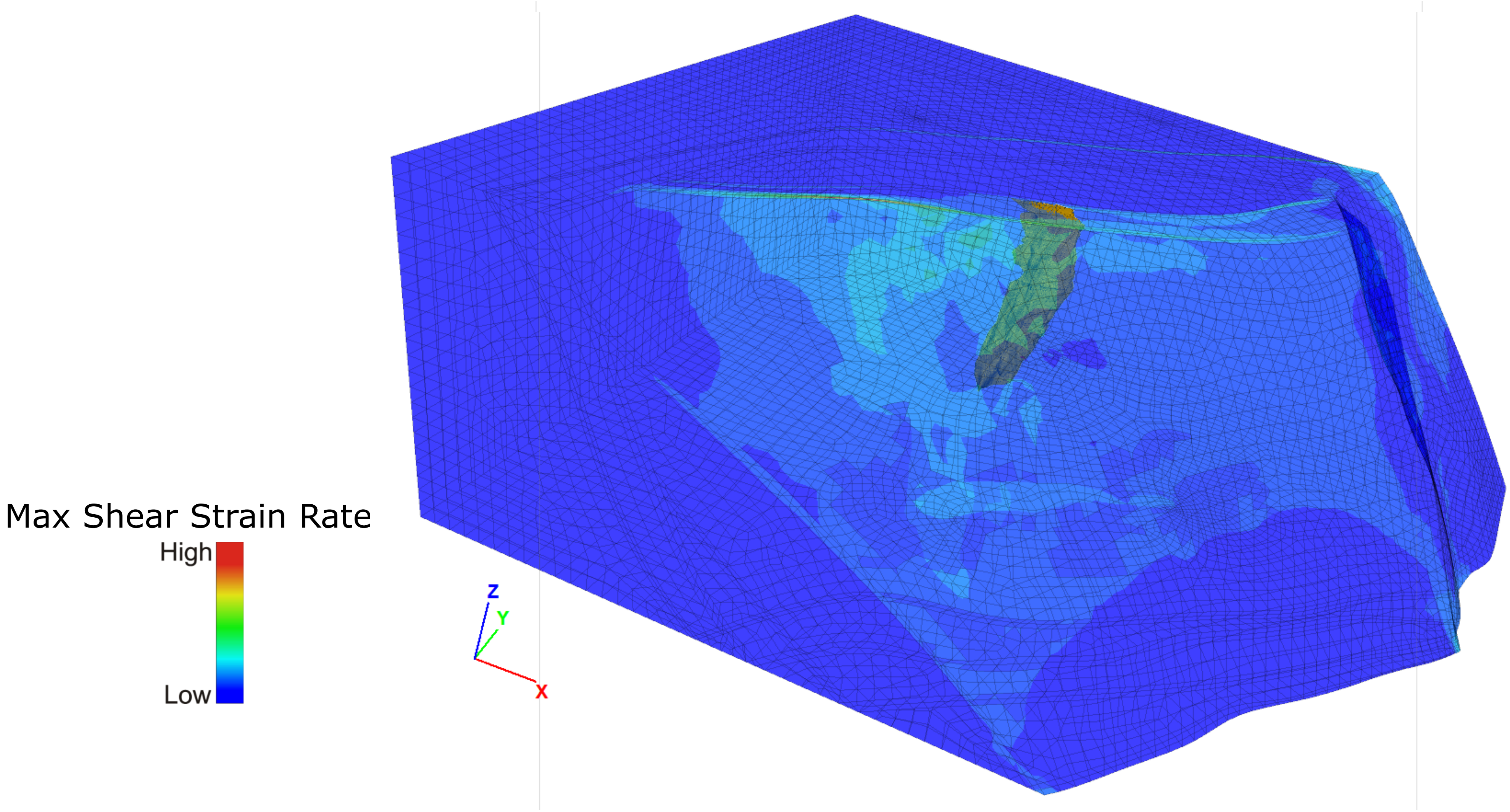
High

Low



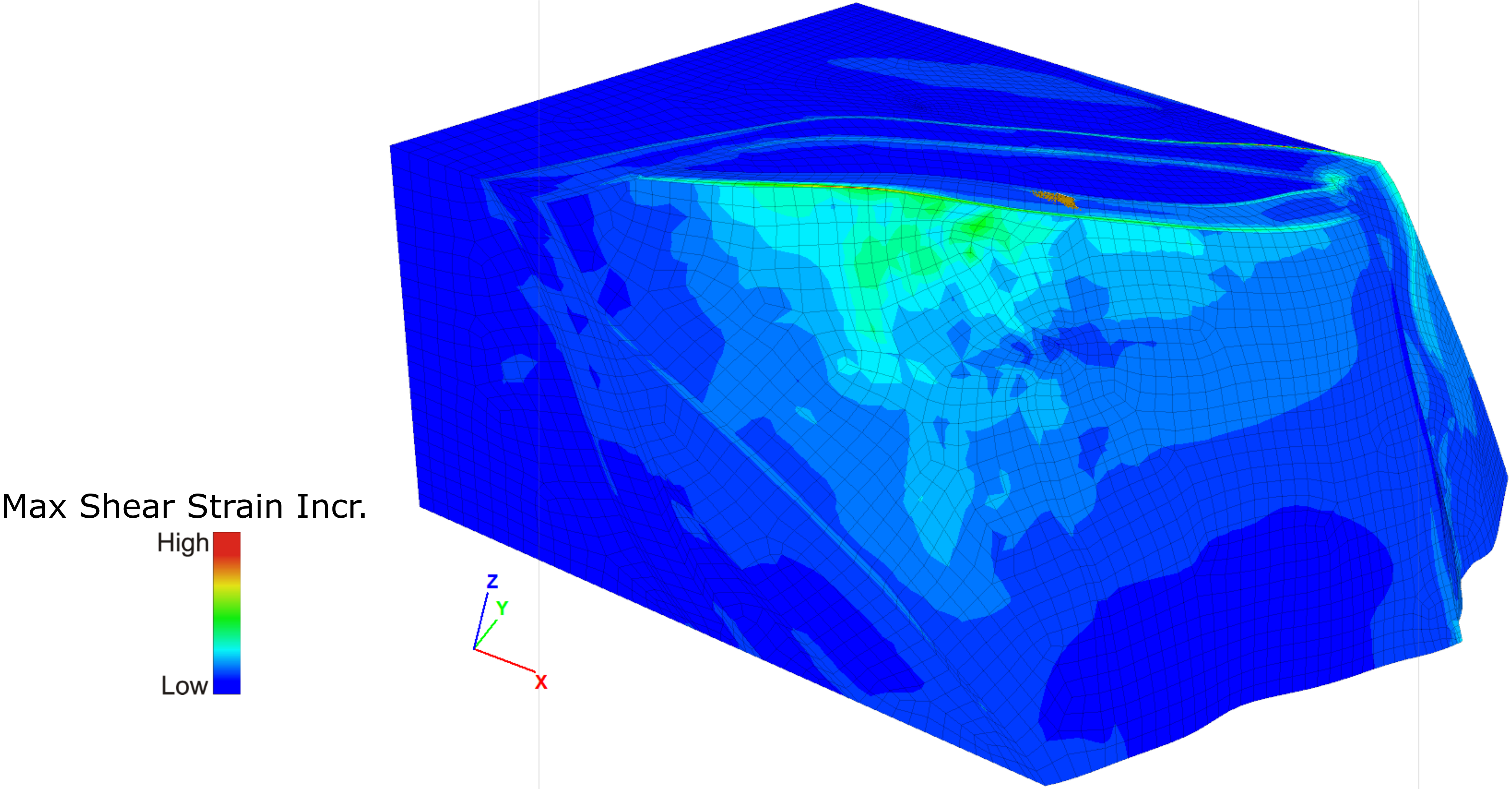
Case Study – EHM

Results: D4 (EARLY STAGES)



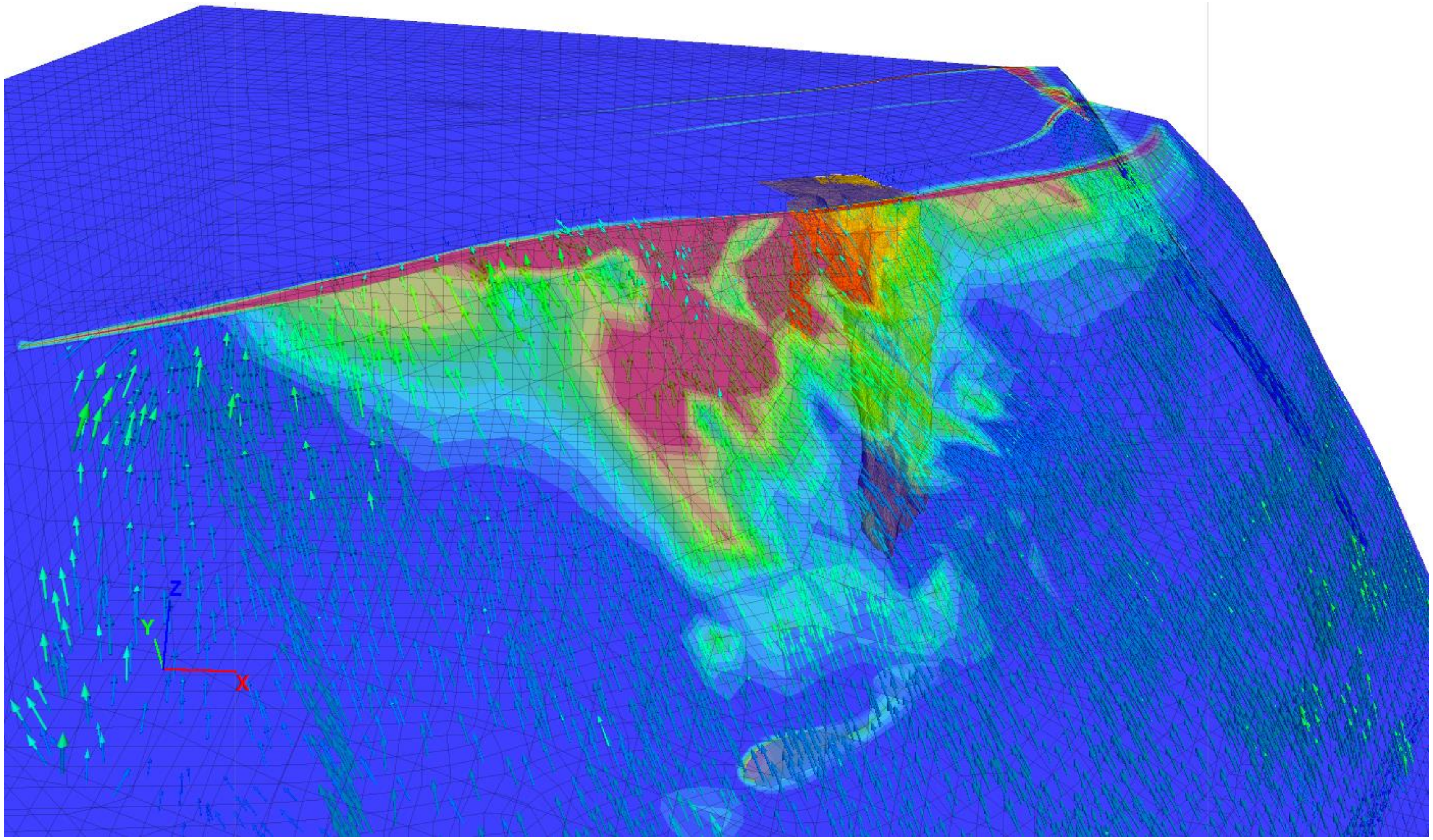
Case Study – EHM

Results: D4 (EARLY STAGES)



Case Study – EHM

Results: D4 (MID STAGES)



Volumetric Strain Incr.
Dilation

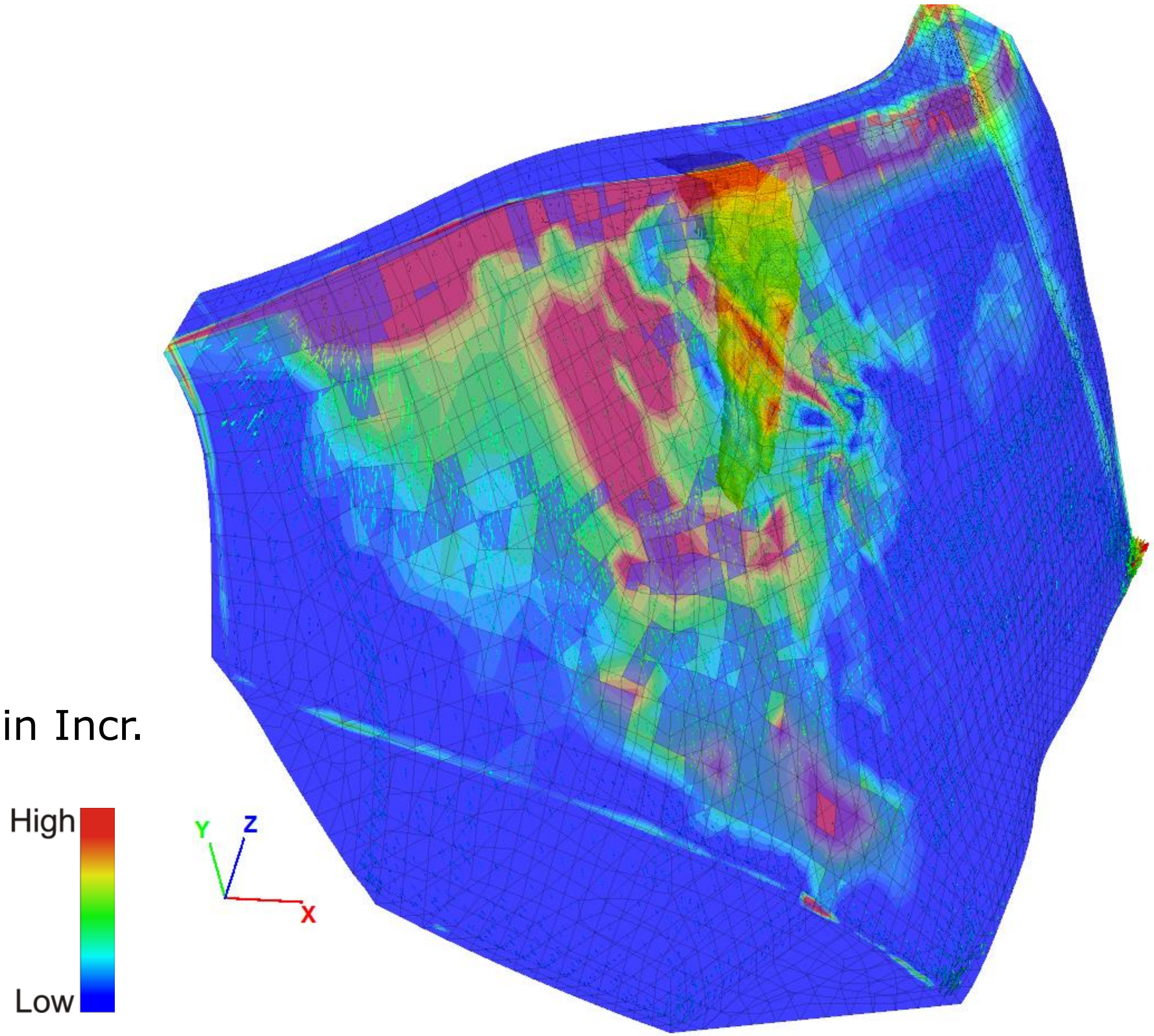
High

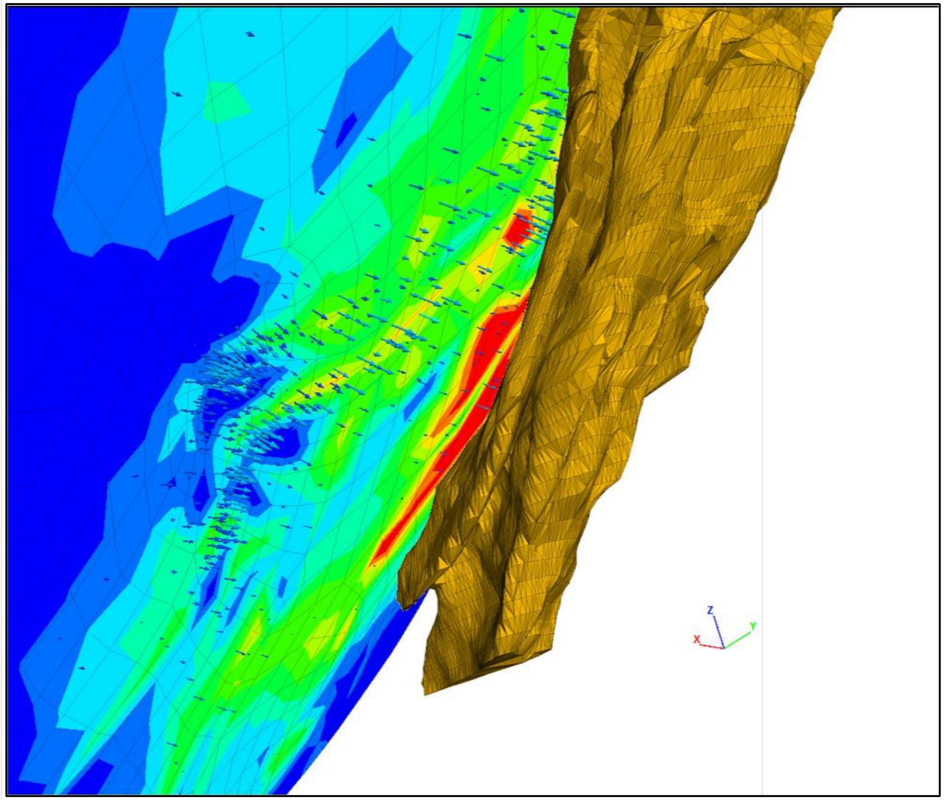
Low

Case Study – EHM

Results: D4 (LATE STAGES)

Volumetric Strain Incr.
Dilation



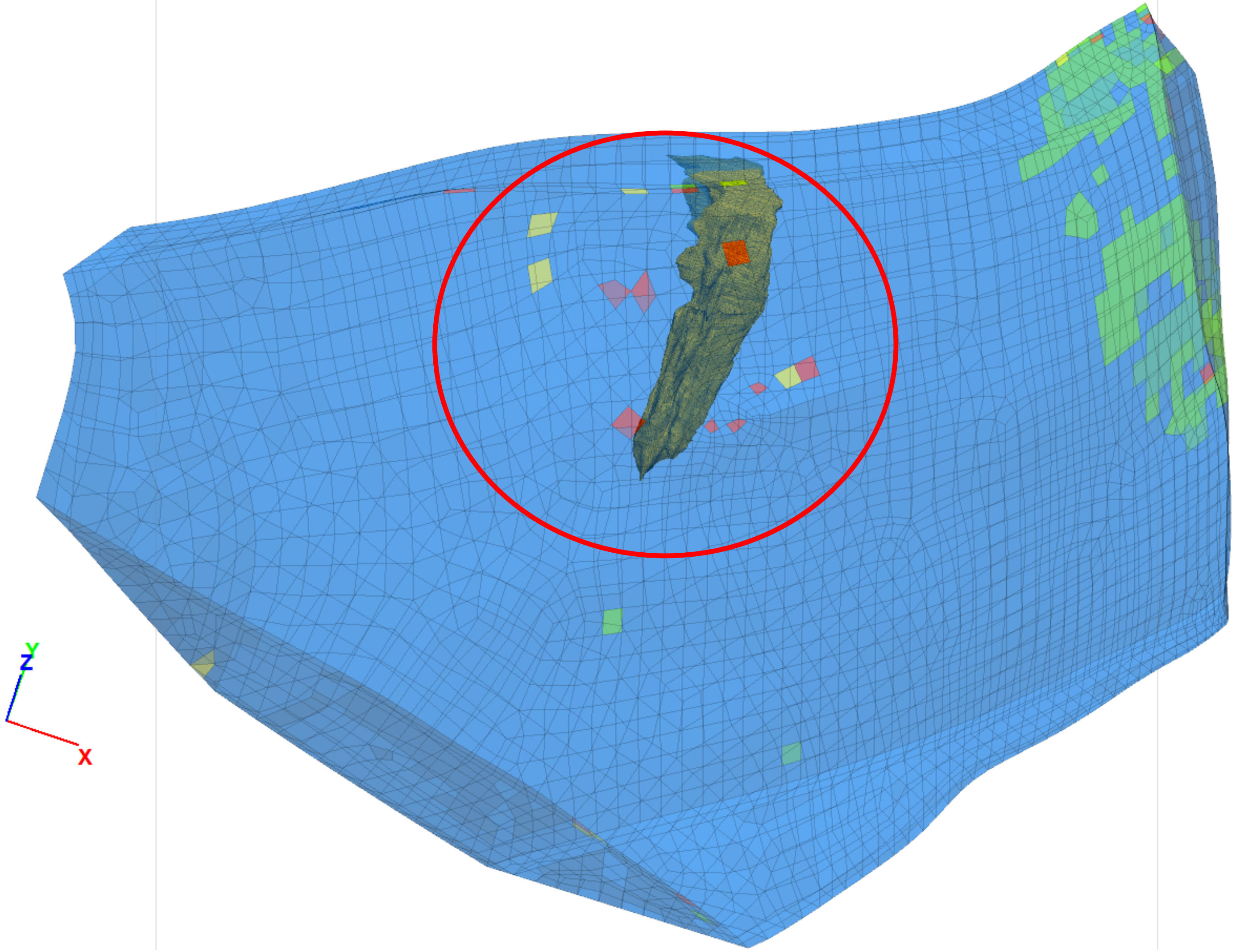


Case Study – EHM

Results: D4 (LATE STAGES)

Failure State

- shear-n shear-p tension-p
- shear-n tension-n shear-p tension-p
- shear-p
- shear-p tension-p
- tension-n shear-p tension-p
- tension-p



Case Study – EHM

Result Outcomes

- EHM Geology team have gained a greater understanding of:

1) Why the breccia system is where it is!
2) The interplay between deformation and fluid flow
3) The association between strain localization and failure
4) Why the earlier D3 deformation event was critical in pre-conditioning the rocks for later fluid infiltration and ultimately mineralisation during D4

- Outcomes of this work have contributed towards precise targeting and development strategies for both the Ernest Henry and Erebus deposits

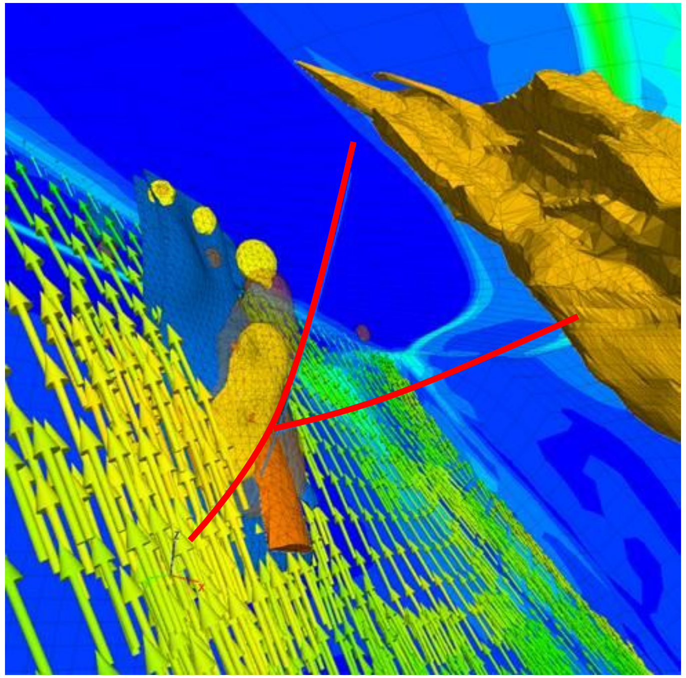
- It has shown that:

1. Geomechanics can provide an alternate and critical dataset for targeted drilling
2. Areas not previously considered by conventional means can be highlighted as predictive
3. Good structural geology and geomechanical modelling go hand-in-hand in identifying the best structural targets based on a rigorous scientific approach

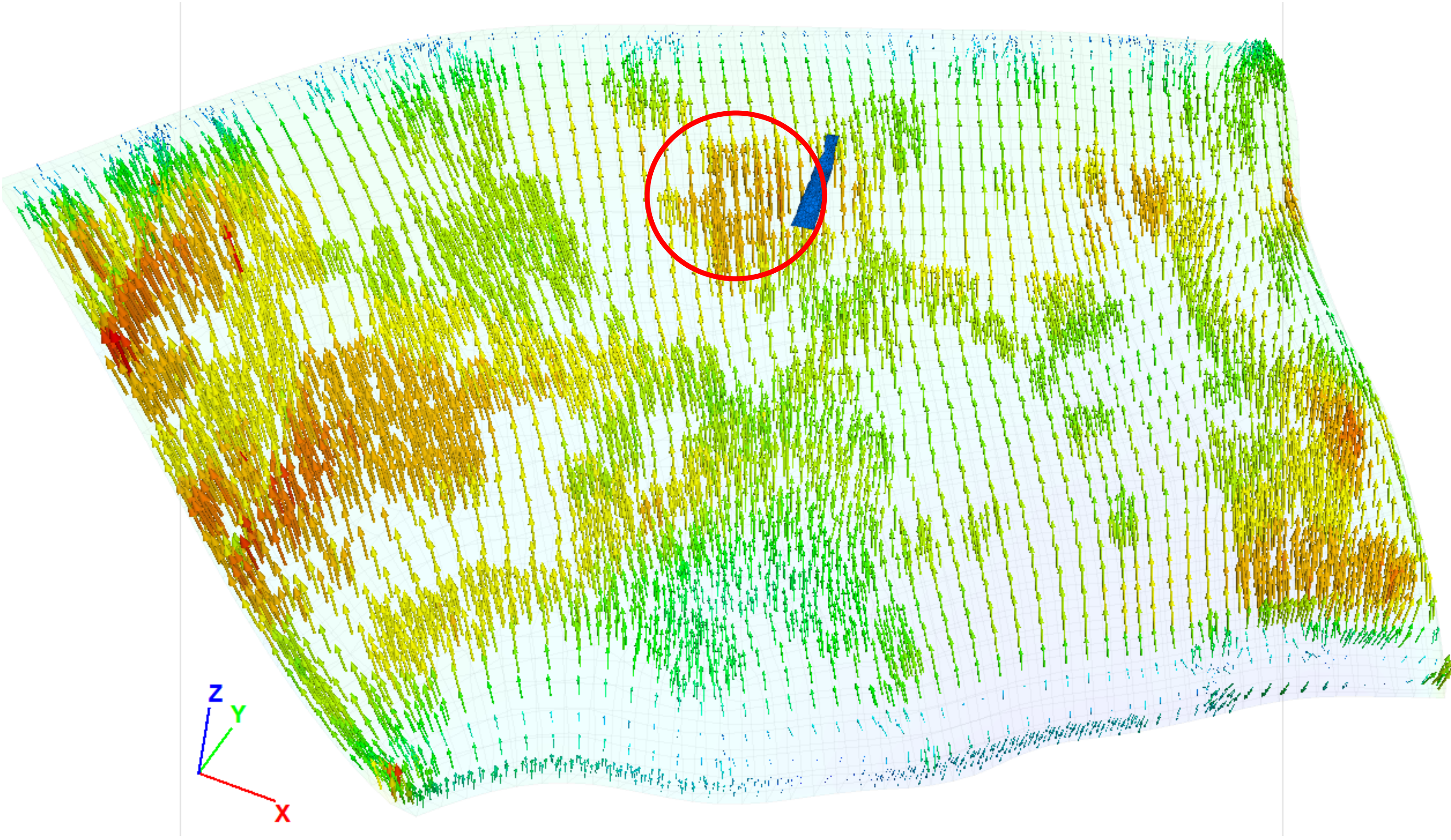
Case Study – EHM

Near Mine Targeting

Current drill targeting specifically addressing the high fluid flow vectors to the Southwest-west of the current known mineralisation. Re-logging of drilling has revealed new extents of the mineralised zones to be in areas that the modelling has predicted favourable flow. Other targets evident to both the north and south of the deposit.



Targeting Erebus extensions



WHY GEOMECHANICS?

- Geomechanics can provide an alternate and critical dataset for targeted drilling
- Areas not previously considered by conventional means can be highlighted as predictive
- Good structural geology and geomechanical modelling go hand-in-hand in identifying the best structural targets based on a rigorous scientific approach
- Identifying key structural locations and combining these with your empirical datasets can provide a unique targeting strategy