Structural Geology and Ore Deposits

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Numerous UZ students and staff

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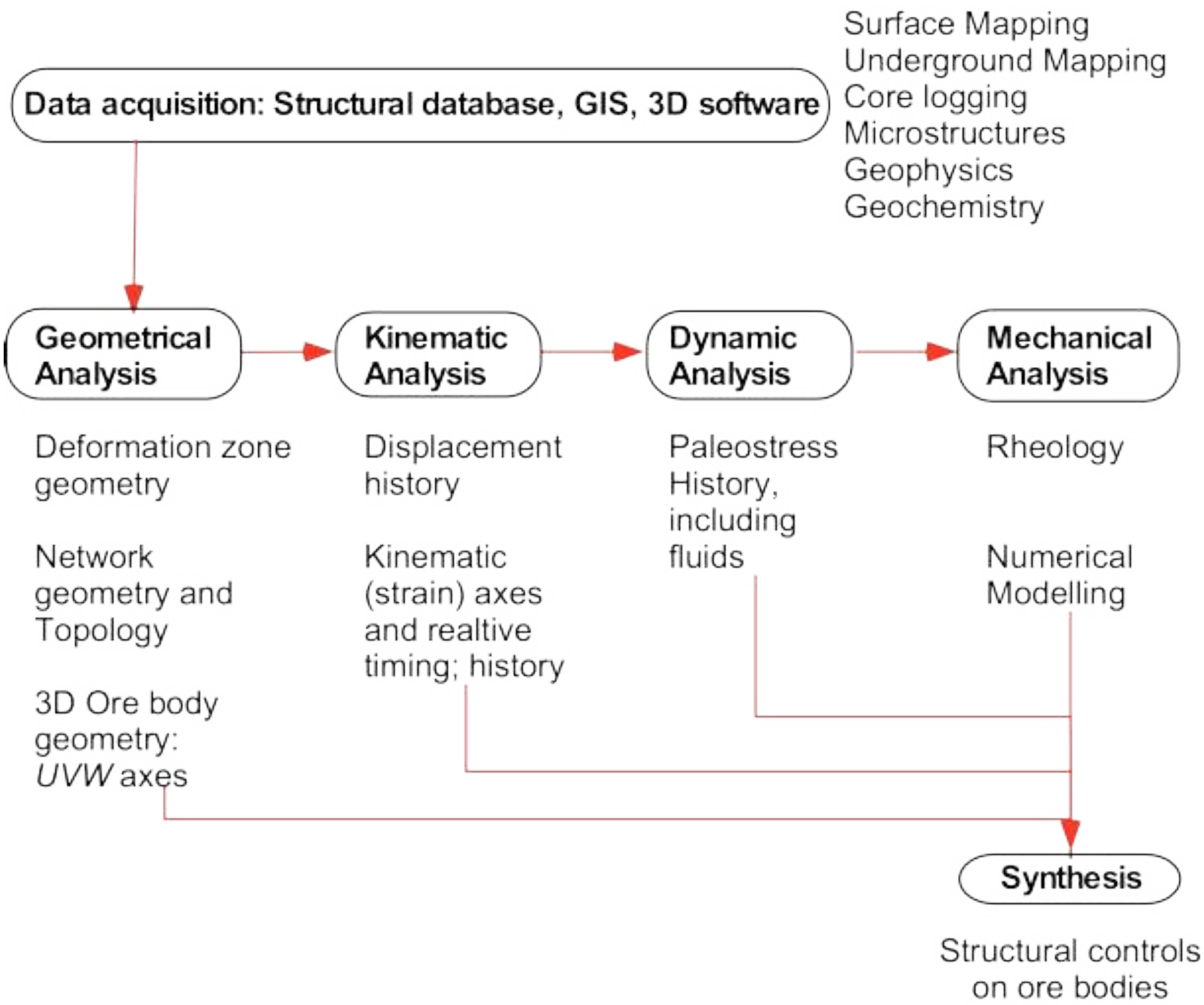
Outline

Topic		Techniques
Introduction	Why structures are important for hydrothermal mineralization Faults, fault zones, shear zones	
Faults and Fault Networks	The fault zone	Orientation analysis
	Fault networks	Younging table
	Faults and ore deposits	Connectivity and Intensity
Shear Zones	Pure, general and simple shear: geometry and kinematics of shear zones	Autocorrelation Shear sense determination
	Shear zones and ore deposits	Kinematic analysis
		GIS based prospectivity

Applying structural geology to ore deposits

Flourite and chalcopyrite
Monakoff IOCG deposit
Queensland, Australia



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Geometry

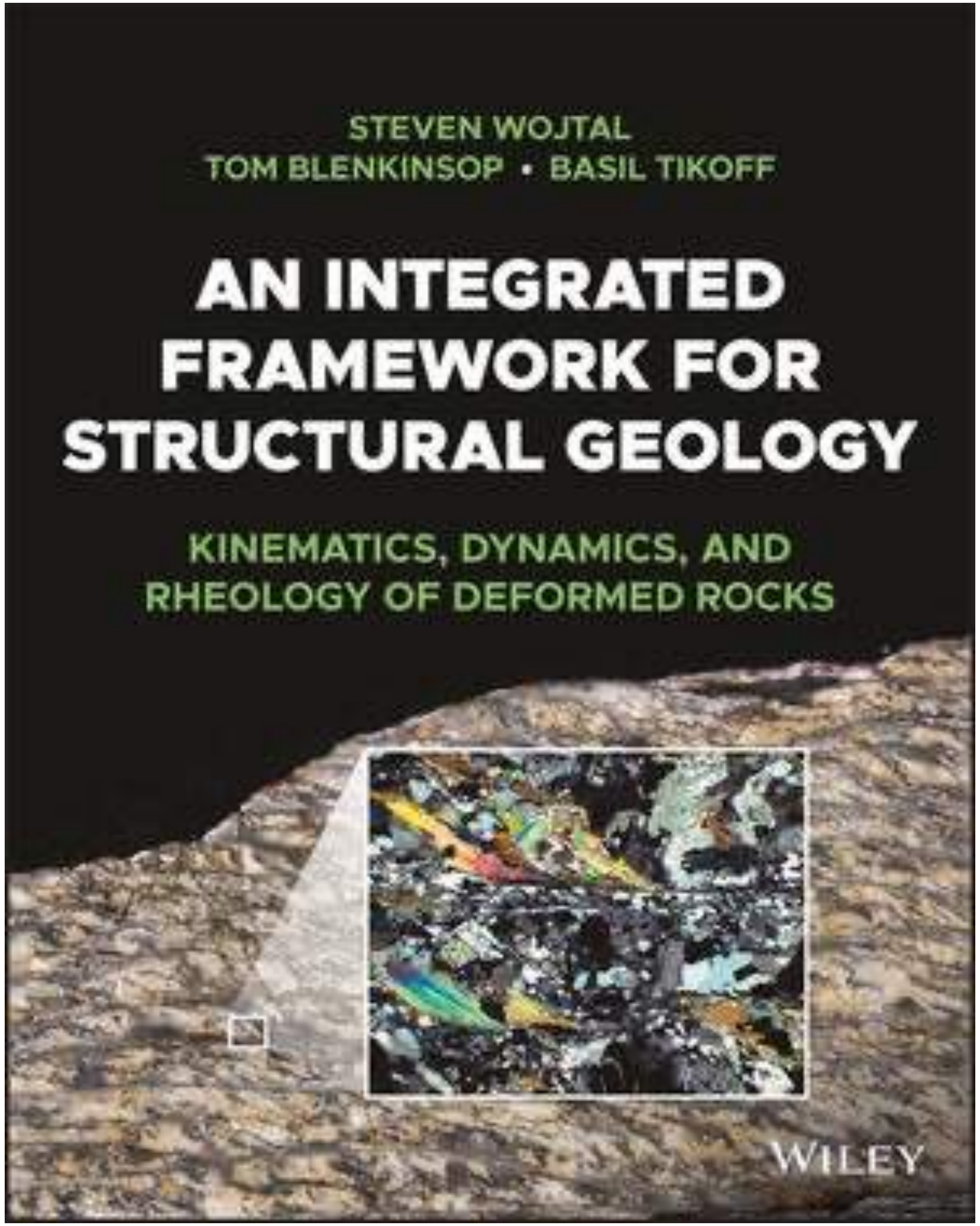
↓

Kinematics

↓

Mechanics

Blenkinsop, T., Oliver, N., Dirks, P., Nugus, M., Tripp, G., & Sanislav, I. (2020). Structural geology applied to the evaluation of hydrothermal gold deposits. In *Reviews in Economic Geology, v.21* (pp. 1–23). https://doi.org/10.5382/rev.21.01



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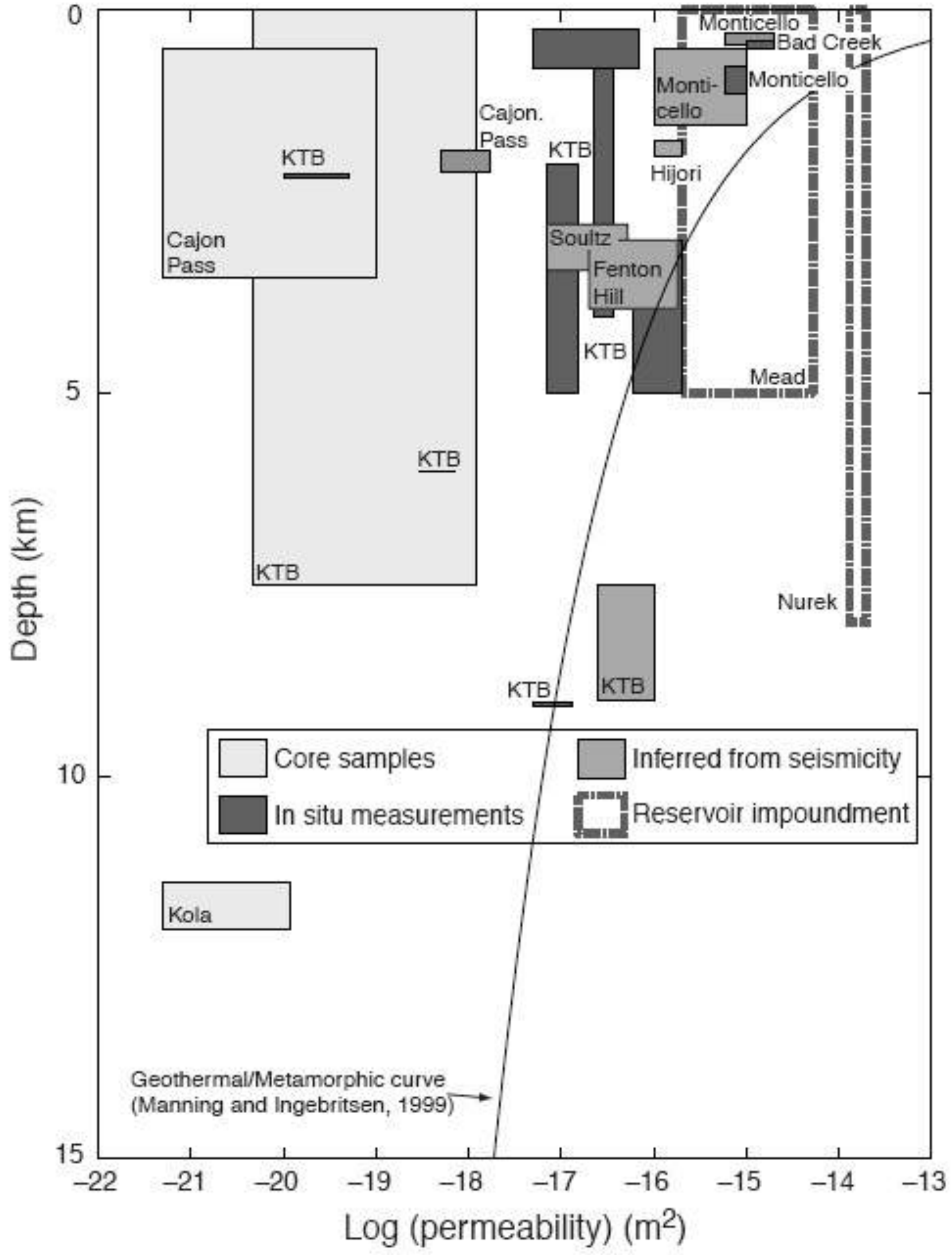

Paradox:
Crustal permeability is too low to form ore deposits on feasible time scales

Townend and Zoback 2000

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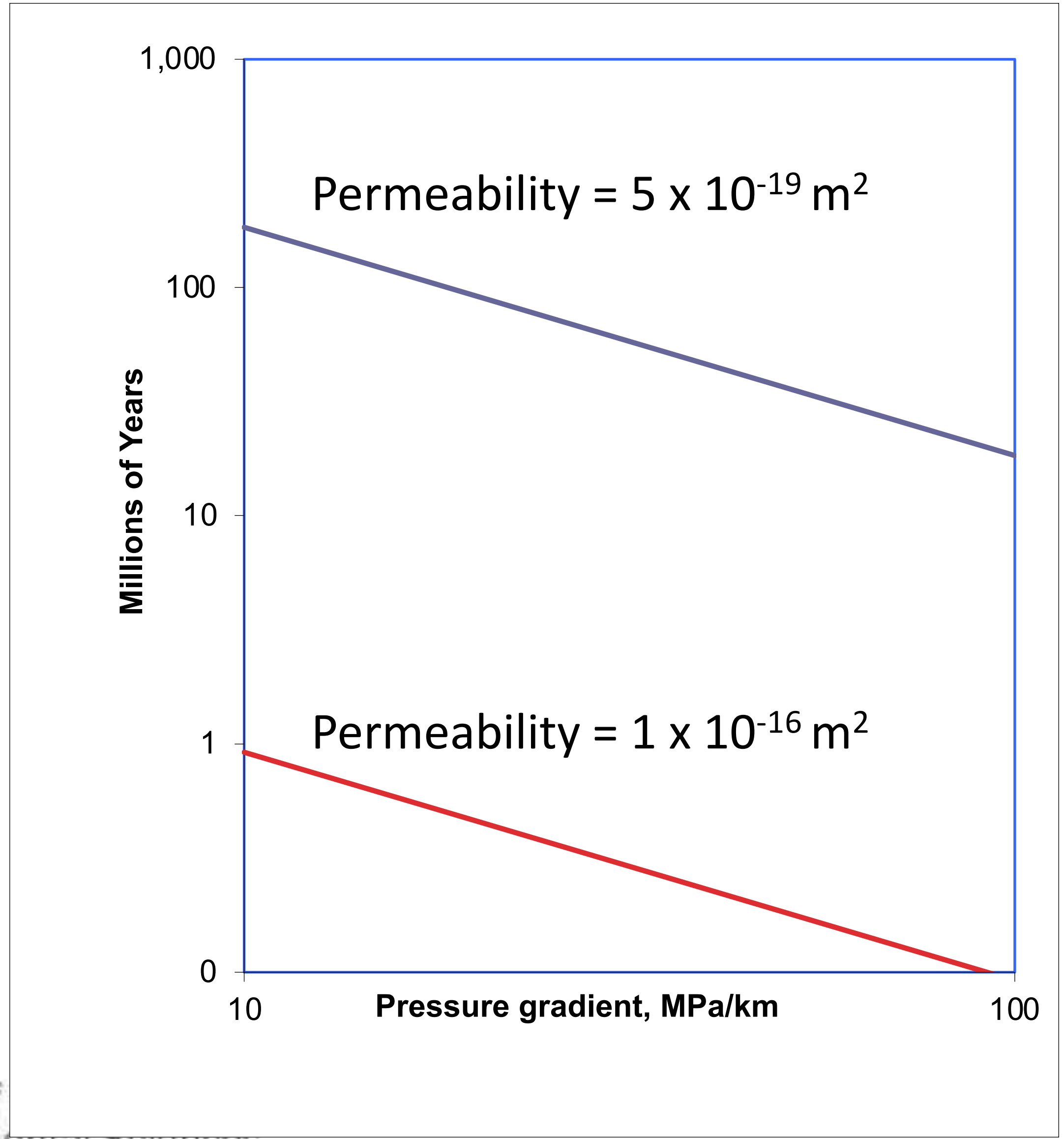
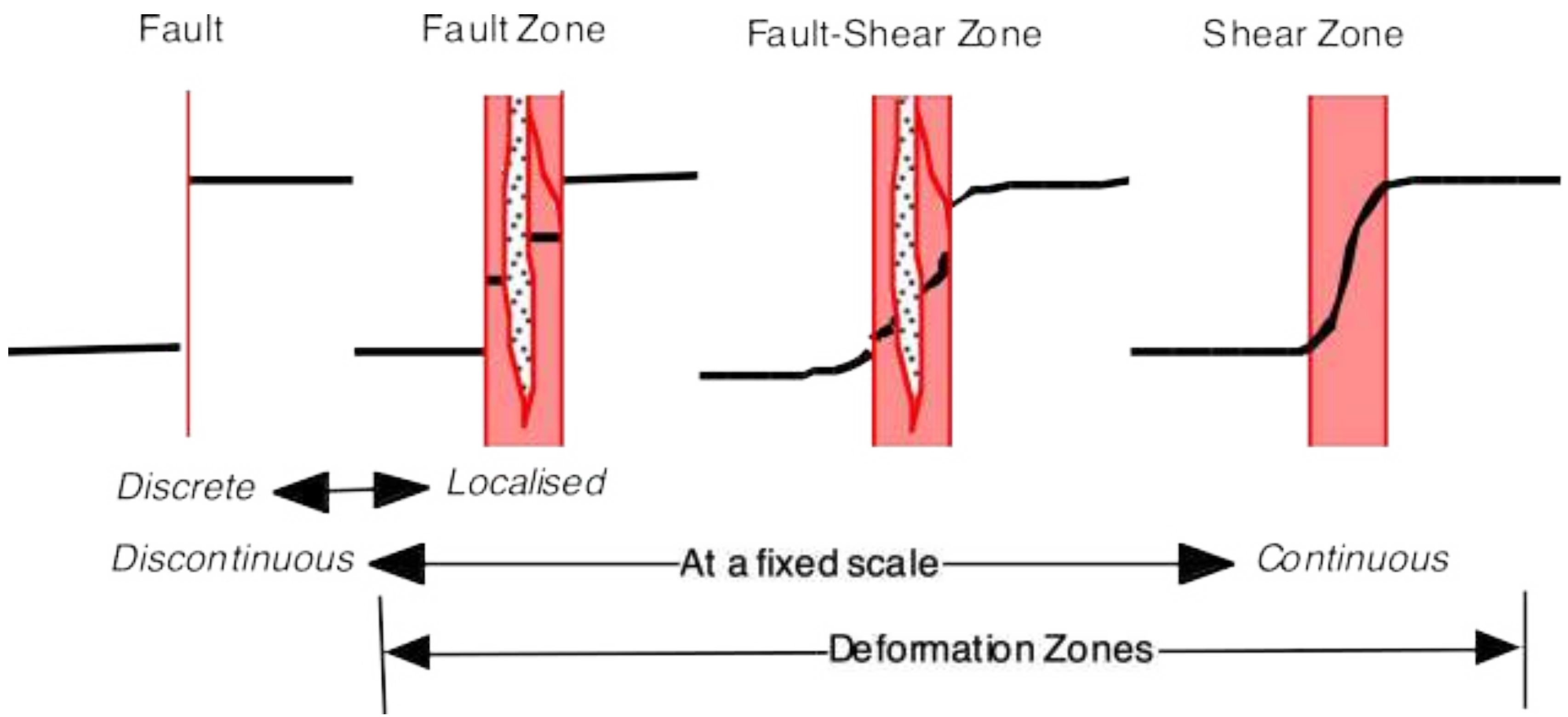
Time to form a 10 Moz gold deposit




Deformation is necessary

Faults, Fault Zones, and Shear Zones



Zones of permeability

Sunrise Dam, WA

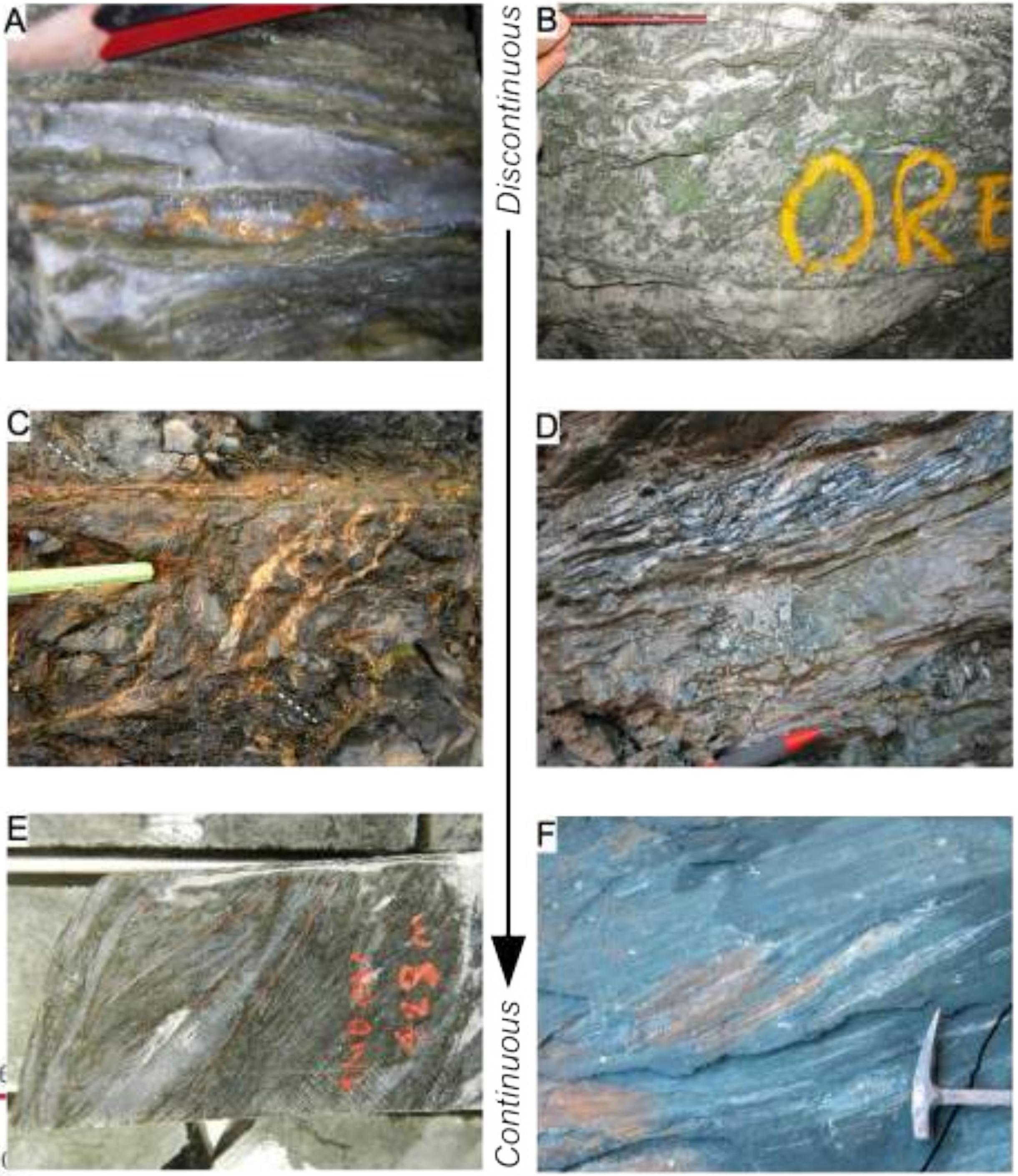
Sunrise Dam, WA

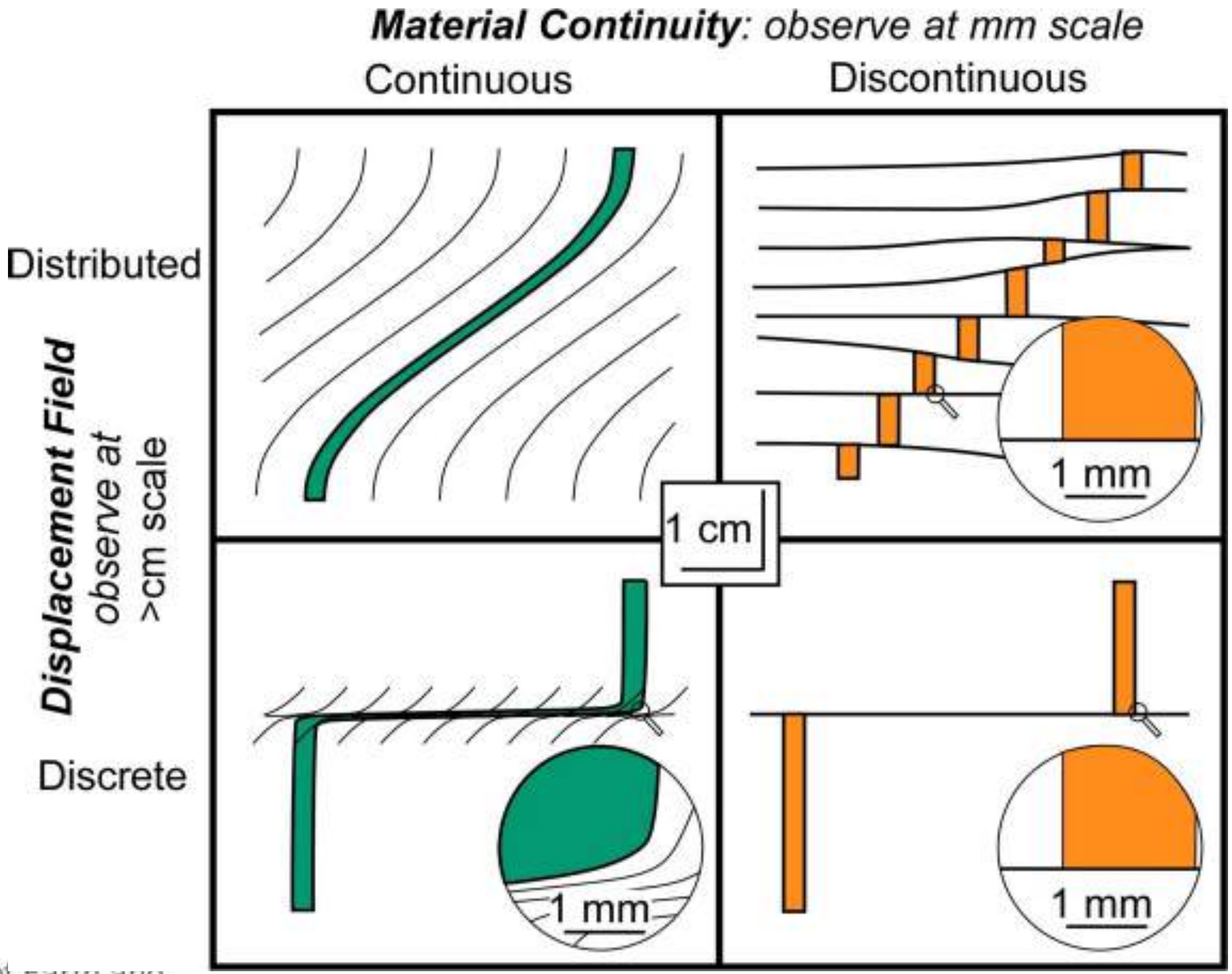
Geita Gold Mine, Tanzania

Sunrise Dam, WA

Tropicana Gold Mine, Wa

Cornishman, WA




Material Continuity: observe at mm scale
Continuous
Discontinuous
Distributed
Discrete
Displacement Field
observe at
>cm scale
1 cm
1 mm
1 mm
1 mm

Cap de Creuz, Spain

Photo: Jordi Carerras

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Cap de Creuz, Spain

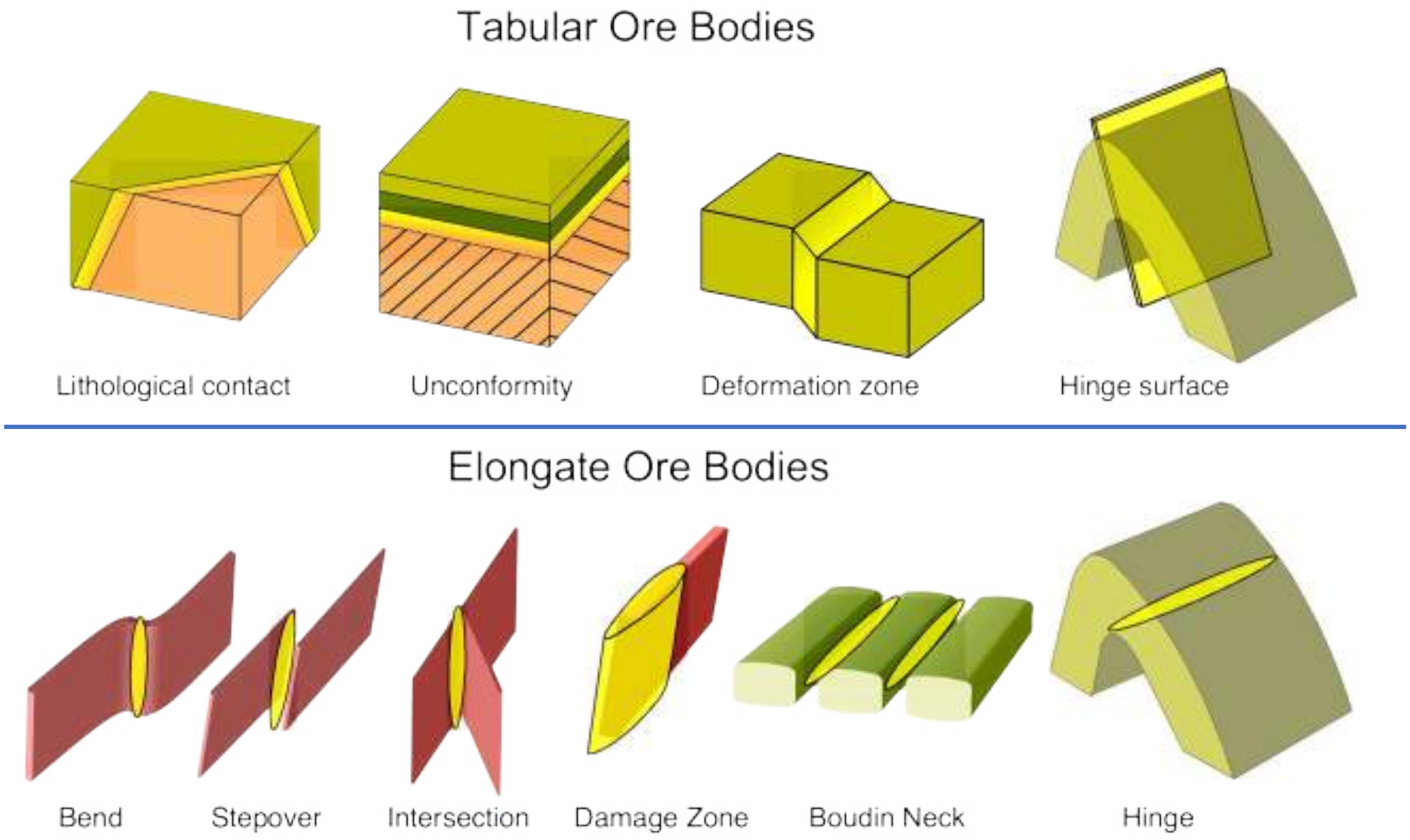
Photo: Jordi Carerras

Cap de Creuz, Spain

Photo: Jordi Carerras

Shear zone in massive sulphides,
Currawong VHMS deposit, Victoria

Geometry



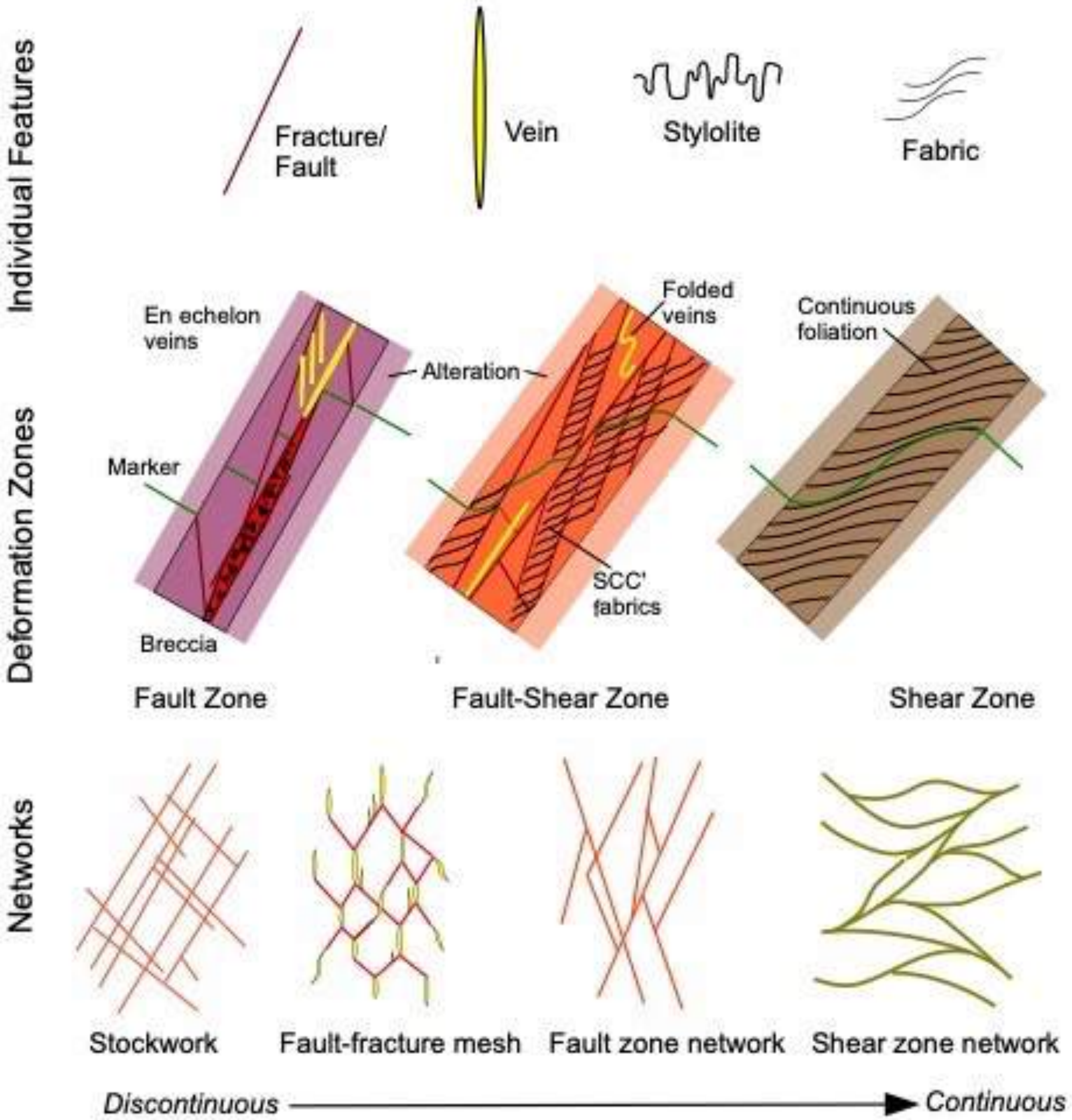
Tabular Ore Bodies
Lithological contact
Unconformity
Deformation zone
Hinge surface
Elongate Ore Bodies
Bend
Stepover
Intersection
Damage Zone
Boudin Neck
Hinge

Geometry

Individual features

Deformation Zones

Networks



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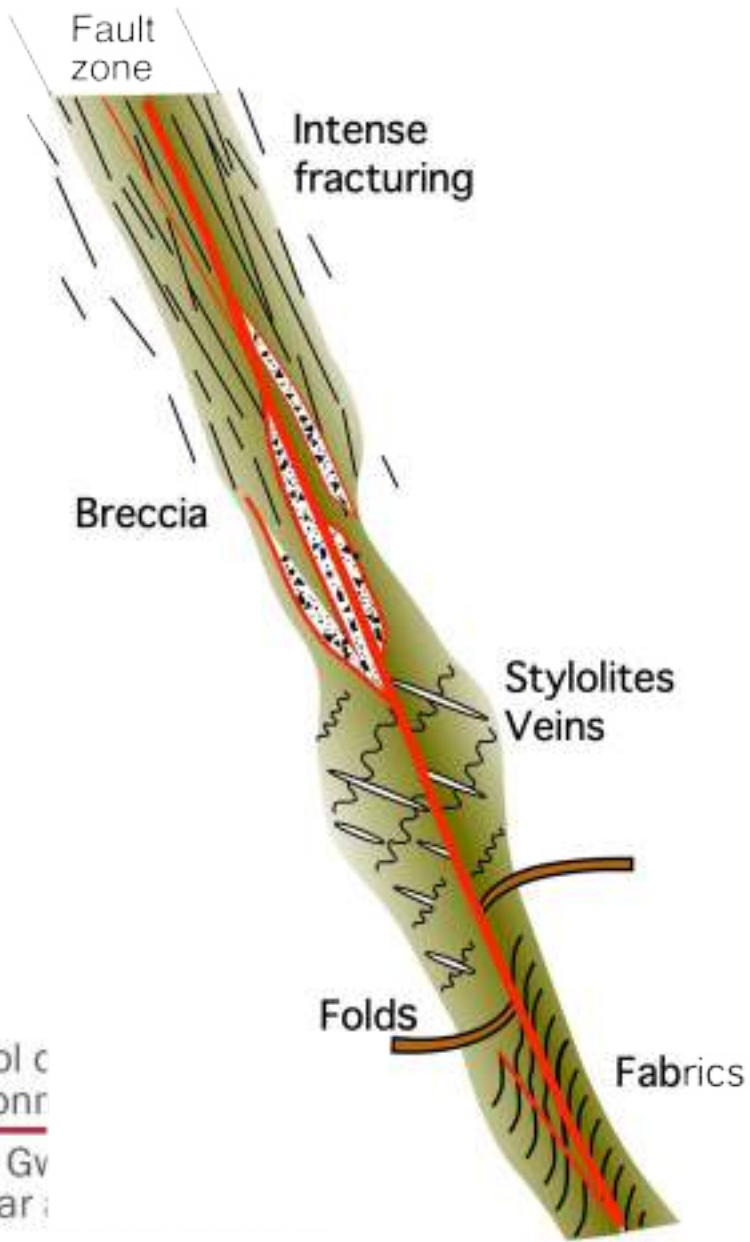
The Fault Zone
= Damage Zone + Core



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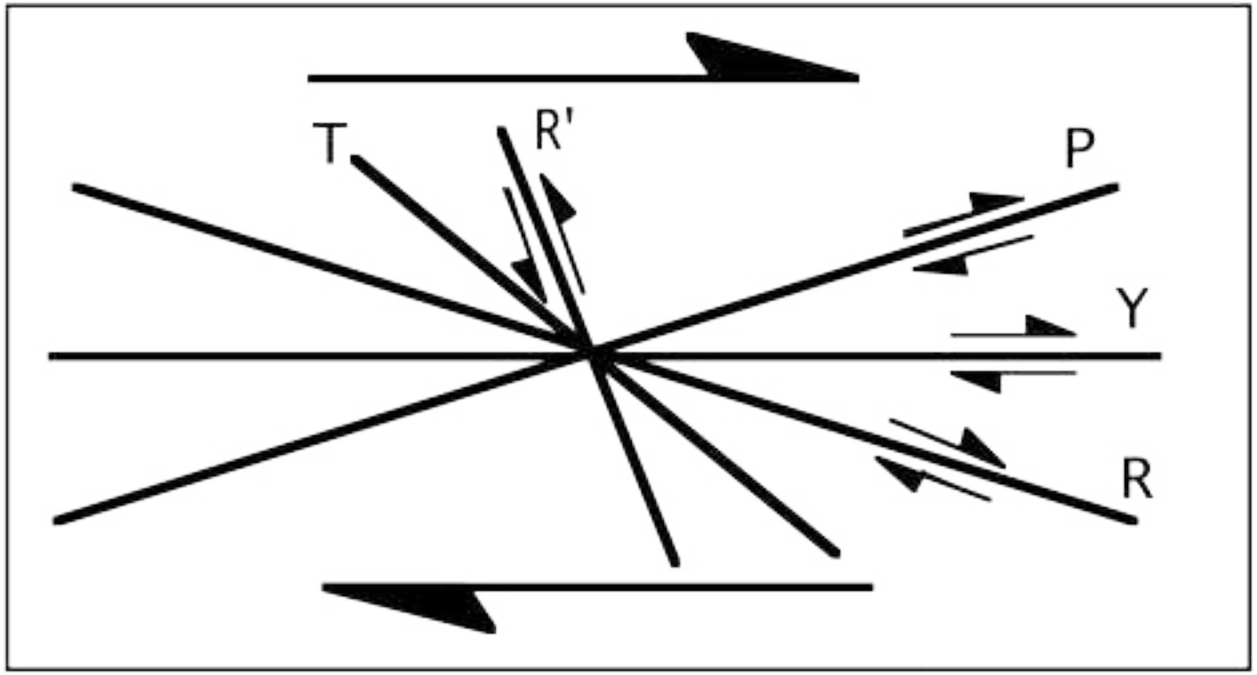
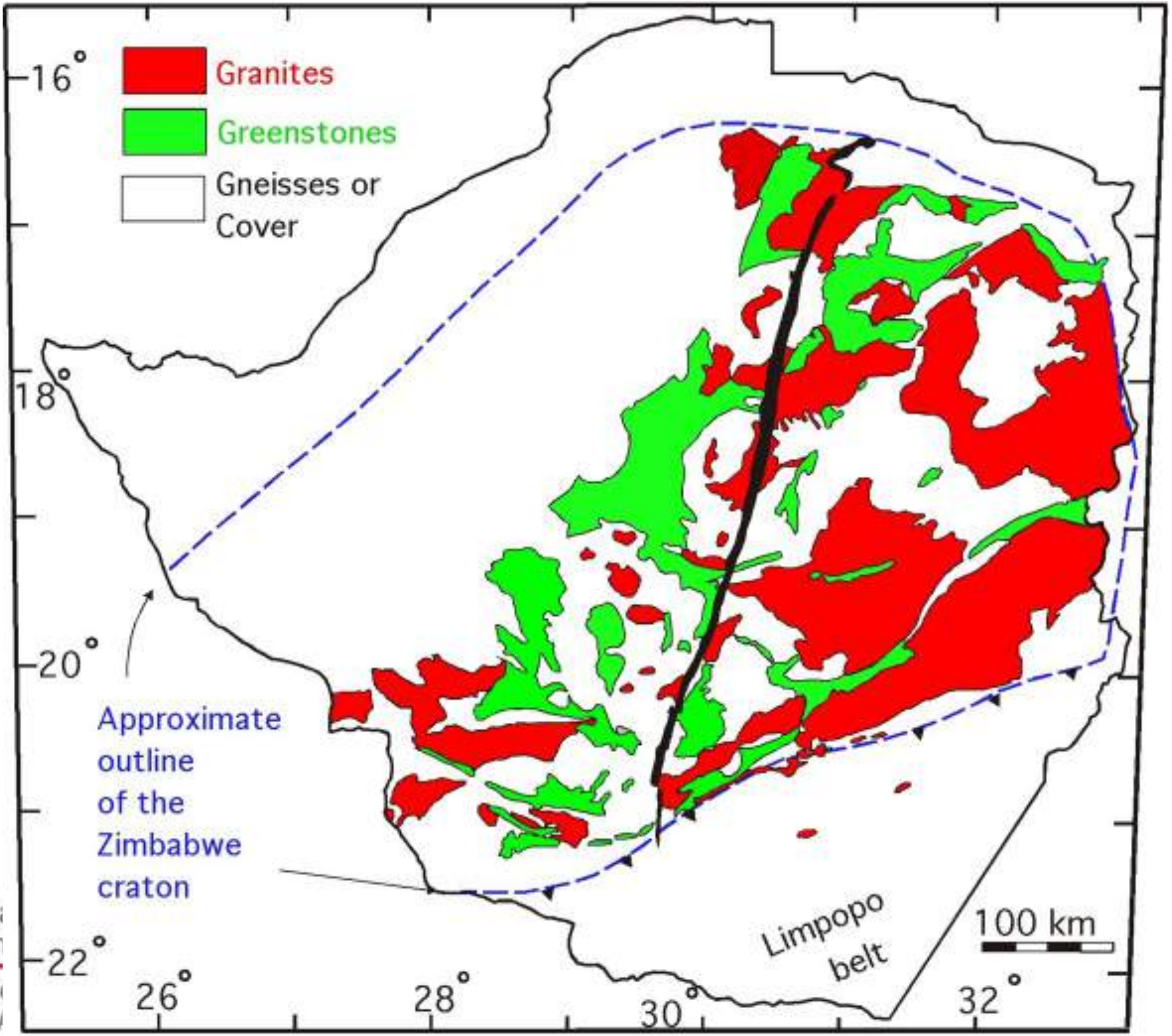
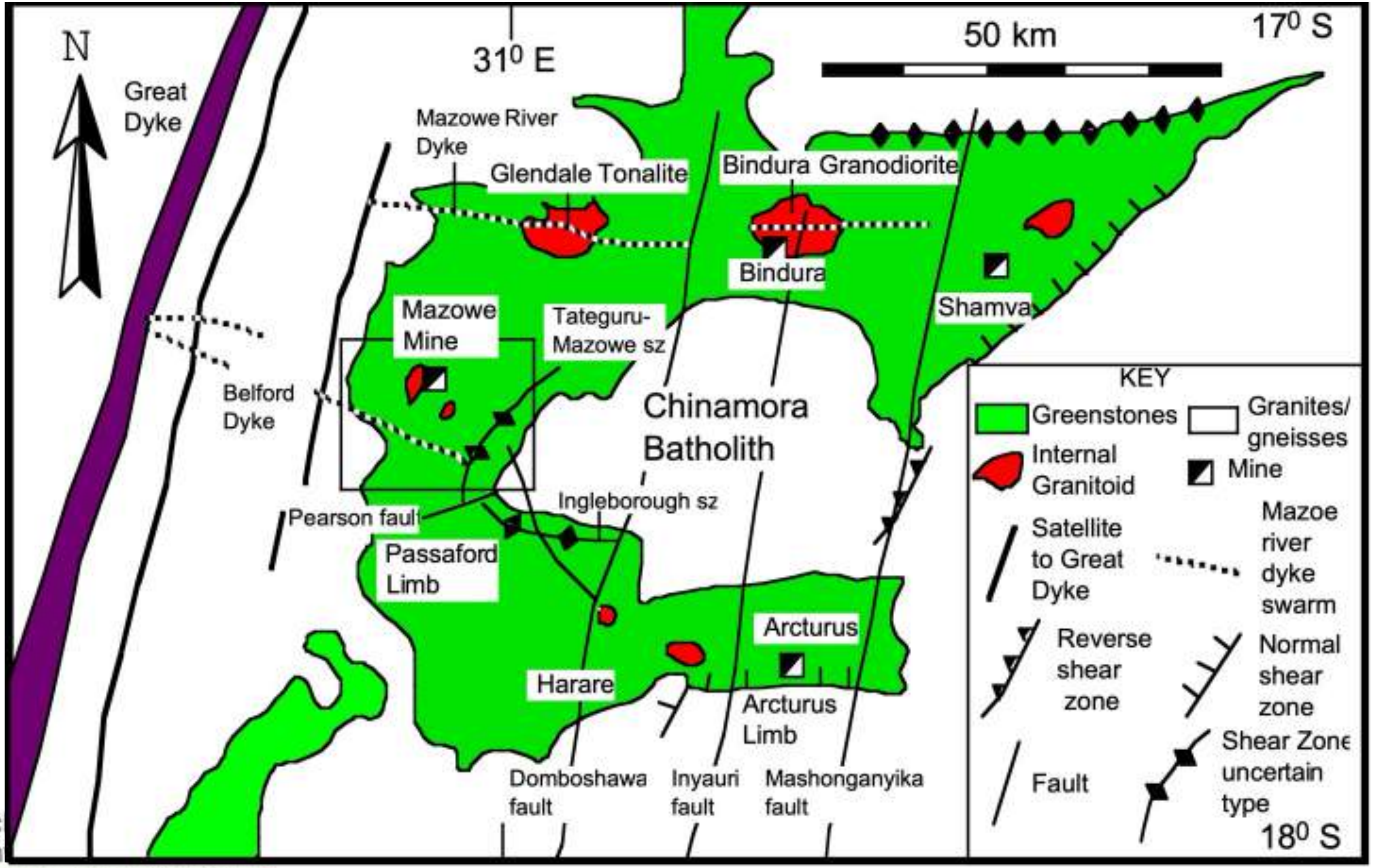
Discontinuities in Fault Zones

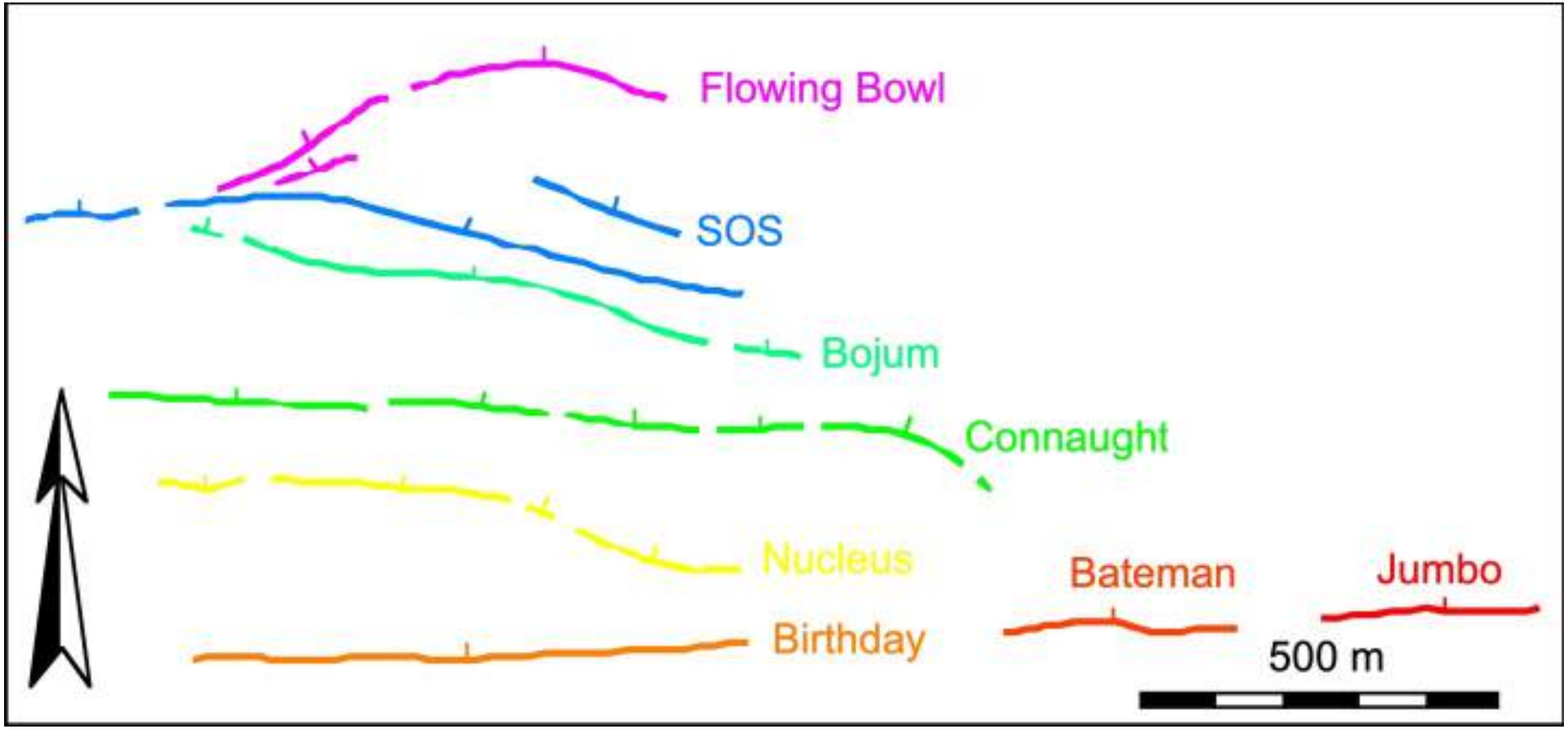


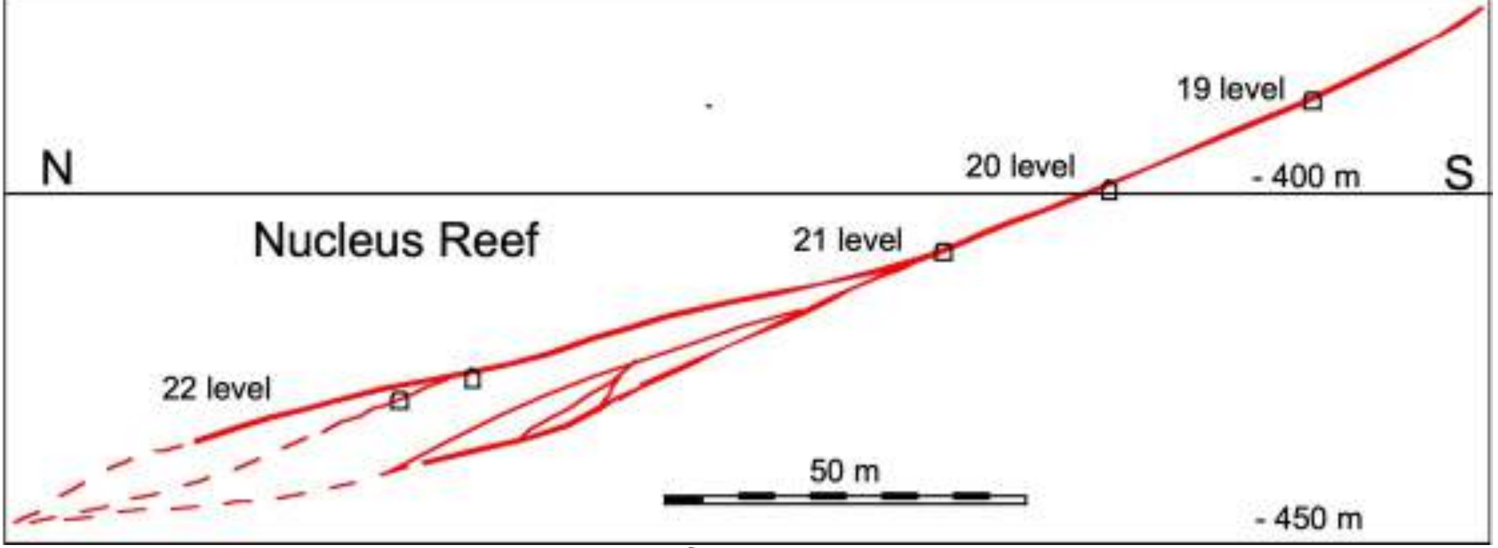
	Initial orientation	Sense
P shears/P foliation	low	synthetic
Riedel shears/Synthetic shears	low	synthetic
Conjugate Riedel shears/Antithetic	high	antithetic
T or extension fractures	45°	antithetic
Y shears/principle deformation zones	0°	synthetic

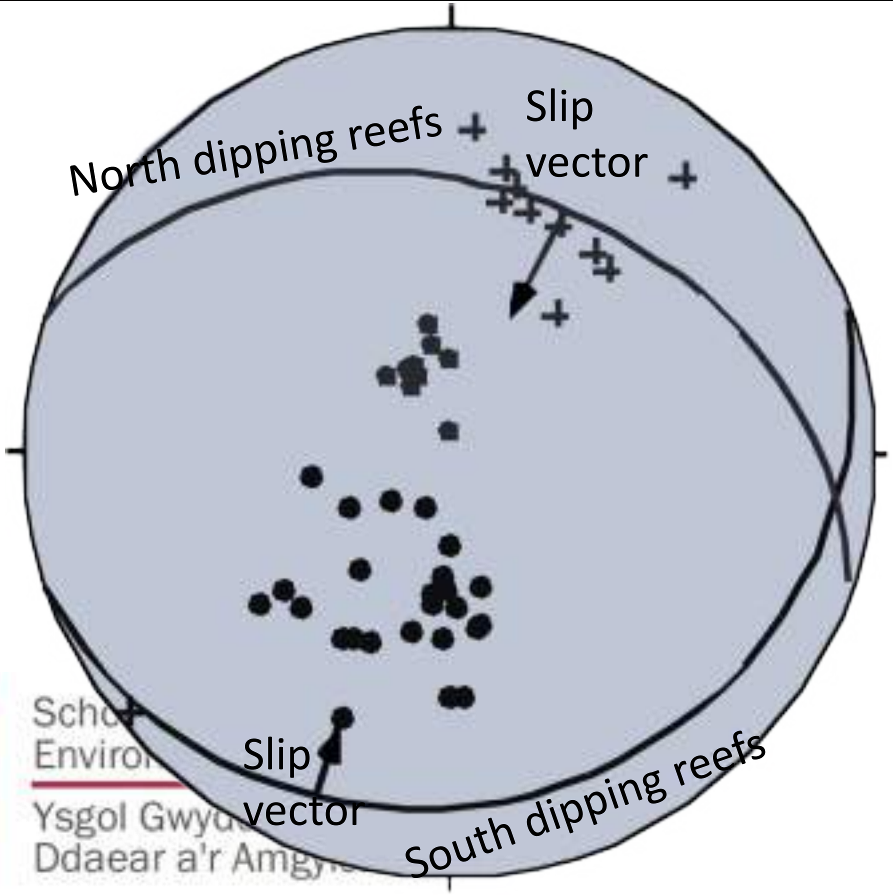


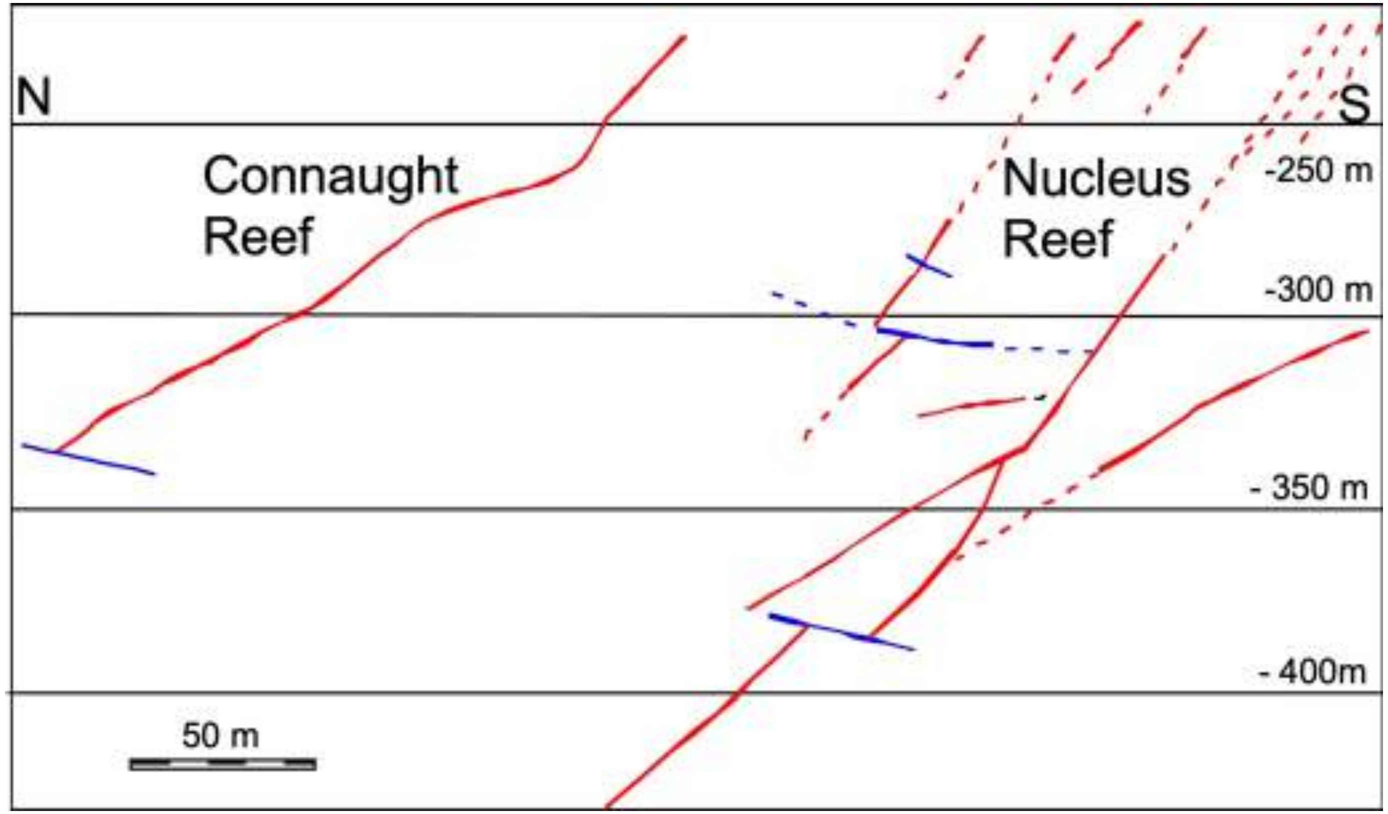
Mazowe Mine Example of fault-controlled mineralization


N
Great Dyke
31⁰ E
50 km
17⁰ S
Mazowe River Dyke
Glendale Tonalite
Bindura Granodiorite
Bindura
Shamva
Mazowe Mine
Tateguru-Mazowe sz
Belford Dyke
Chinamora Batholith
Ingleborough sz
Pearson fault
Passaford Limb
Arcturus
Harare
Arcturus Limb
Domboshawa fault
Inyauri fault
Mashonganyika fault
KEY
Greenstones
Granites/ gneisses
Internal Granitoid
Mine
Satellite to Great Dyke
Mazoe river dyke swarm
Reverse shear zone
Normal shear zone
Fault
Shear Zone uncertain type
18⁰ S

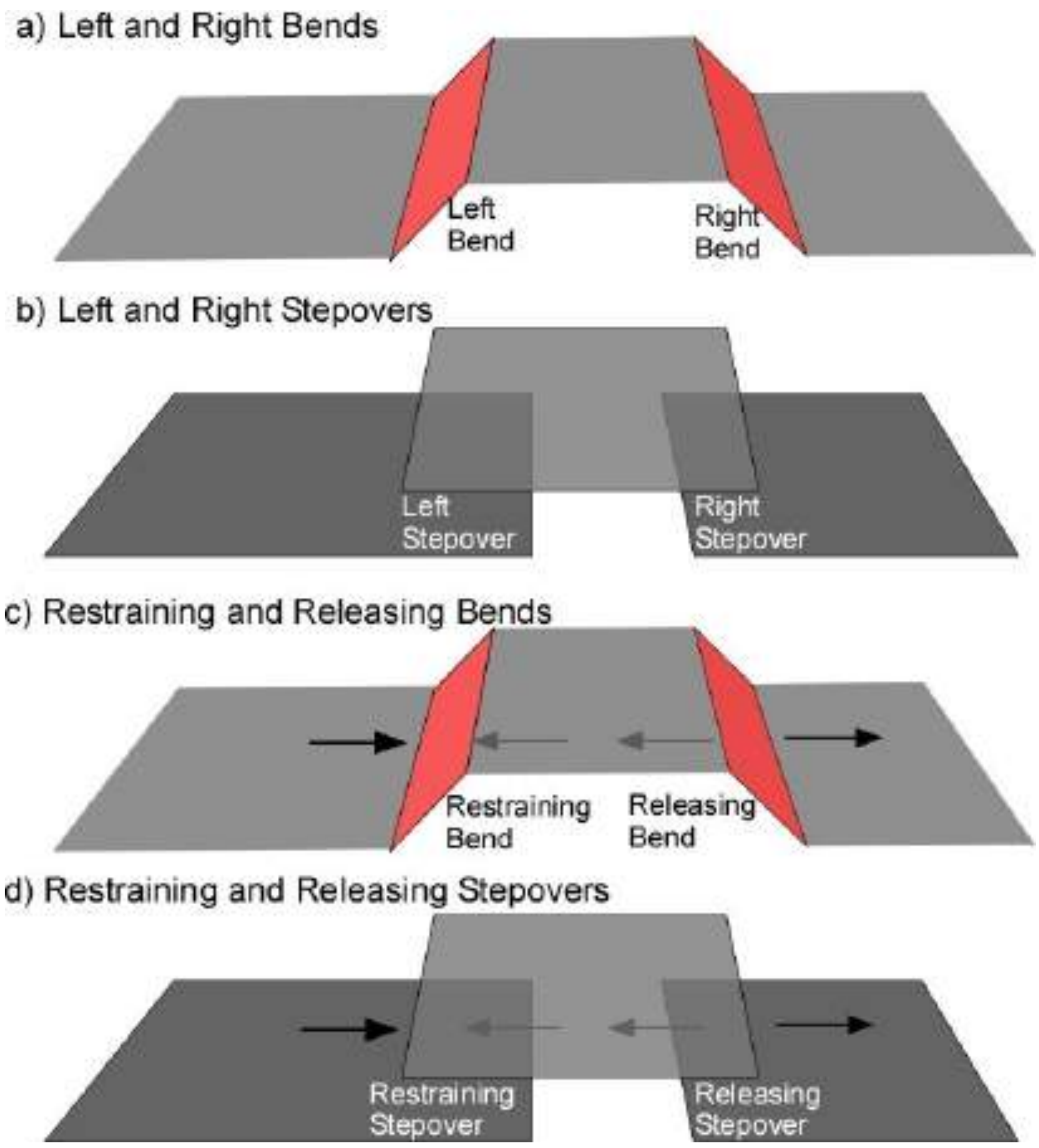

Flowing Bowl
SOS
Bojum
Connaught
Nucleus
Bateman
Jumbo
Birthday
500 m


N
S
19 level
20 level
21 level
22 level
- 400 m
Nucleus Reef
50 m
- 450 m

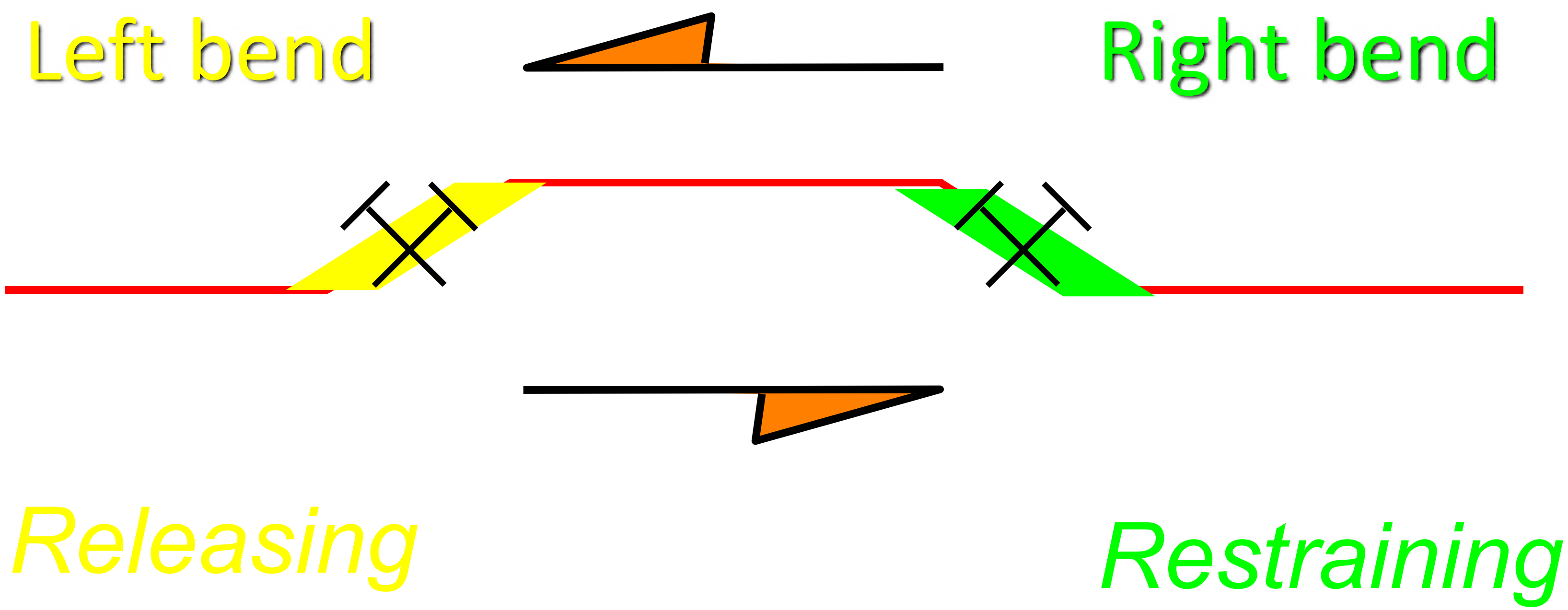

North dipping reefs
Slip
vector
Slip
vector
South dipping reefs


N
S
Connaught
Reef
Nucleus
Reef
-250 m
-300 m
- 350 m
- 400m
50 m

Bends and Stepovers



Fault Bends and Mineralization



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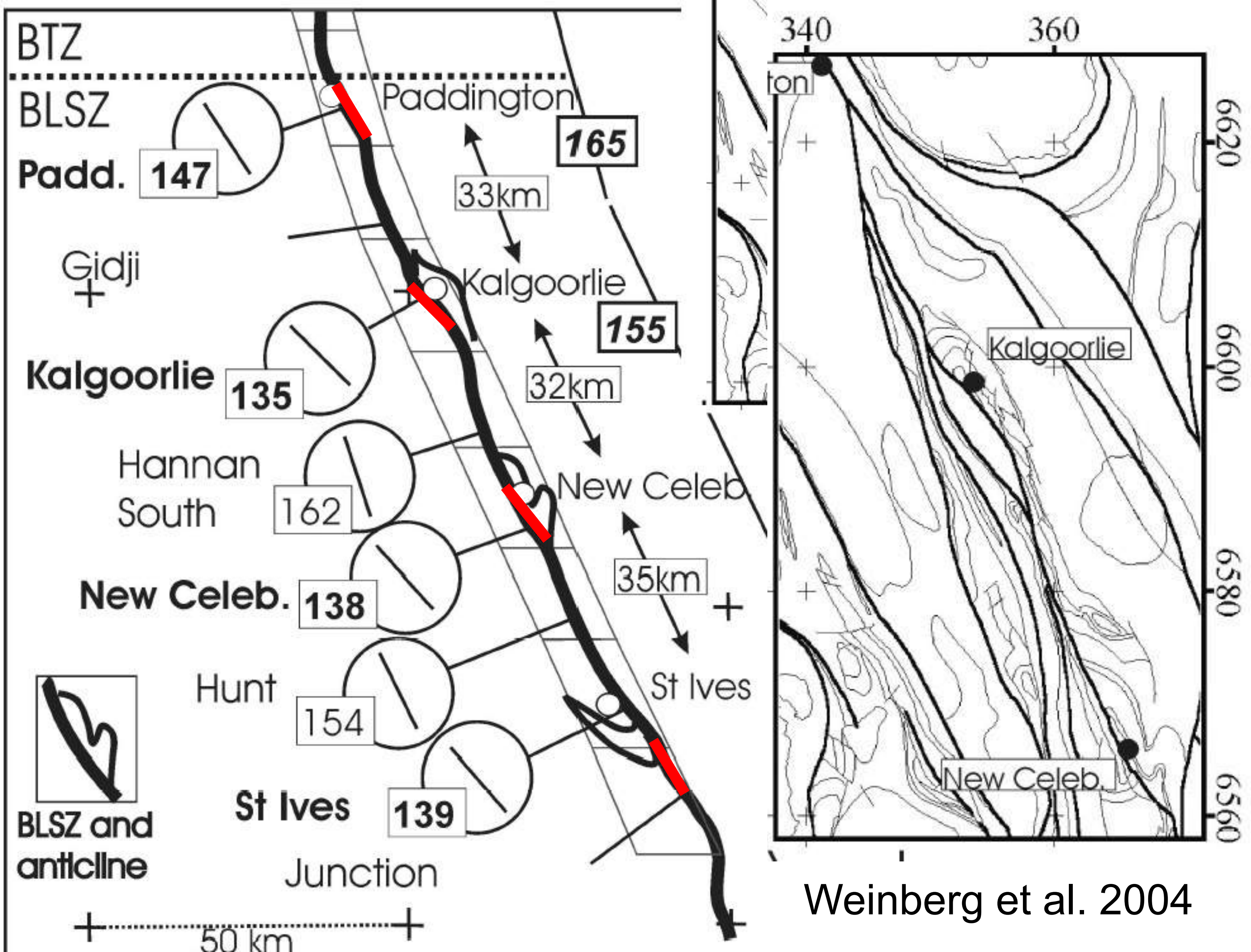
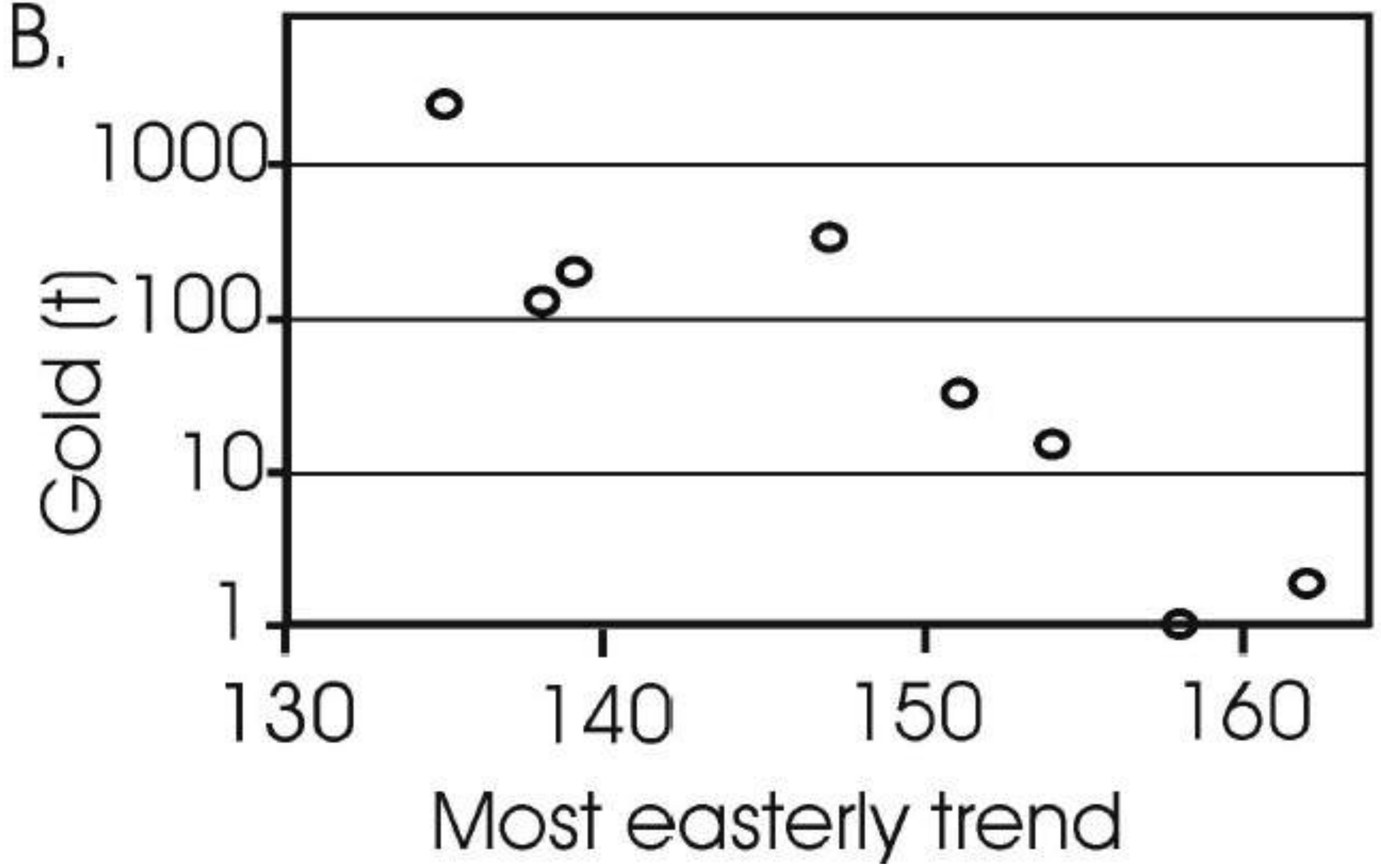


Weinberg et al. 2004



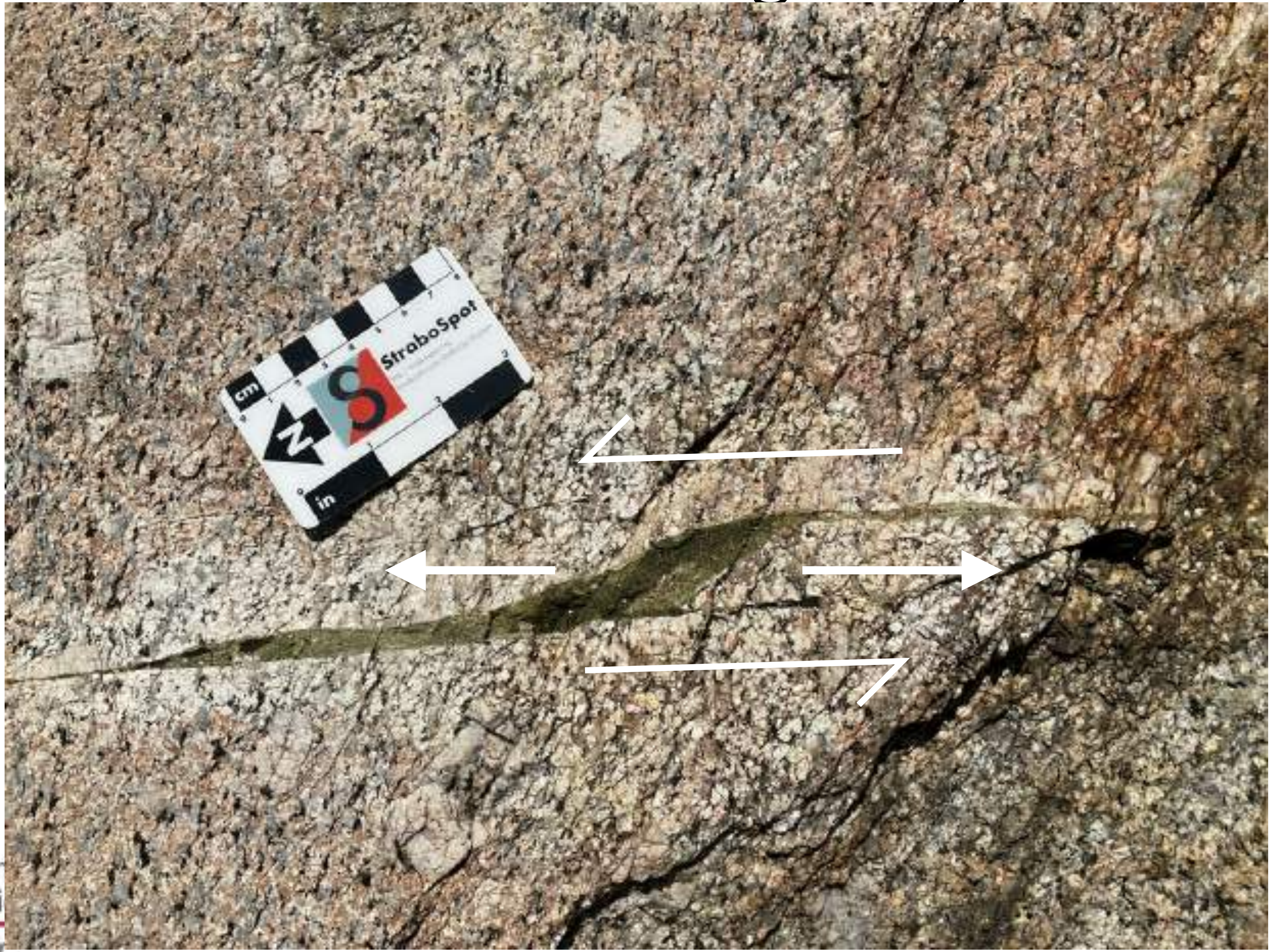
Weinberg et al. 2004

Viceroy mine,
Harare greenstone belt

Roof view

What is the shear sense?

Step overs from Saddlebag lake, California



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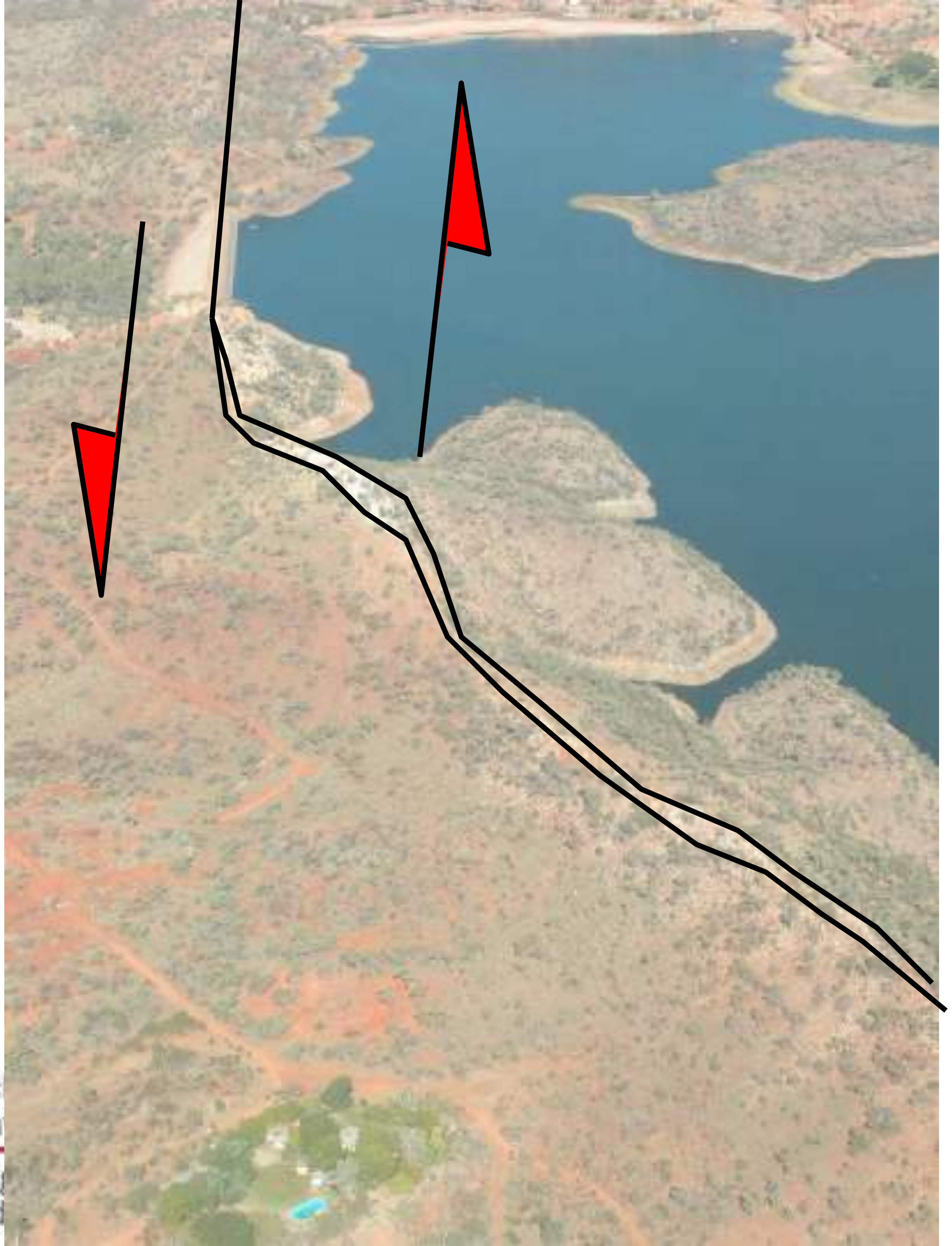
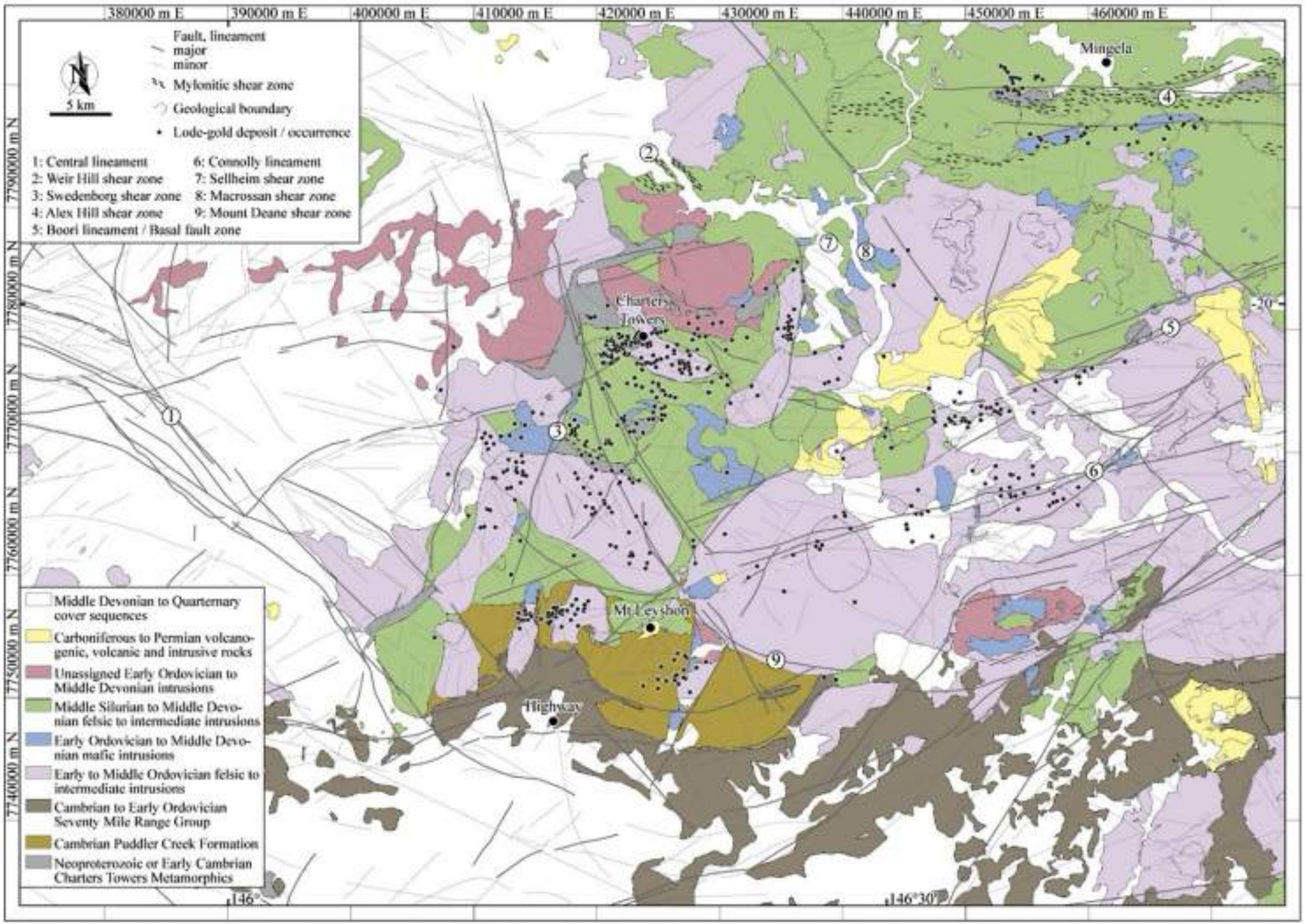


Spillway fault,
Lake Moondara,
Mt Isa

Fountain Range Fault
Mount Isa inlier
Australia

Overlander Fault
Mount Isa inlier
Australia



Charters Towers goldfield, Queensland Australia

Kreuzer, OP, TG Blenkinsop, R. J. Morrison, and S. G. Peters. 'Ore Controls in the Charters Towers Goldfield, NE Australia: Constraints from Geological, Geophysical and Numerical Analyses'. *Ore Geology Reviews* 32 (2007): 37–80. https://doi.org/10.1016/j.oregeorev.2006.12.001.

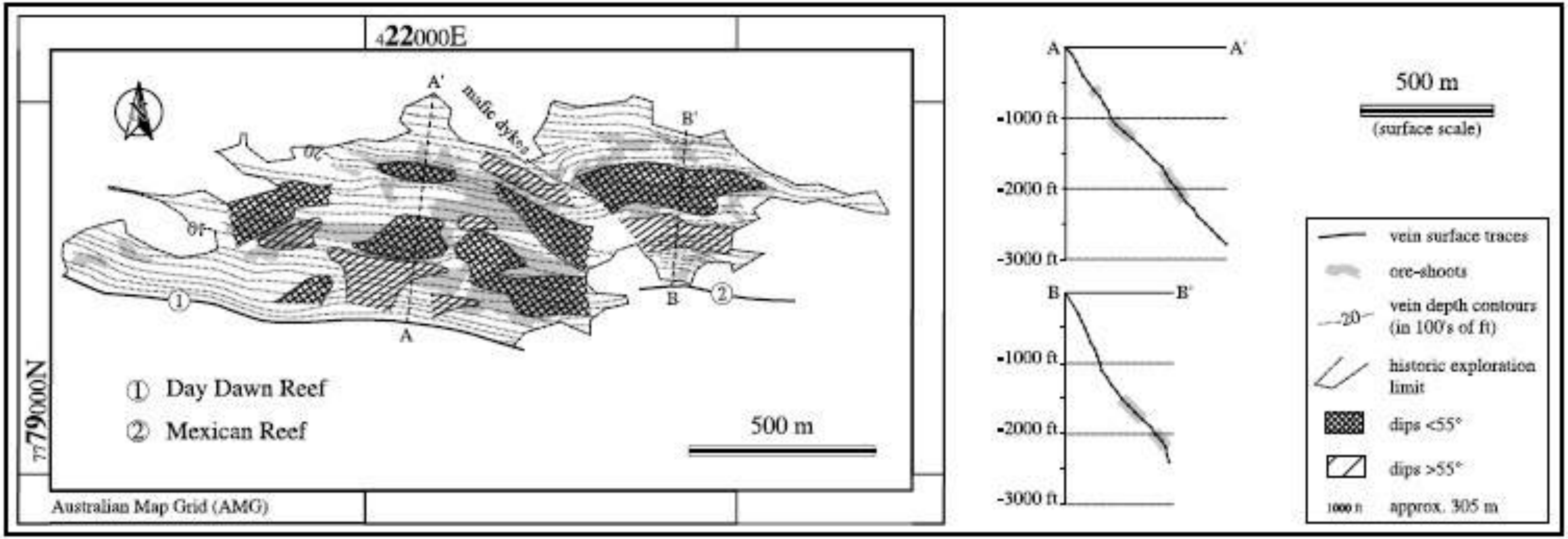


Fig. 4. Vein contour map of the Day Dawn and Mexican Reefs, also illustrating the historically mined orebodies. Vein depth contours were likely derived from plans and cross-sections of the historic workings; modified after Levingston (1972). Ore deposition occurred preferentially in shallower dipping vein segments (< 55°) of the Day Dawn and Mexican Reefs; modified after Peters (1987b). Presented cross-sections are based on the vein depth contour maps.

Kreuzer 2004

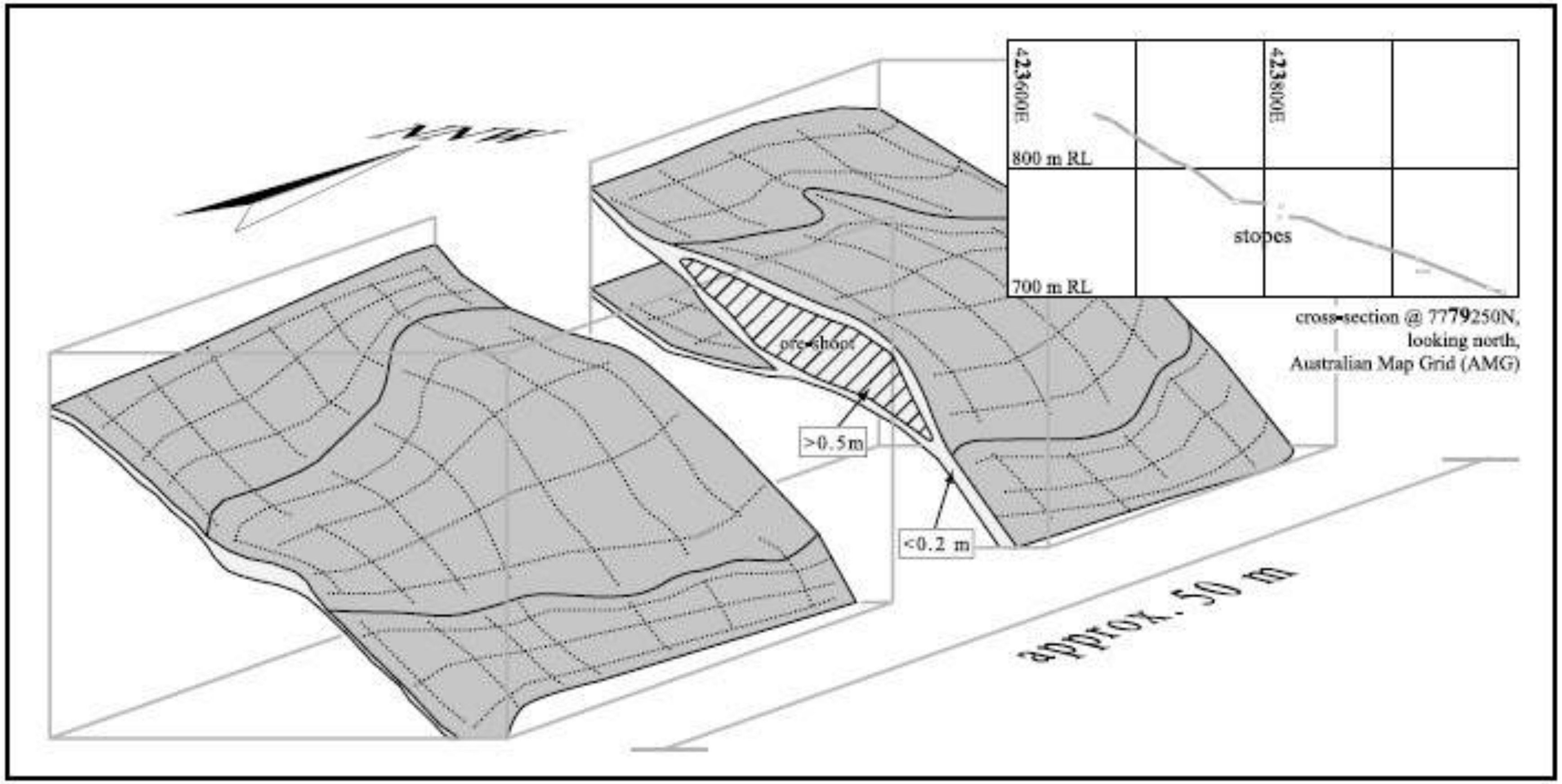


Fig. 7. Schematic block diagram of the studied segment of the Maude St Ledger Reef, illustrating how the (stoped) ore-shoot is confined to a shallow dipping, lenticular, and apparently dilatant vein segment. Inset: cross-section of the same segment, showing significant flattening of the host structure where the stopes are situated; SURPAC-based section kindly provided by Charters Towers Gold Mines staff.

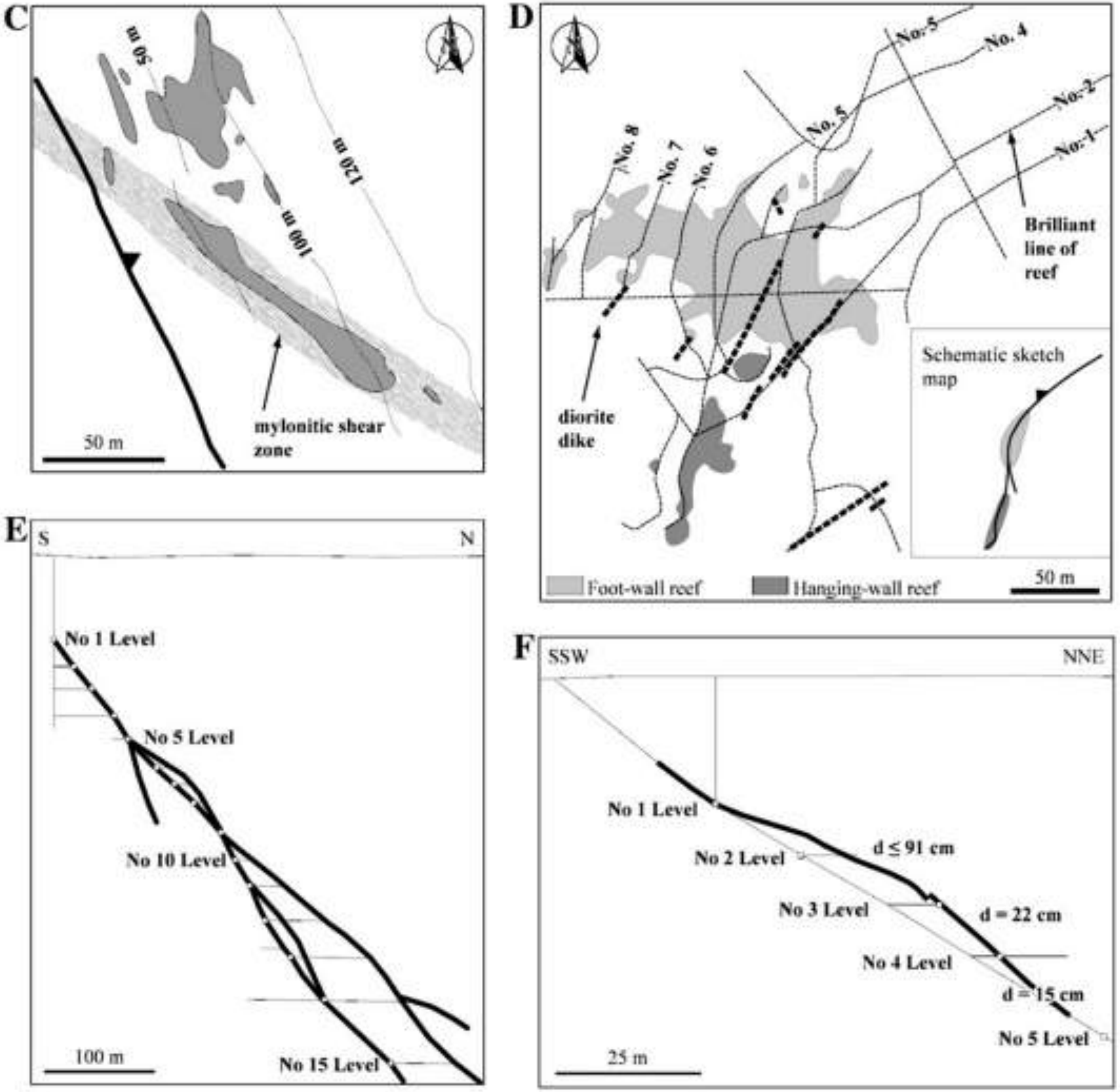
Controls on lode geometry

Pre-existing Shear zone

Splay faults

Bend in map view

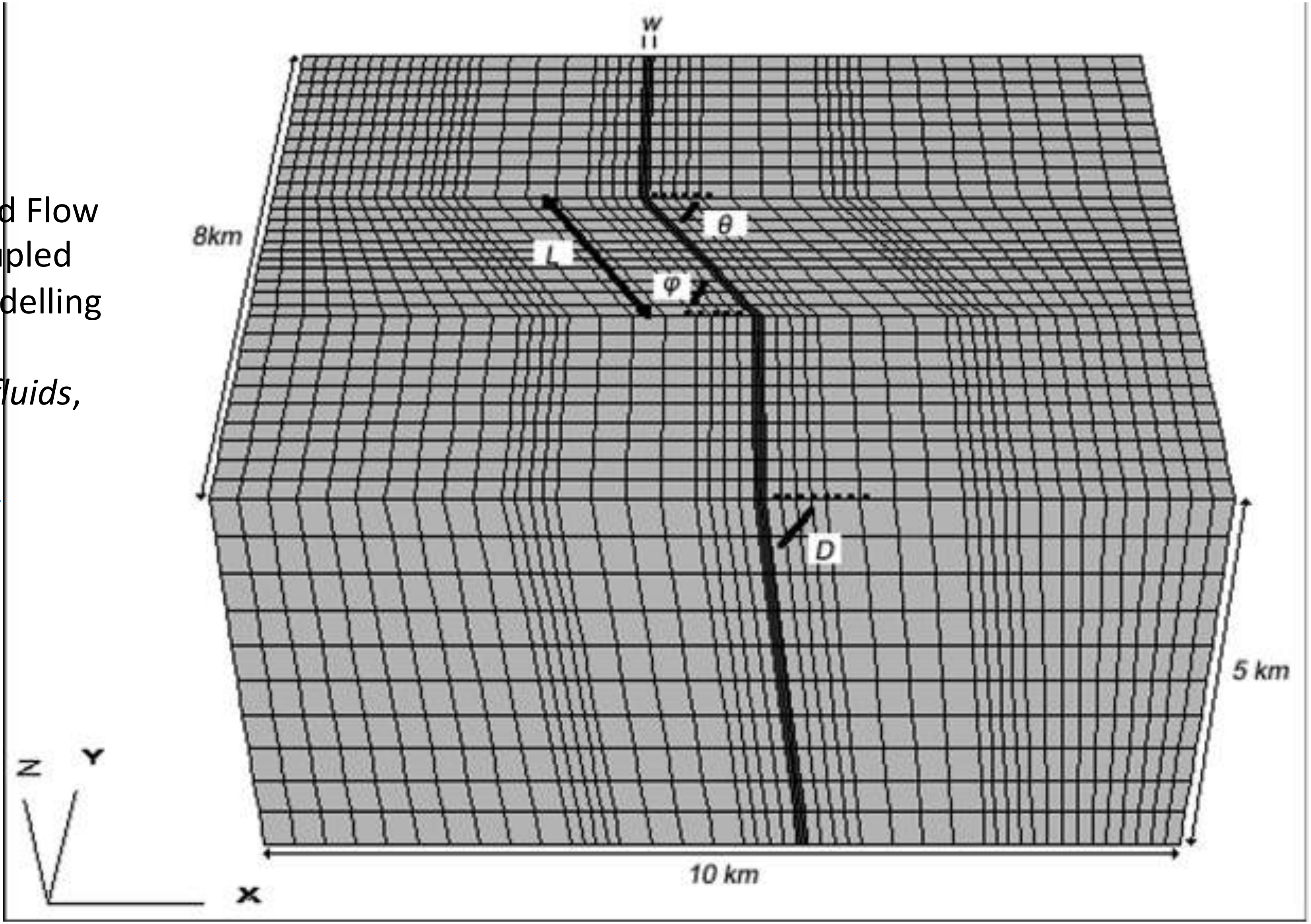
Bend in cross section

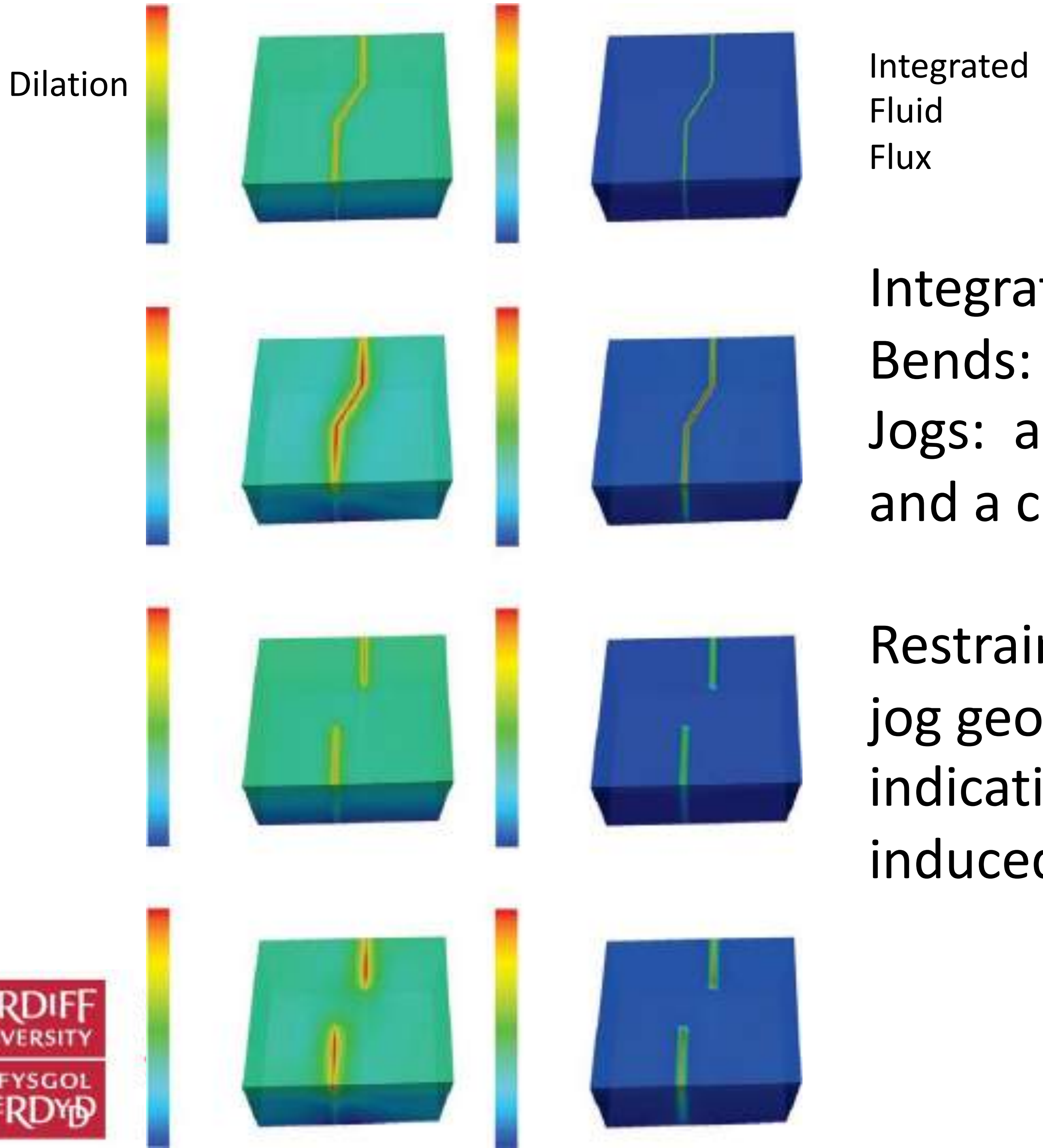


Restraining vs Releasing Bends and Mineralization

Numerical modelling

Ford, A., TG Blenkinsop, and JG McLellan. 'Factors Affecting Fluid Flow in Strike–Slip Fault Systems: Coupled Deformation and Fluid Flow Modelling with Application to the Western Mount Isa Inlier, Australia'. *Geofluids*, 2009, 1–22. https://doi.org/10.1111/j.1468-8123.2008.00219.x.





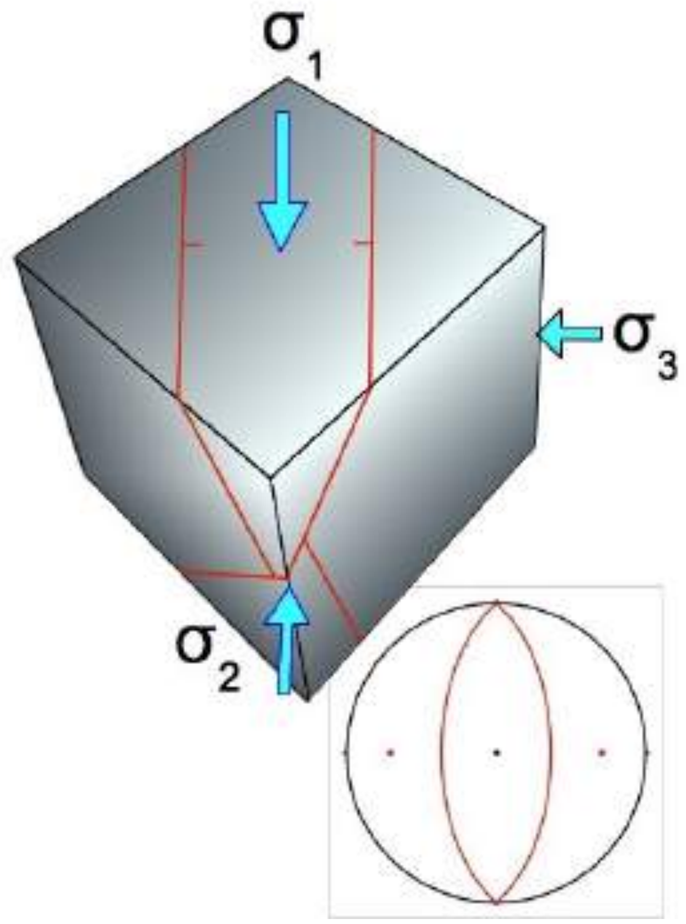
Conclusions

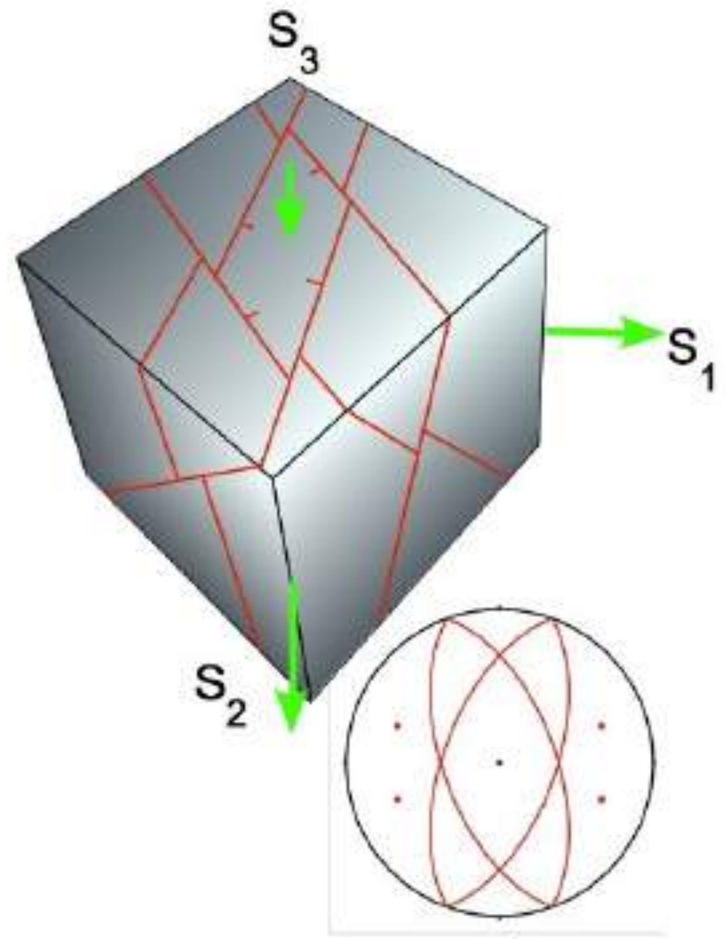
Integrated fluid flux is maximized by:
Bends: a small bend angle and long bend,
Jogs: a large jog angle and a short length,
and a cross-cutting fault.

Restraining and releasing fault bend and jog geometries show similar results, indicating the dominant effect of strain-induced dilatancy in these models.

Ford et al. 2007

Geometry Multiple Fault Sets





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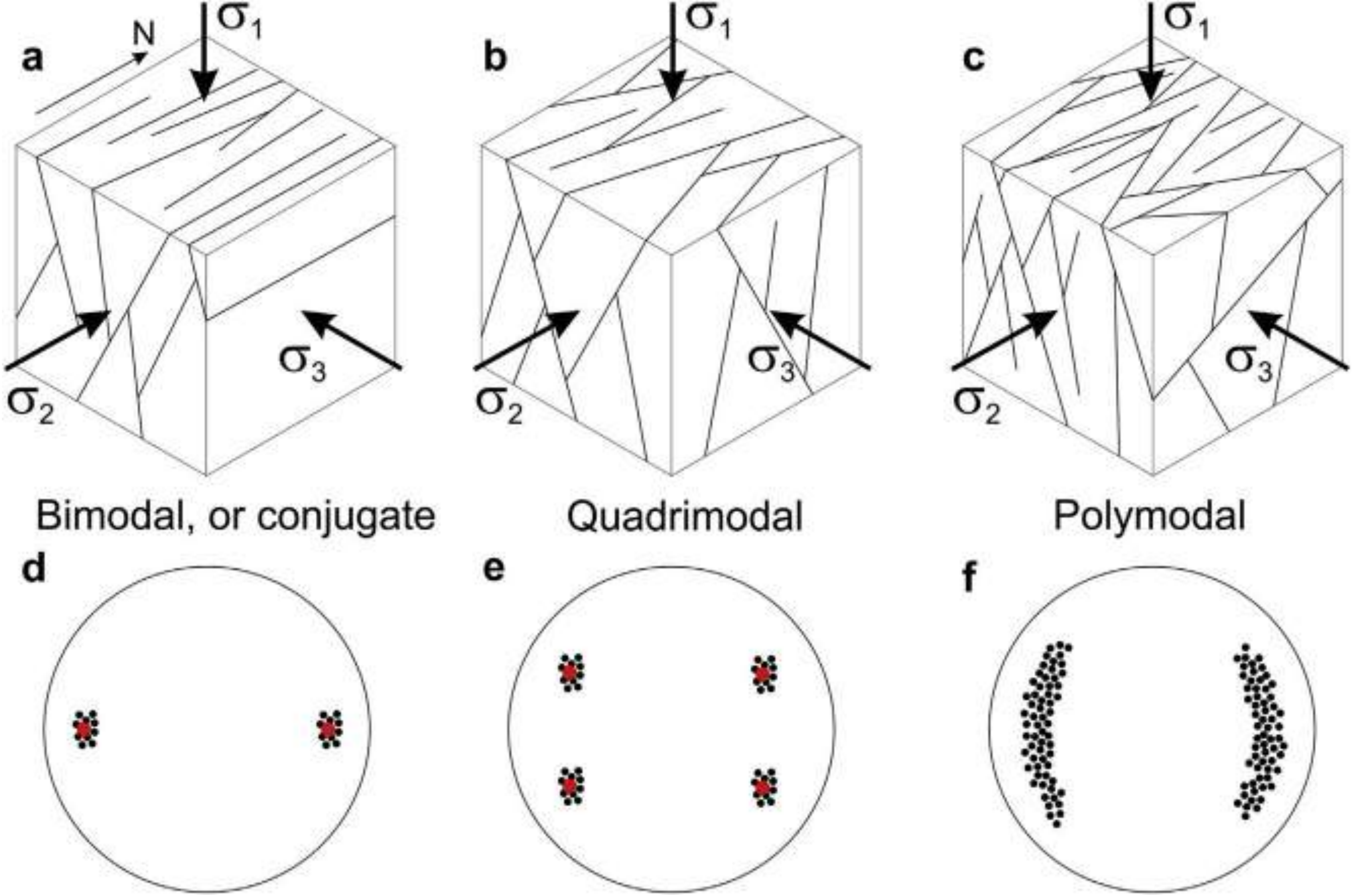
Carvell, J., Blenkinsop, T., Clarke, G., and Tonelli, M. 'Scaling, Kinematics and Evolution of a Polymodal Fault System: Hail Creek Mine, NE Australia'. *Tectonophysics* 632 (September 2014): 138–50. https://doi.org/10.1016/j.tecto.2014.06.003.

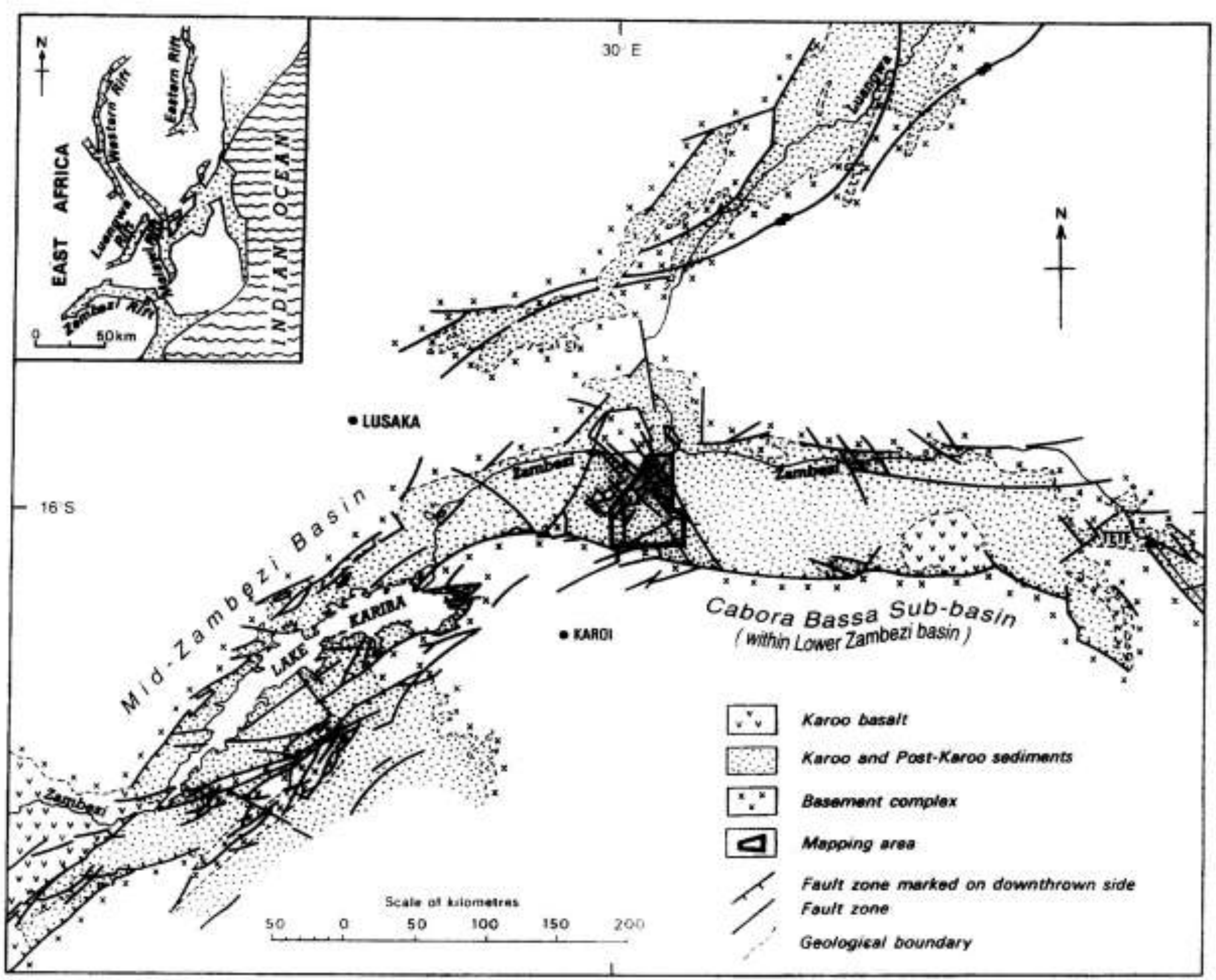
Carvel et al. 2014



Healy, David, Thomas G. Blenkinsop, Nicholas E. Timms, Philip G. Meredith, Thomas M. Mitchell, and Michele L. Cooke. 'Polymodal Faulting: Time for a New Angle on Shear Failure'. *Journal of Structural Geology* 80 (2015): 57–71. https://doi.org/10.1016/j.jsg.2015.08.013.

Zambezi Valley example

Oesterlen, PM, and TG Blenkinsop. ‘Extension Directions and Strain near the Failed Triple Junction of the Zambezi and Luangwa Rift Zones, Southern Africa’. *Journal of African Earth Sciences* 18, no. 2 (1994): 175–80.



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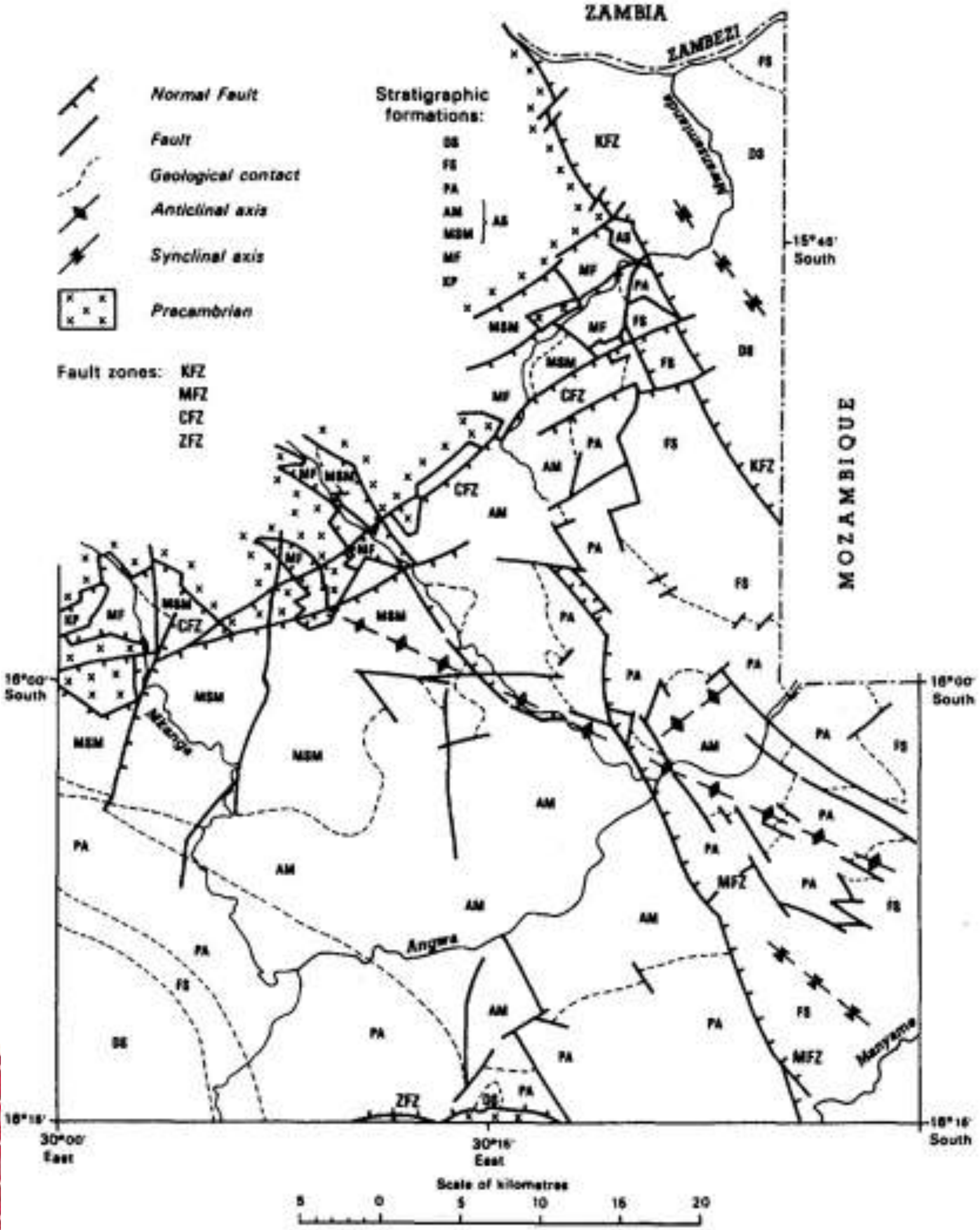
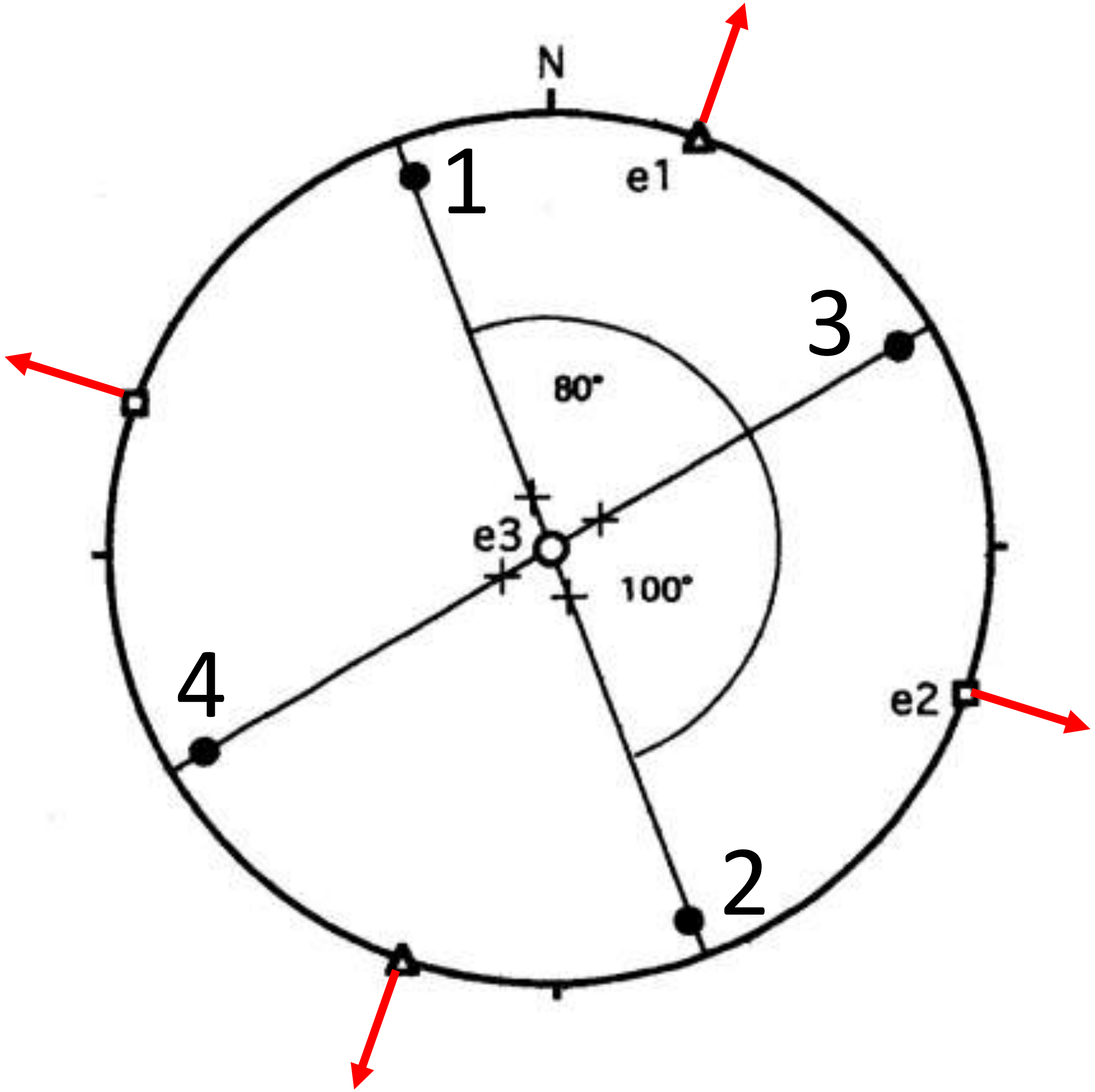
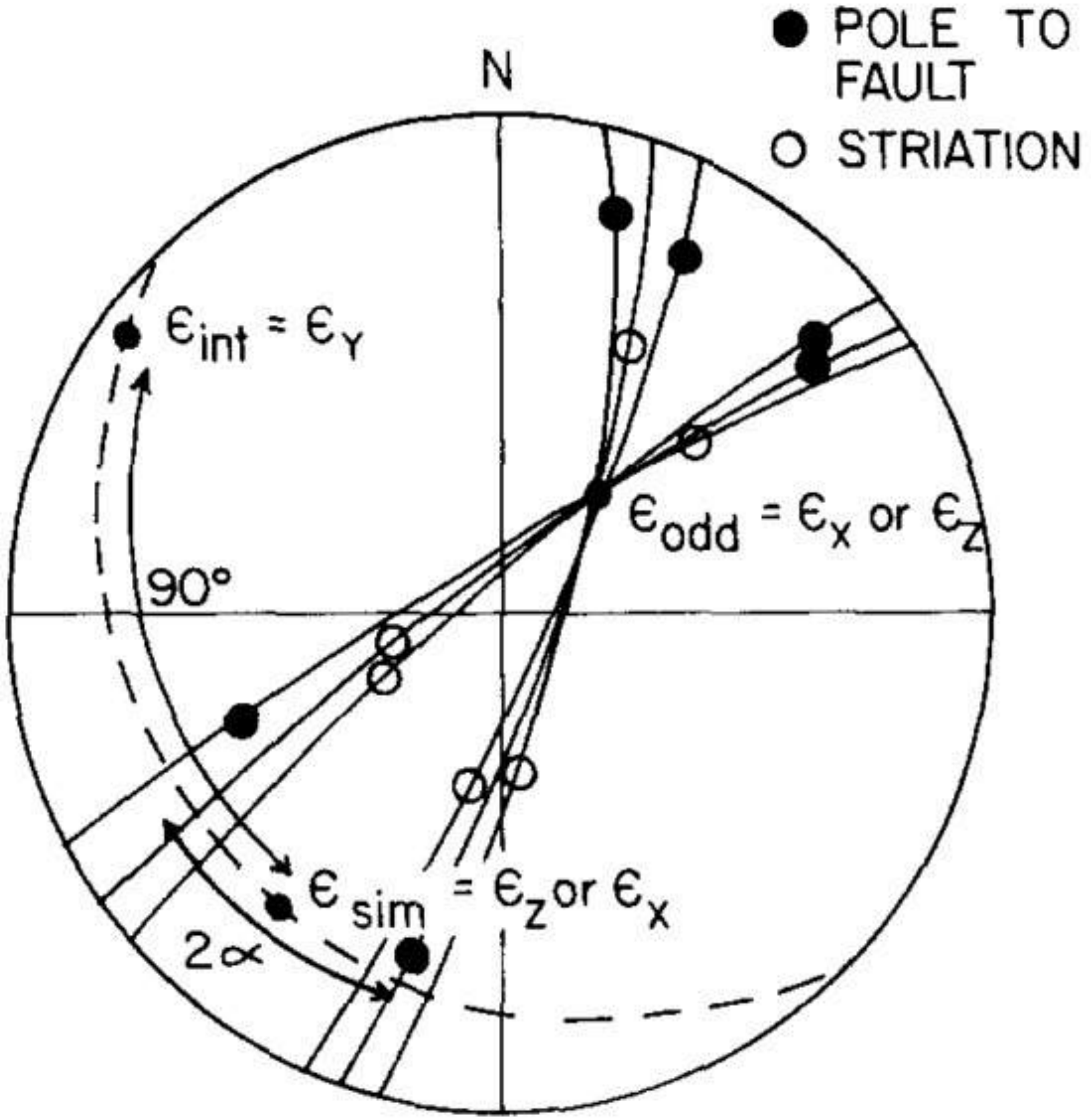
Zambezi Valley example





The Odd Axis Construction for polymodal faults

Krantz 1988



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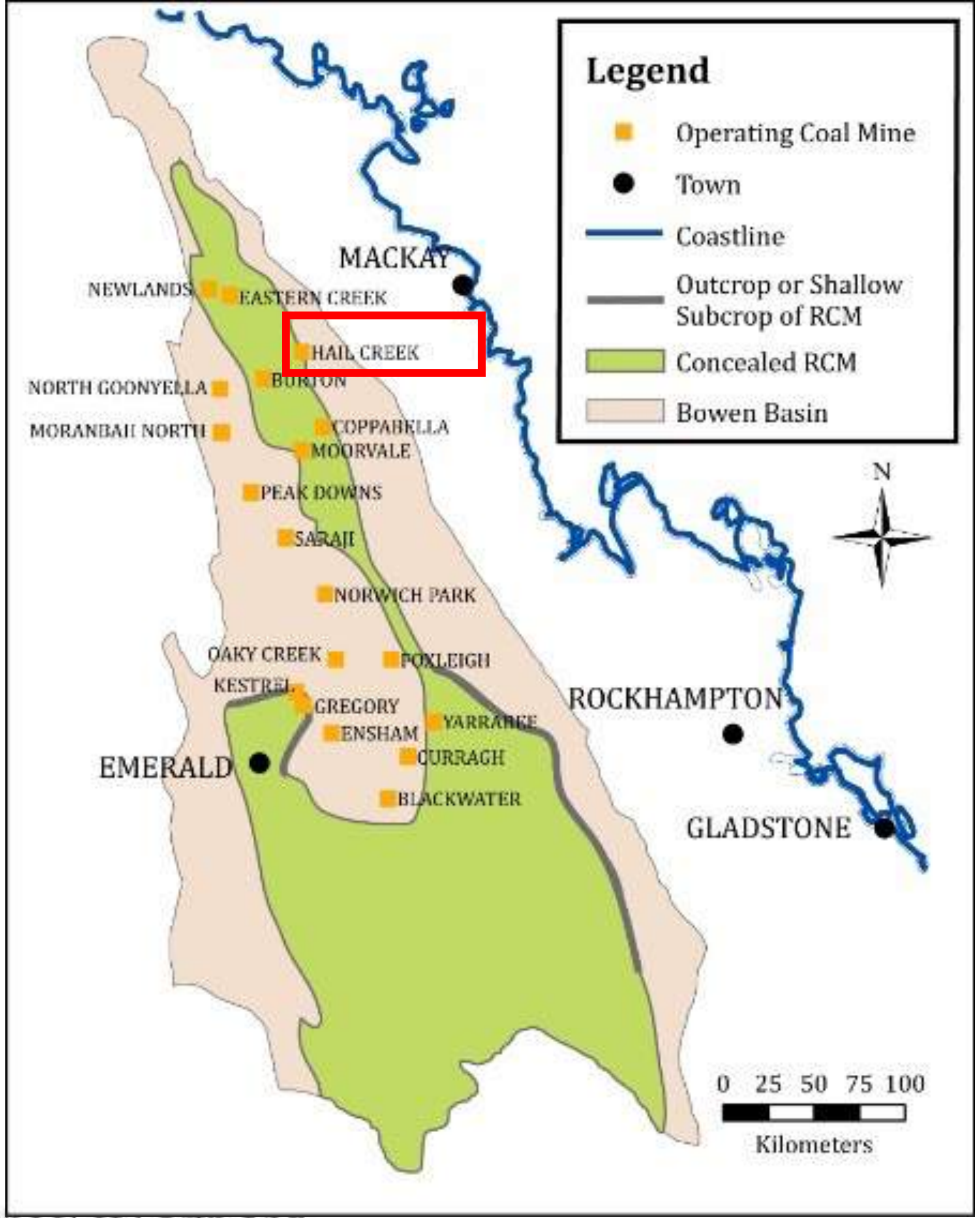

Hail Creek Coal Mine

Rangal Coal Measures: Late Permian

Carvell, J., Blenkinsop, T., Clarke, G., Tonelli, M., 2014. Scaling, kinematics and evolution of a polymodal fault system: Hail Creek Mine, NE Australia. Tectonophysics 632, 138–150. doi:10.1016/j.tecto.2014.06.003

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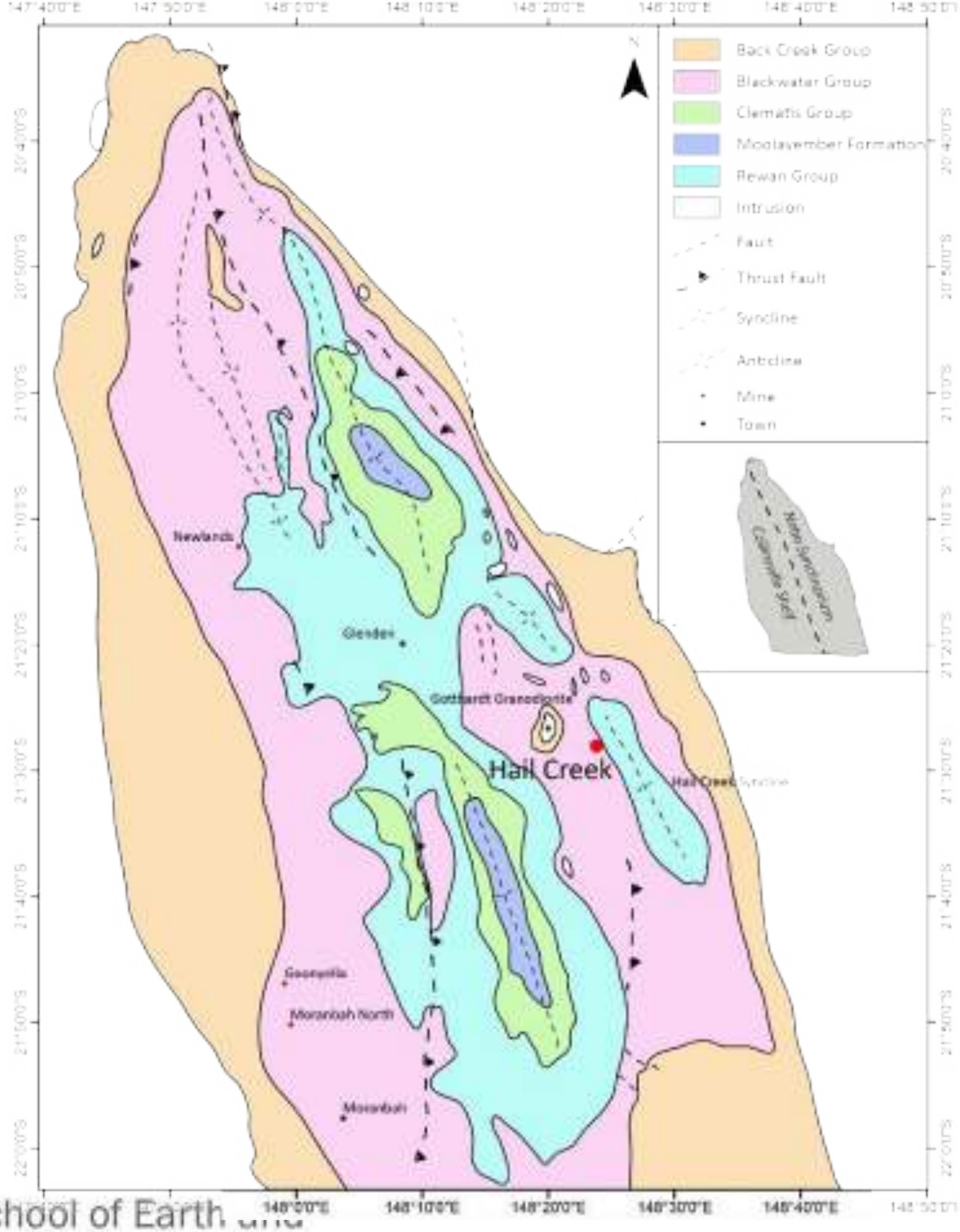

Structural setting

Hail Creek Syncline
in the
Nebo Synclinorium

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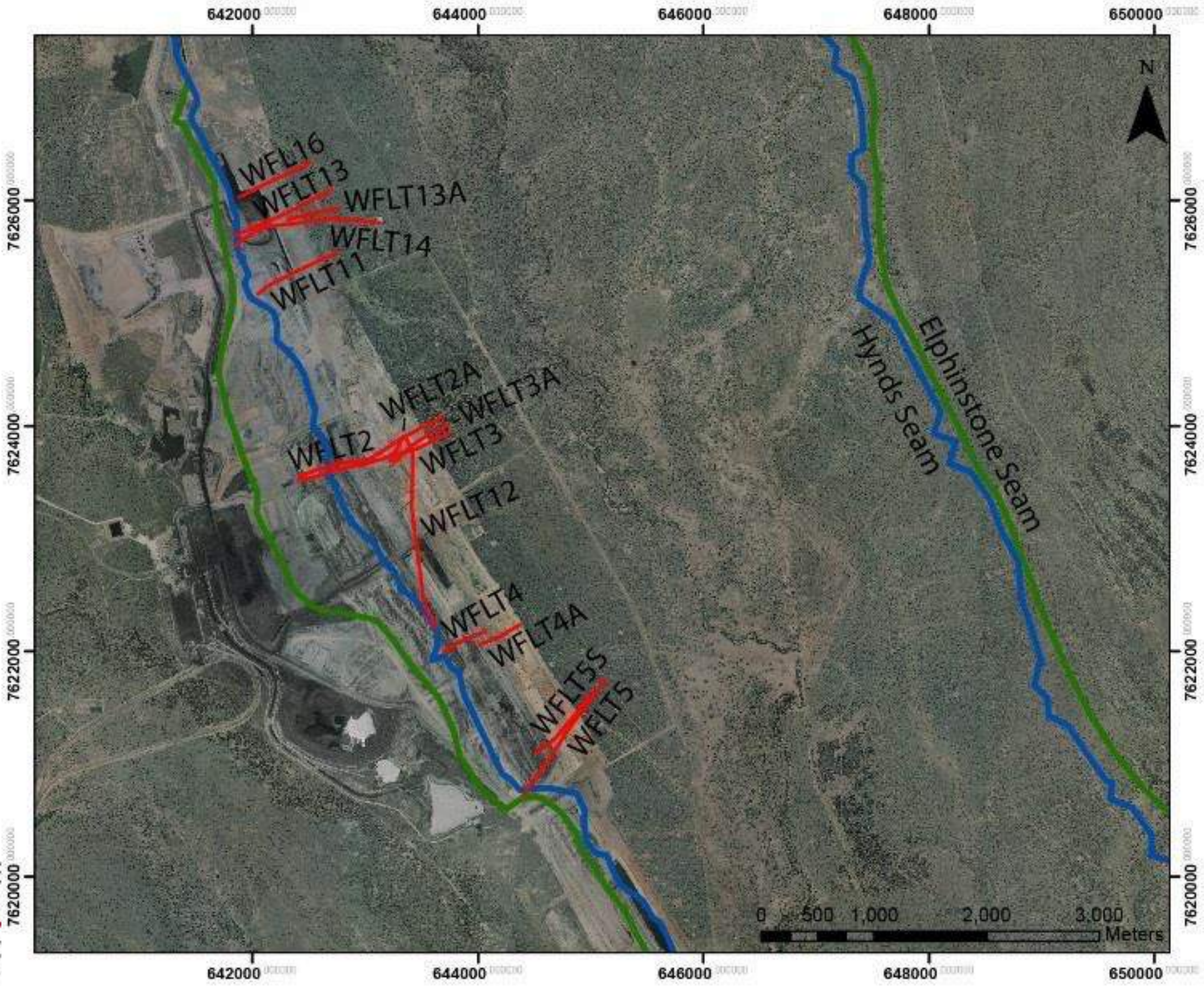

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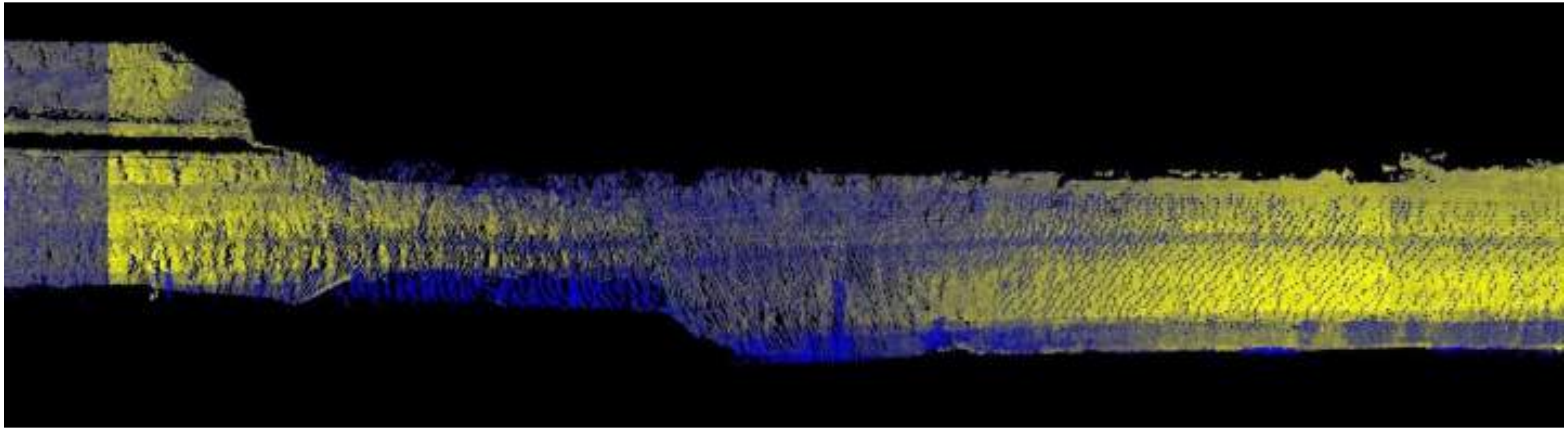
Data for the 3D model

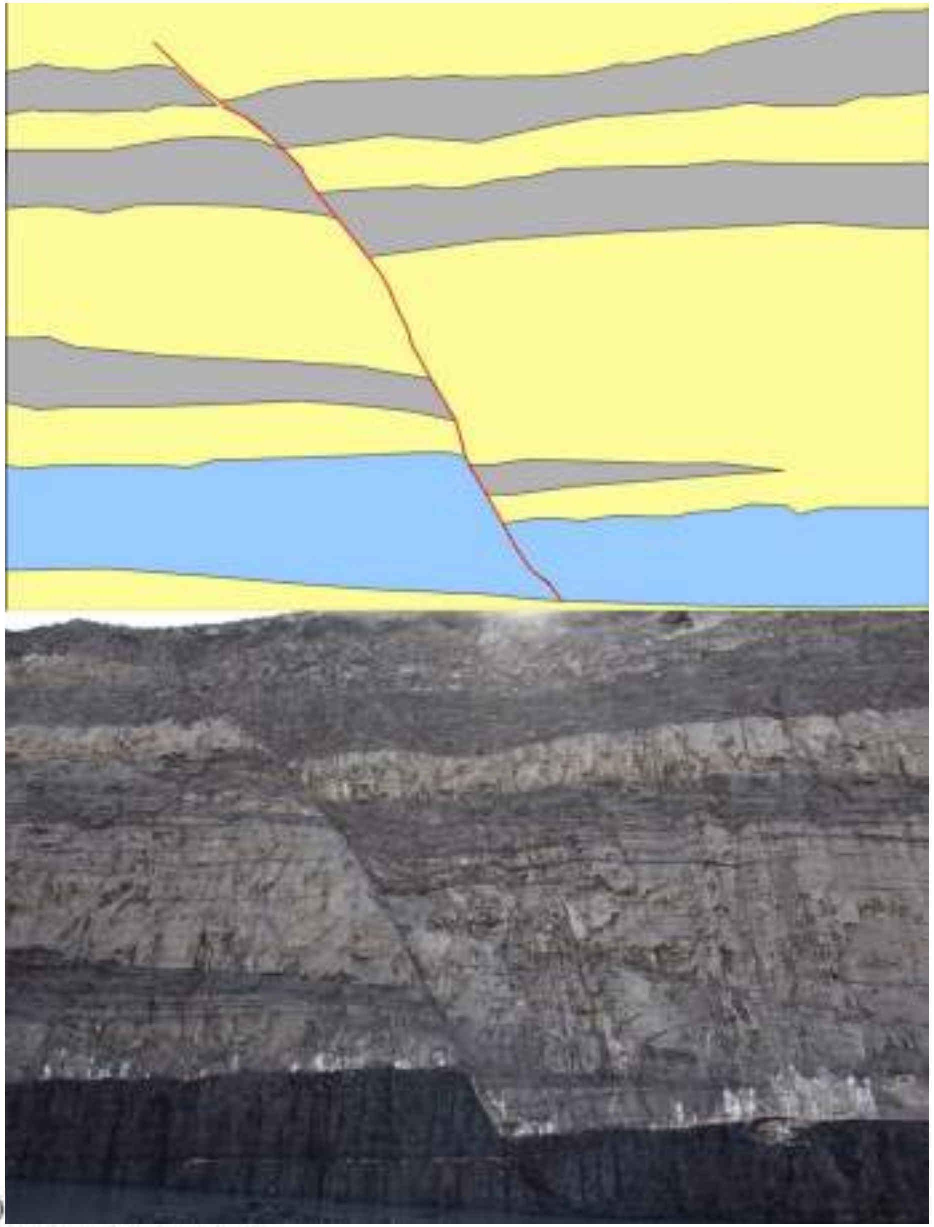


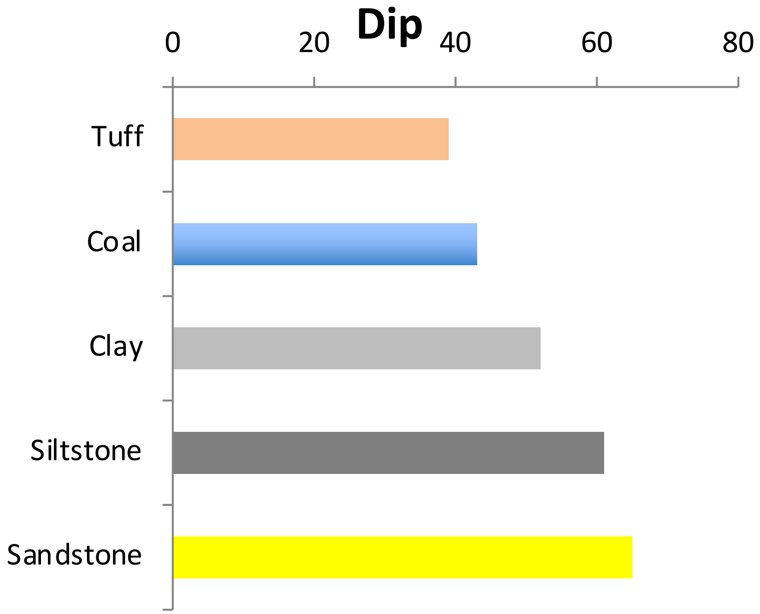
High-wall laser scan and a trace of West Fault 4.

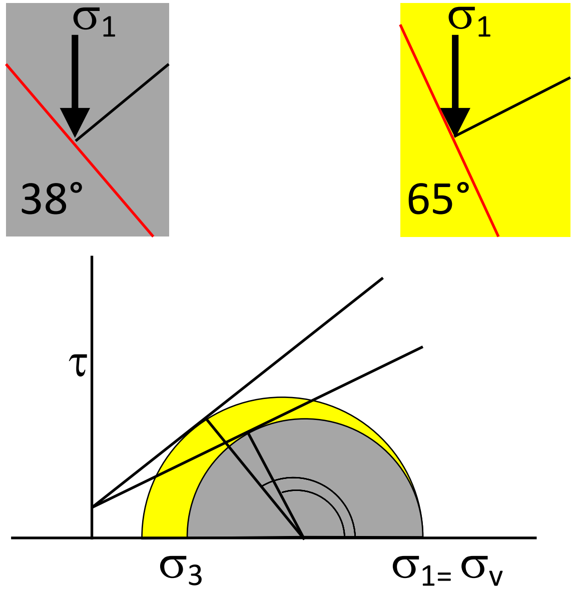
Pointset of the top of Elphinstone seam, generated from the seam pick database (8008 drillholes)

The refined surface of the top of the Elphinstone Seam

Normal Fault Geometries







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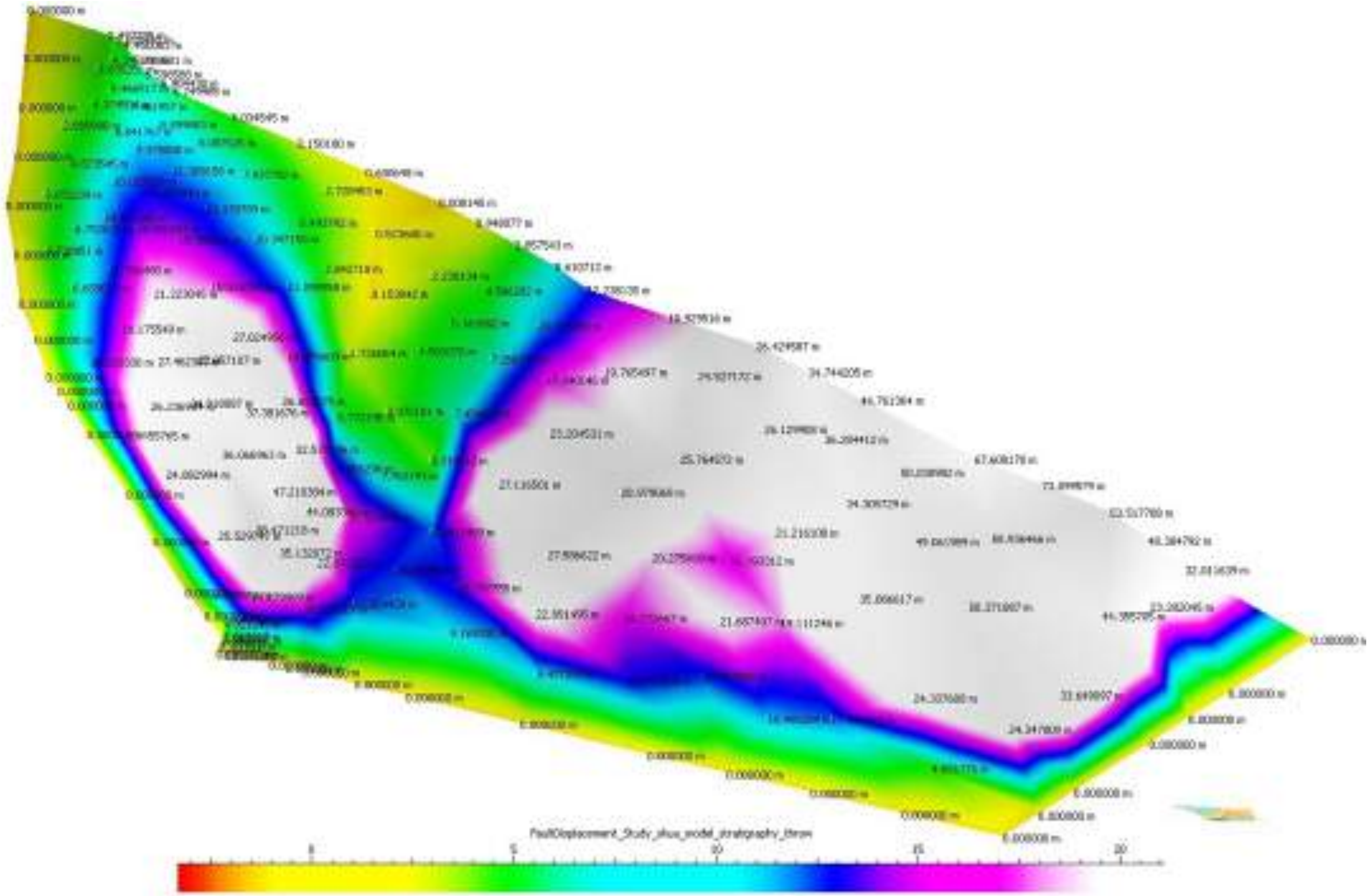
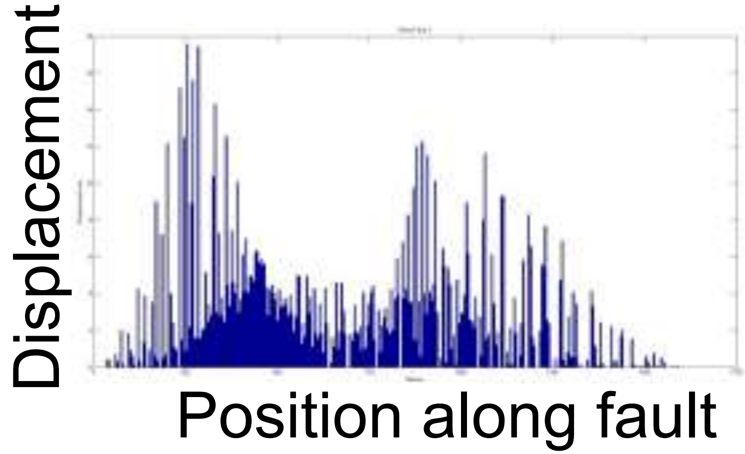
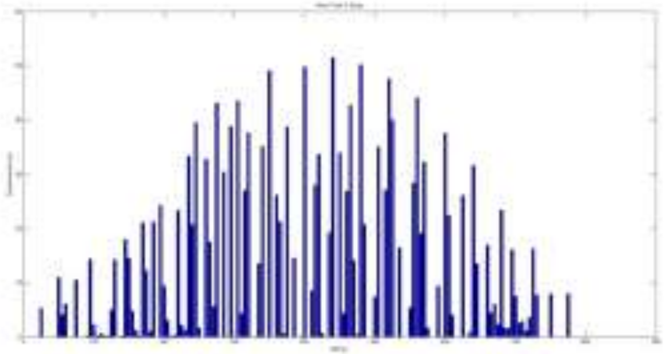
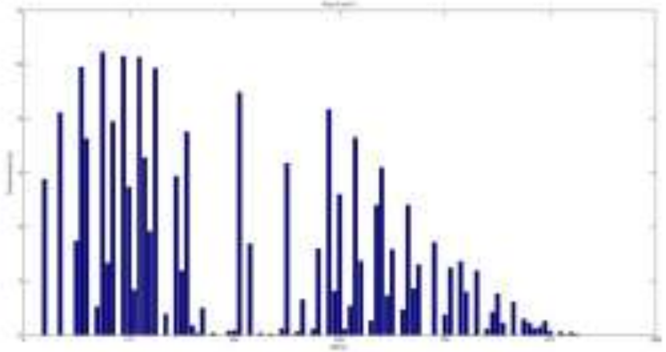
Displacement Gradients









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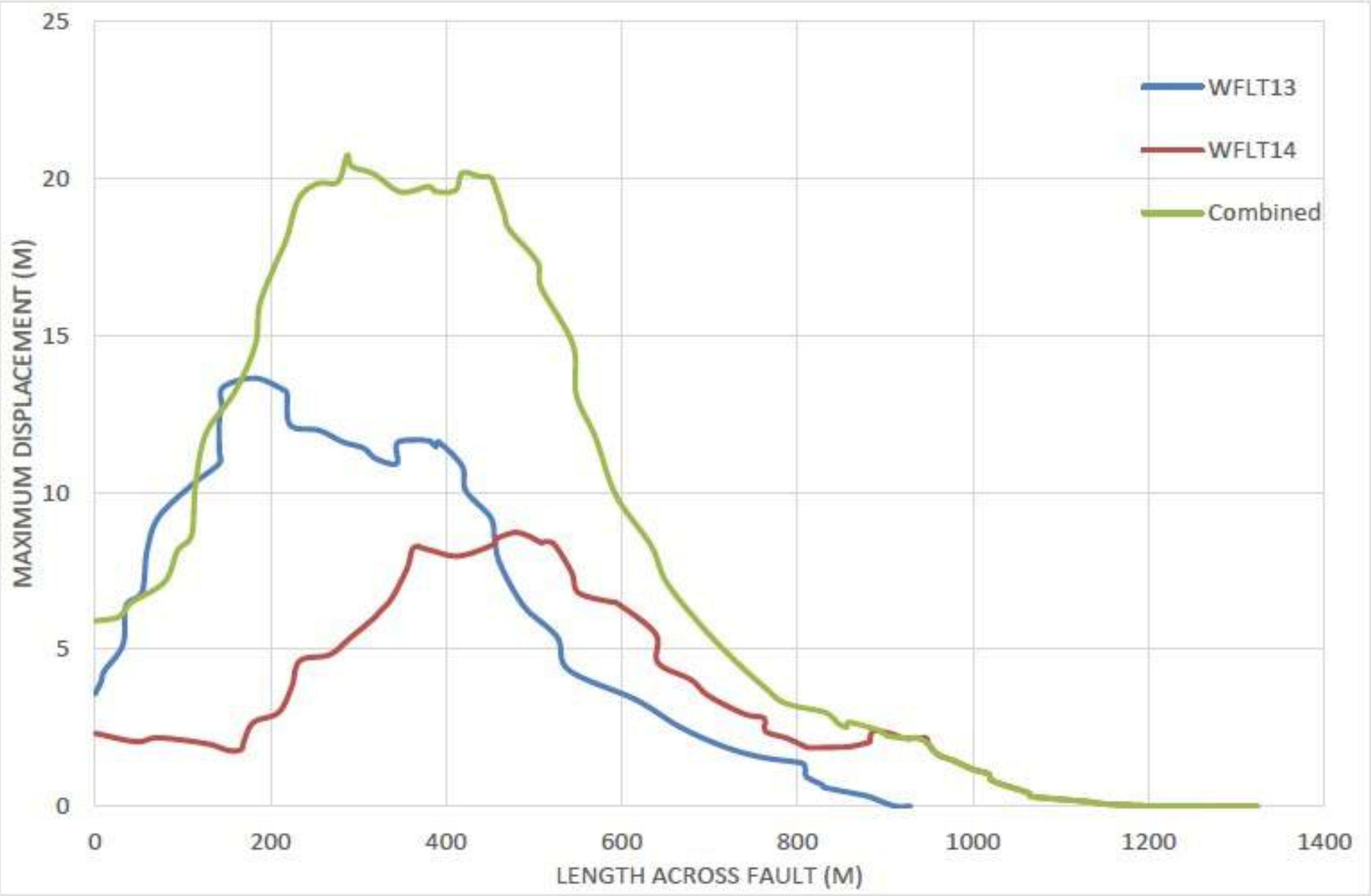
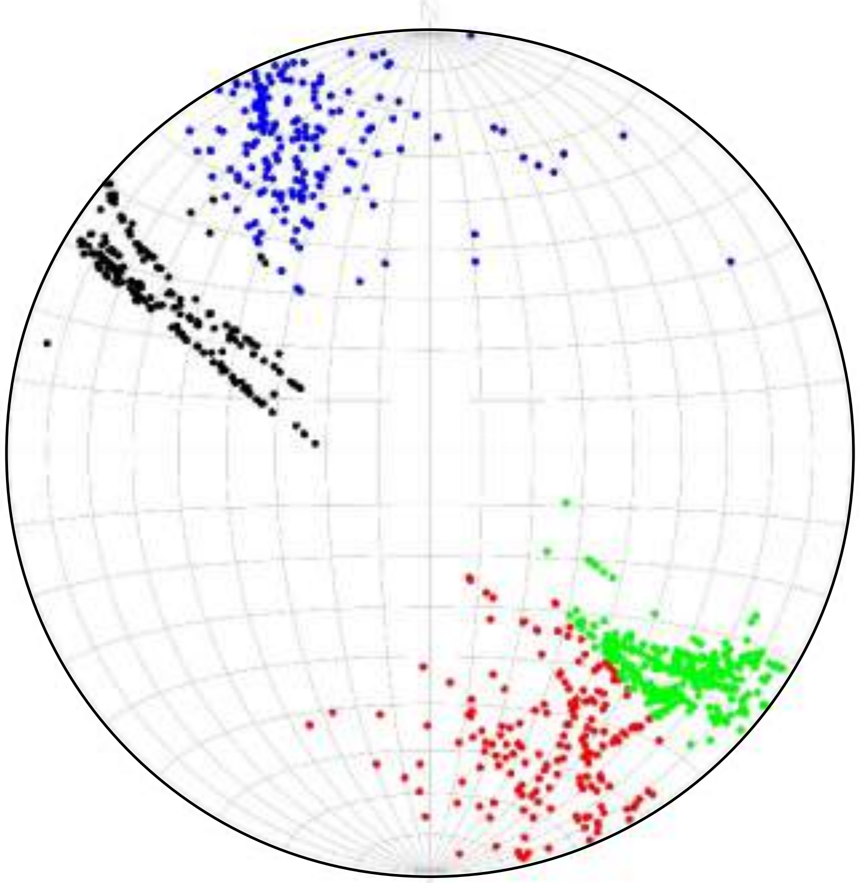
Displacement profiles: Segment Linkage

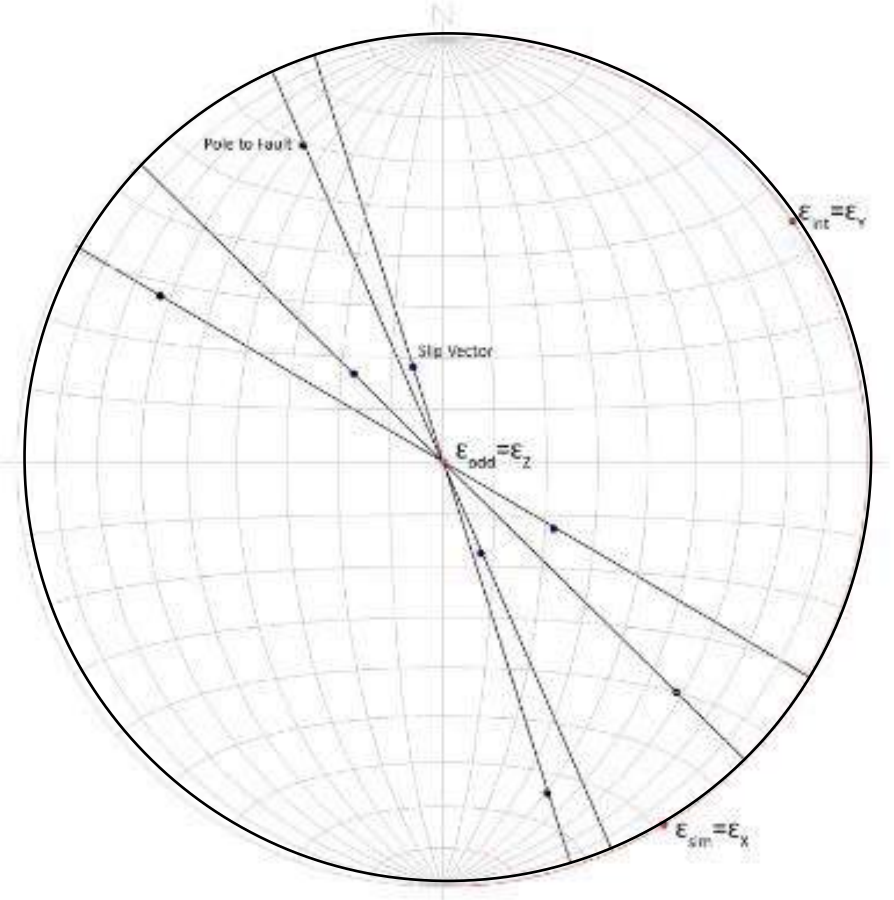


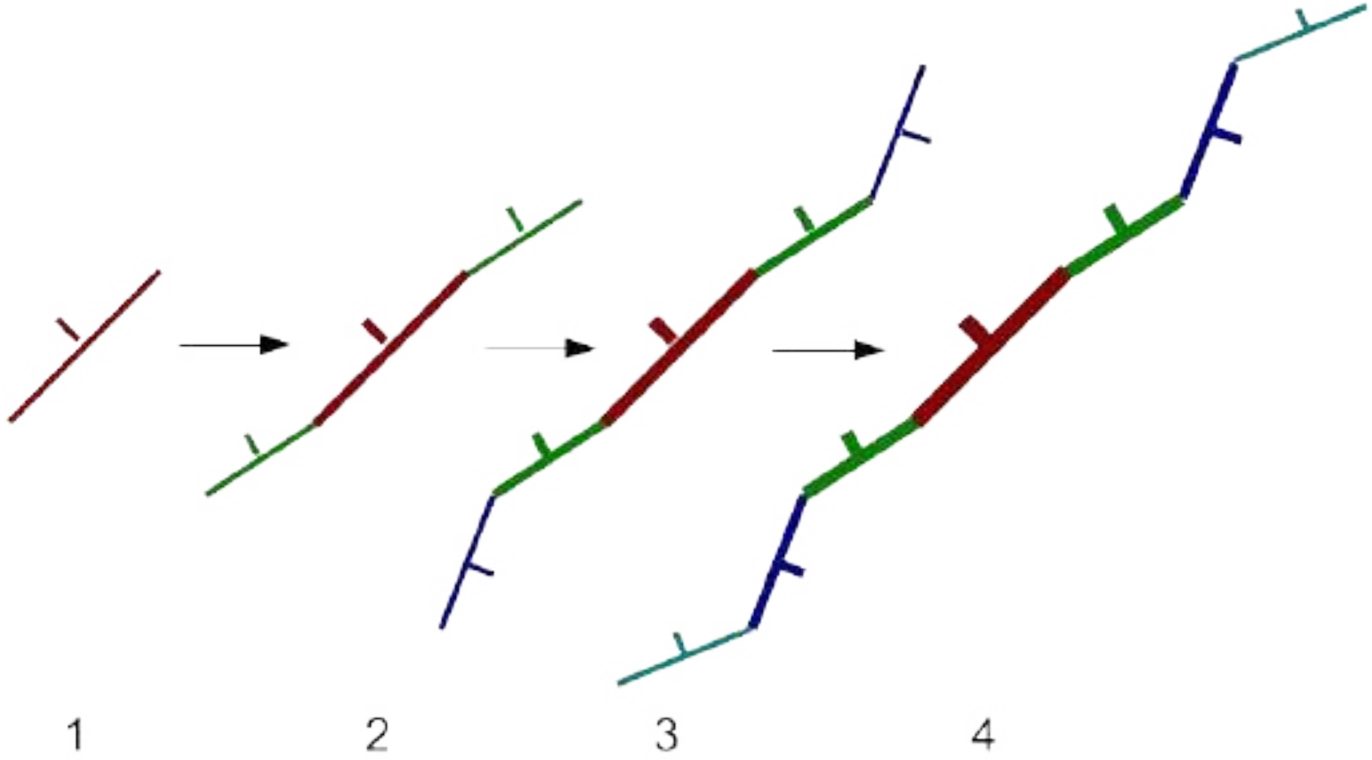
Polymodal, polyscale faults

Grouped Triangulations

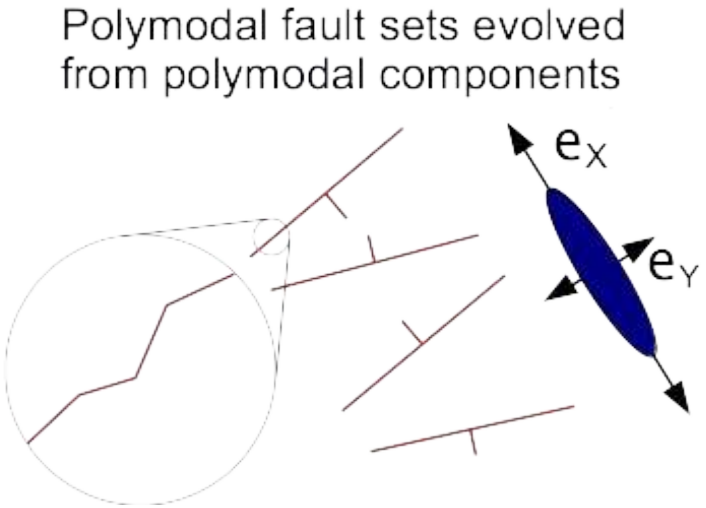


Odd Axis Construction




1
2
3
4

Conclusions



- The faults at Hail Creek form an orthorhombic (polymodal) fault array related to triaxial strain.
- The fault network grew by linkage of polymodal segments.
- Polymodal faulting is predicted where any triaxial strain accommodated by faulting

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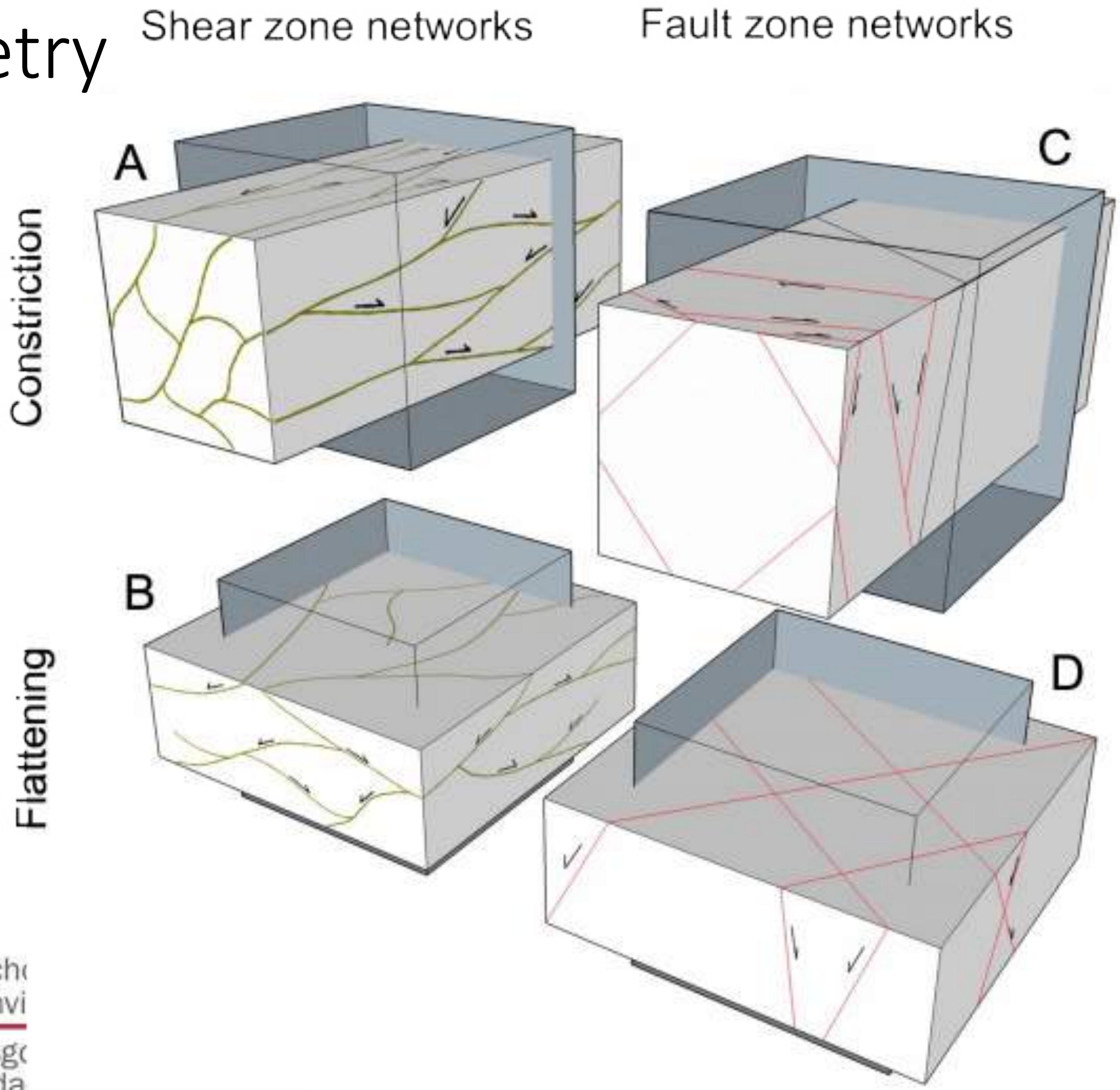
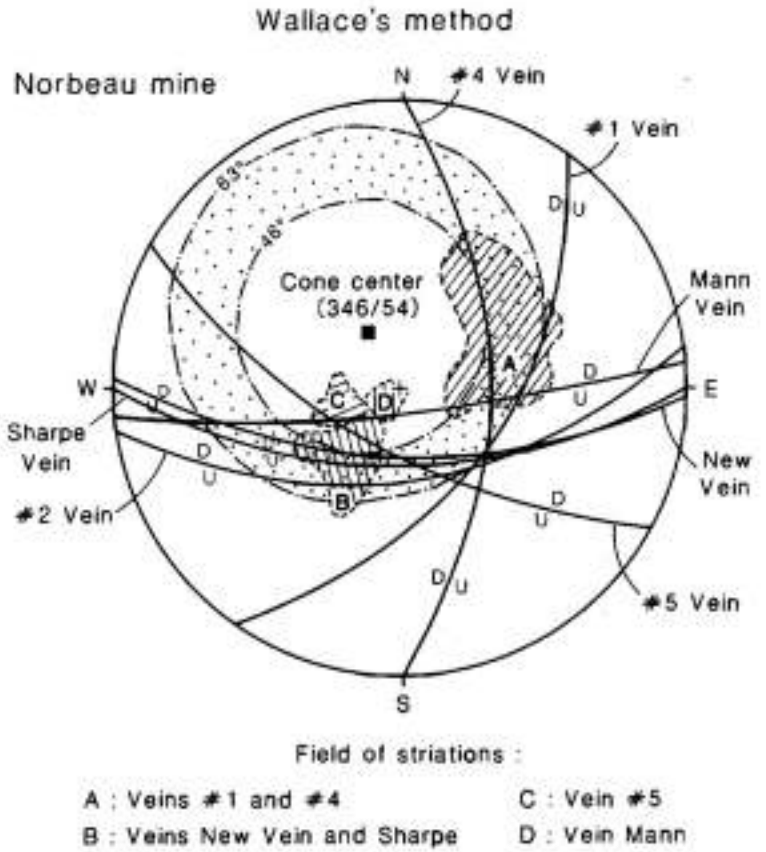
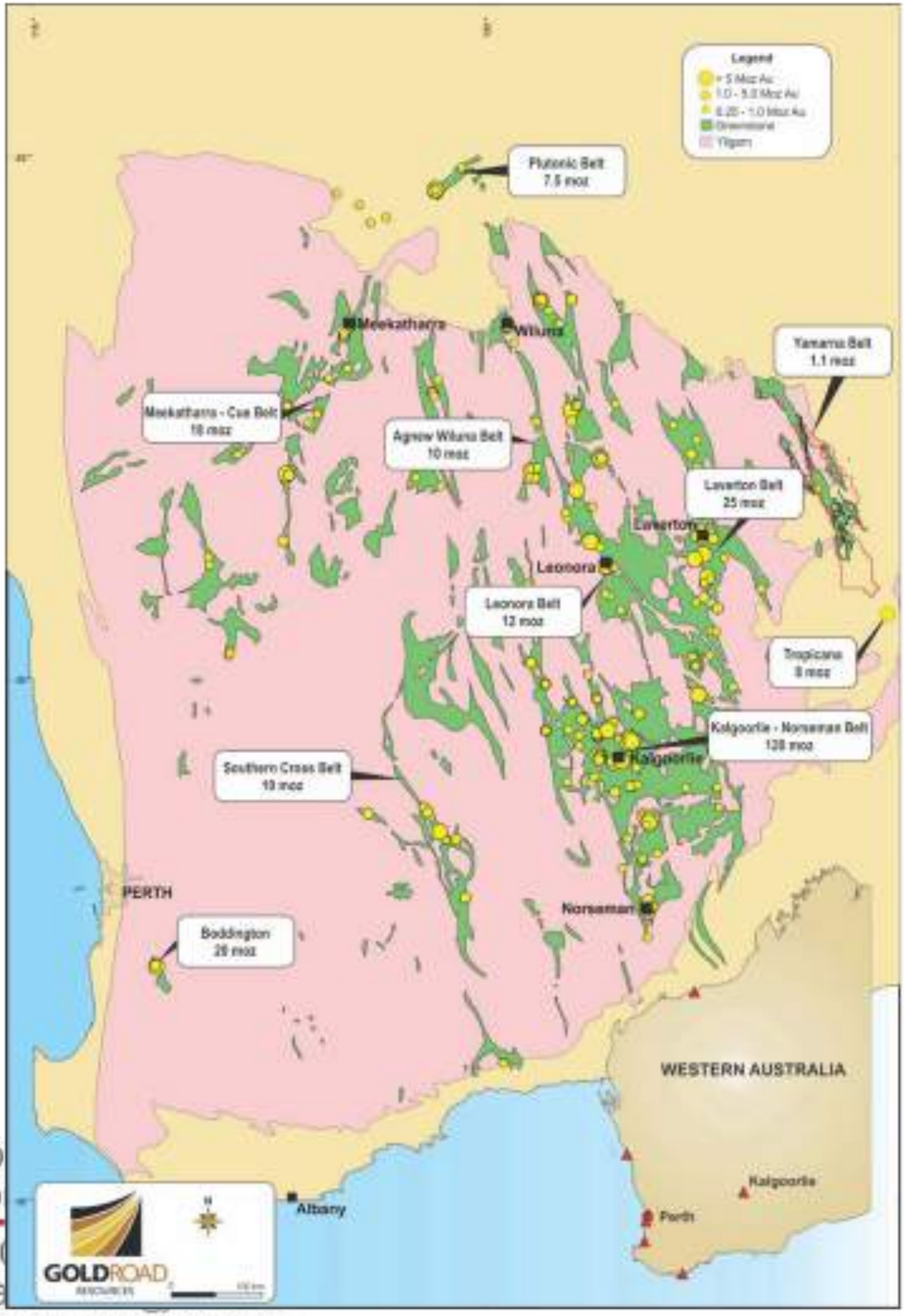
Geometry



Application:
Norbeau mine, Quebec



Dube et al. 1989



The Yilgarn Craton,
Western Australia

http://www.goldroad.com.au/projects-yamarna.php

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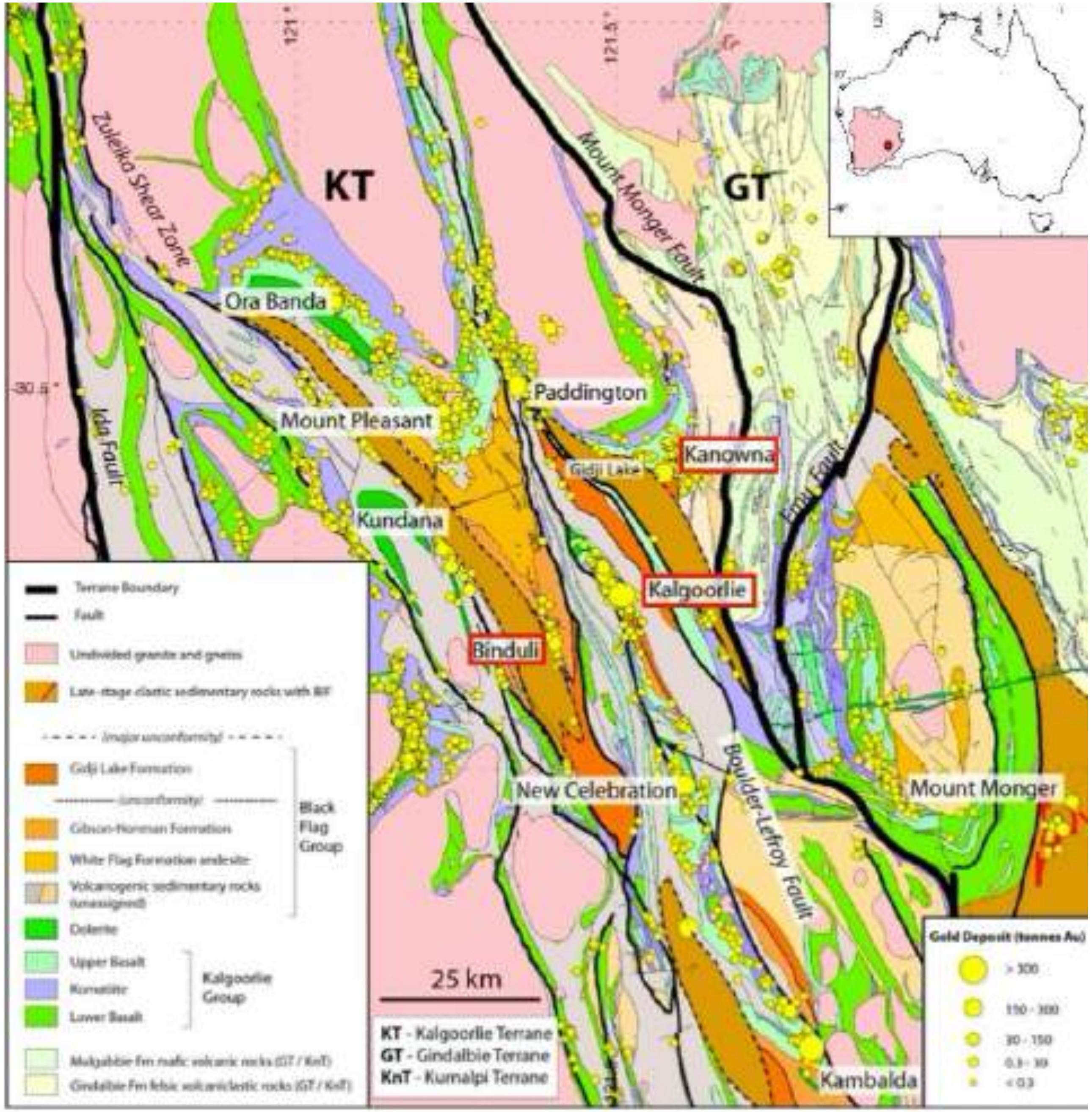
Ddaea

Kalgoorlie WA – A World Class gold district

- ~100 Million ounces of gold from 8 mining camps in a 50 km radius. **Almost 50% of EGP endowment.**
- Major camps include:

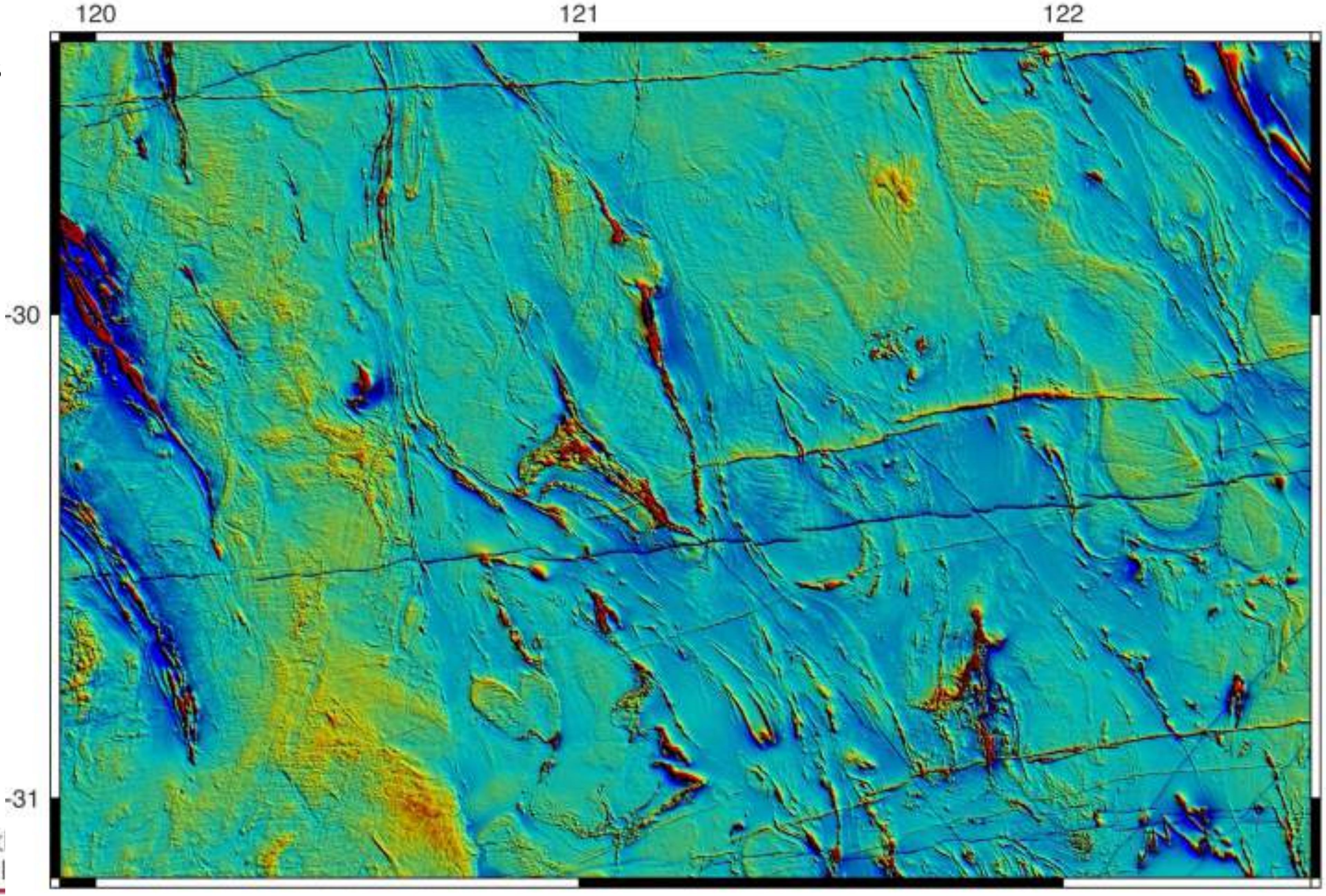
Golden Mile - **+60 M oz,** Kambalda/St Ives **+16 M oz,** Kanowna - **+7 M oz**, Kundana - **+5.5 M oz,** New Celebration - **+5 M oz**, Mount Pleasant - **+3 M oz,** Mount Monger **+2 M oz,** Binduli - **+2 M oz,** Ora Banda **+2 M oz**

- ***Regional scale*** spatial association of Kalgoorlie district with extensive preservation of late clastic rocks (youngest stratigraphy).
- ***Camp scale*** spatial association with unconformity internal to the Black Flag Group.
- 3 examples: Binduli, Kanowna, Fimiston – **Spatial juxtaposition of early and late mineralization styles.**



Slide courtesy of Gerard Tripp

Major NNW lineaments



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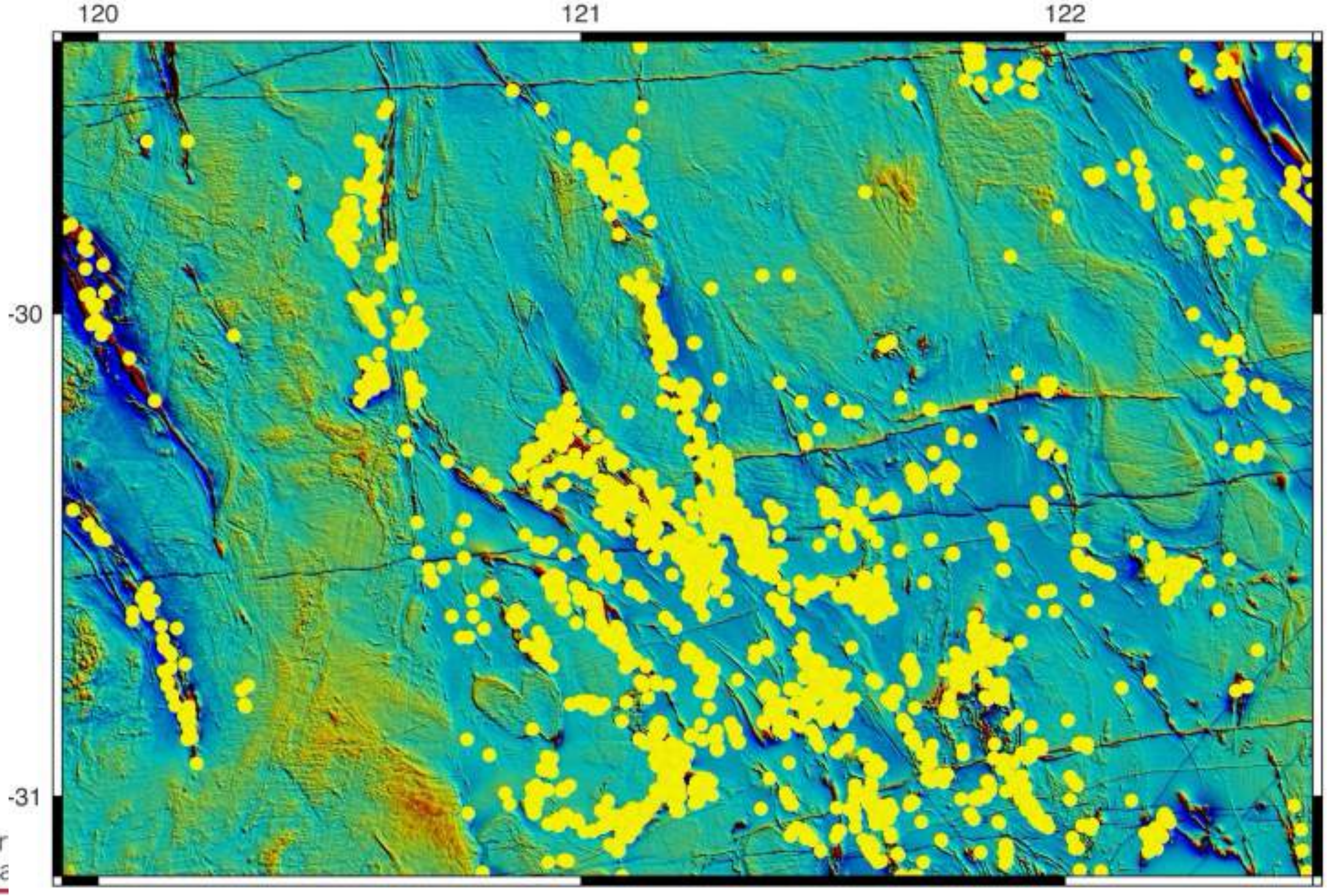

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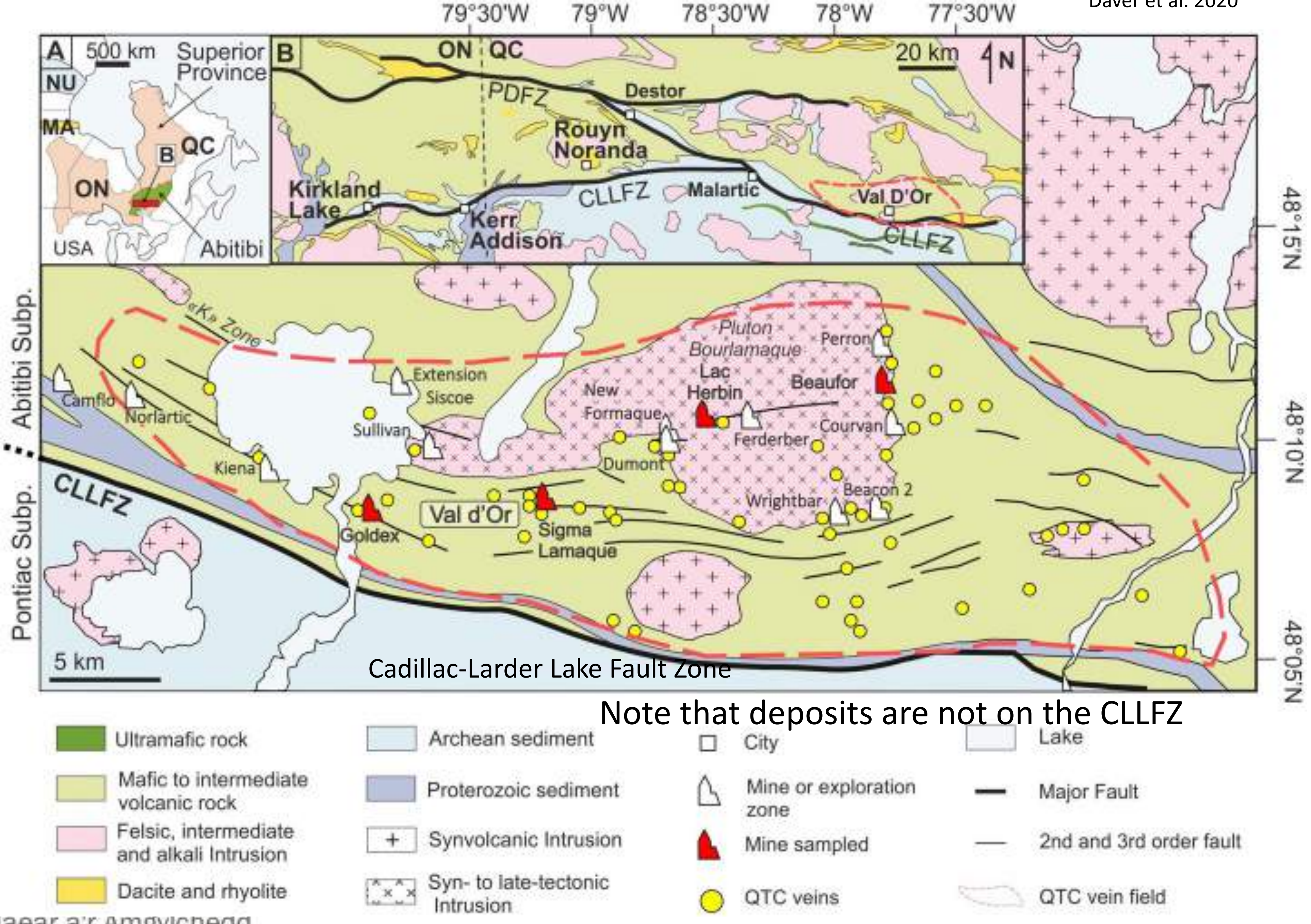
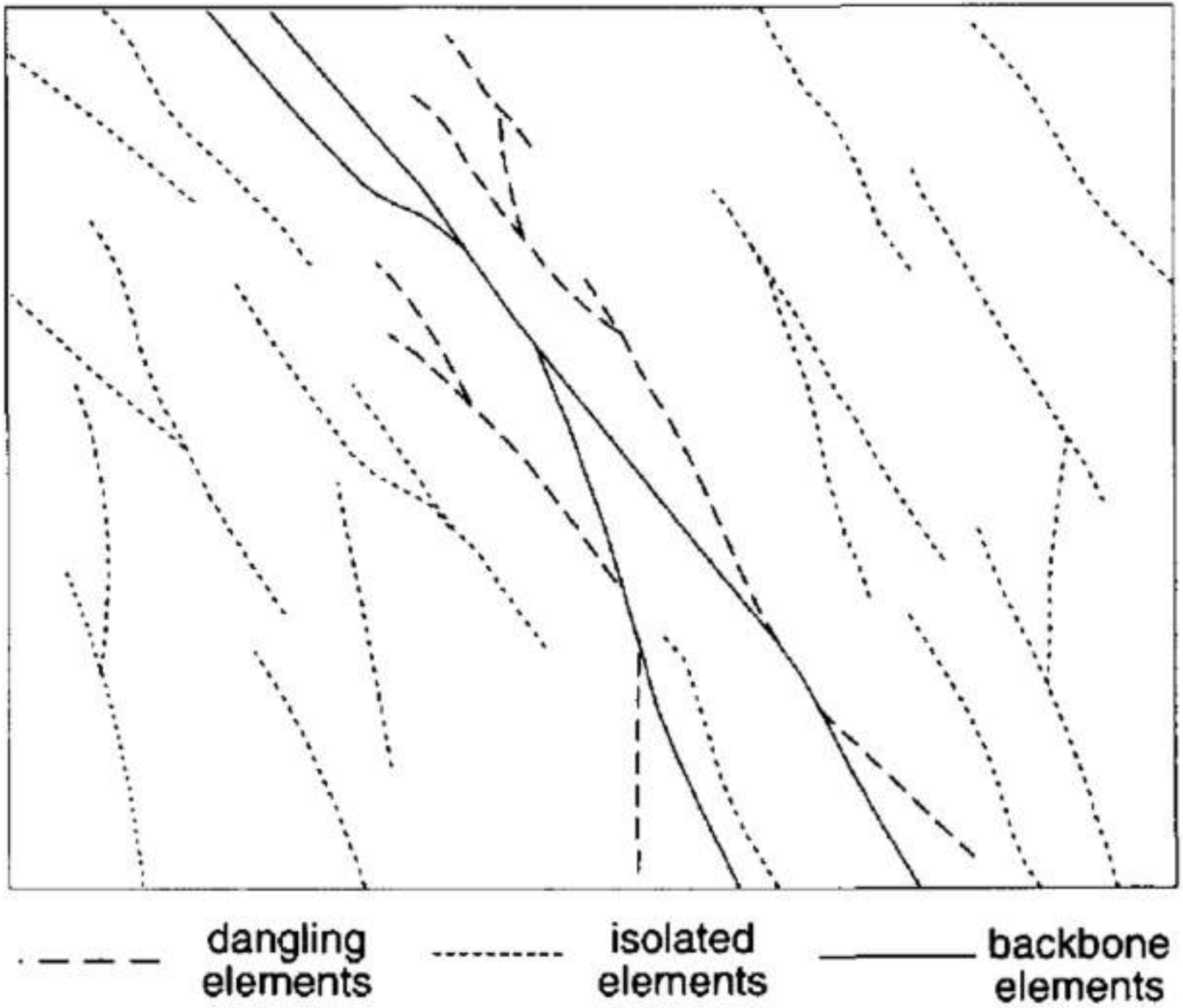
Superior craton: in detail gold deposits are not on major fault zones

Daver et al. 2020



Cadillac-Larder Lake Fault Zone

Note that deposits are not on the CLLFZ



Cox 1999

Topology and fracture connectivity

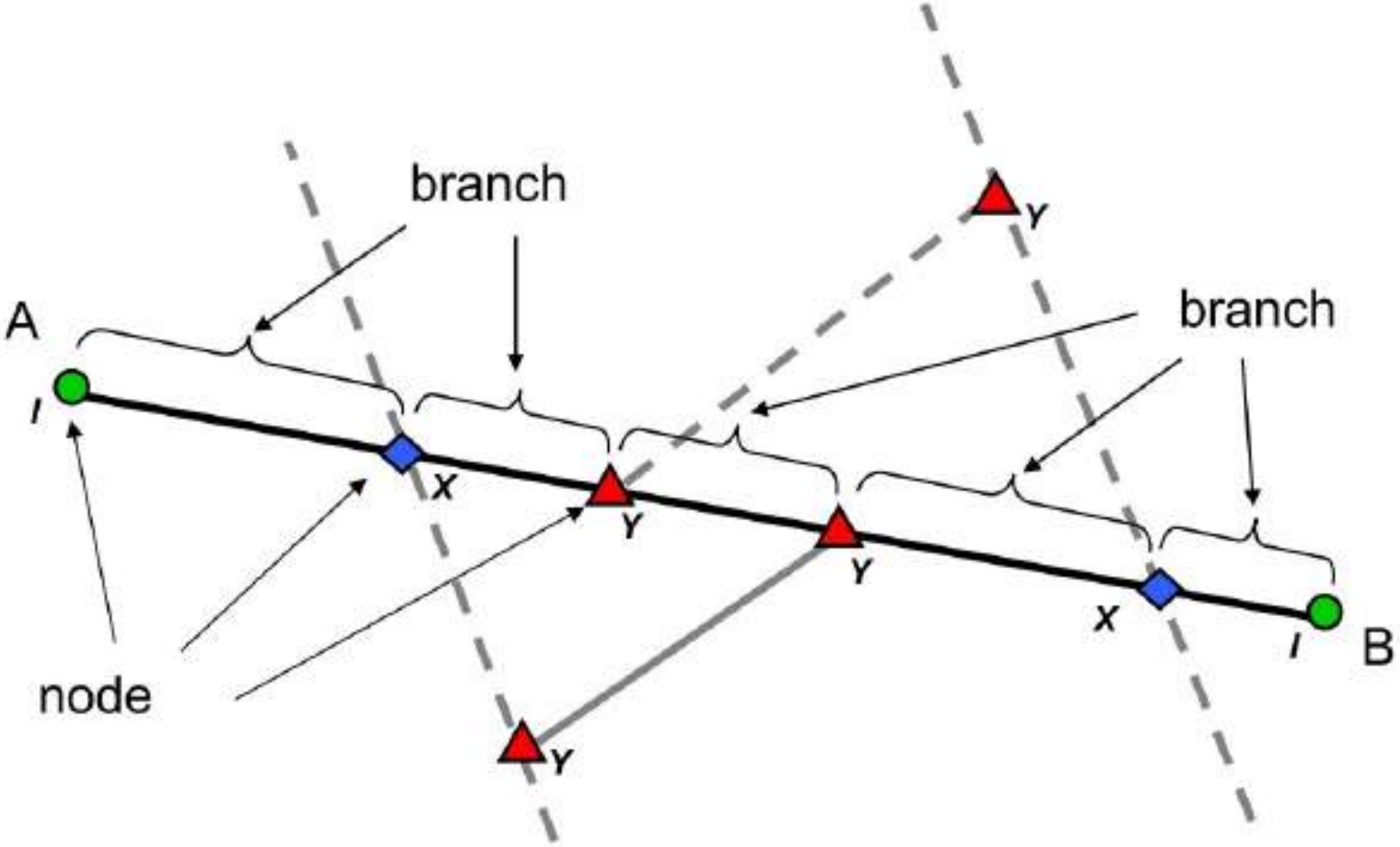


Fig. 1. Fracture trace (A–B), with associated intersecting fractures (dashed), showing arrangement of nodes and branches: *I*-nodes (circles); *Y*-nodes (triangles); *X*-nodes (diamonds).

Sanderson and Nixon 2015

Geometry

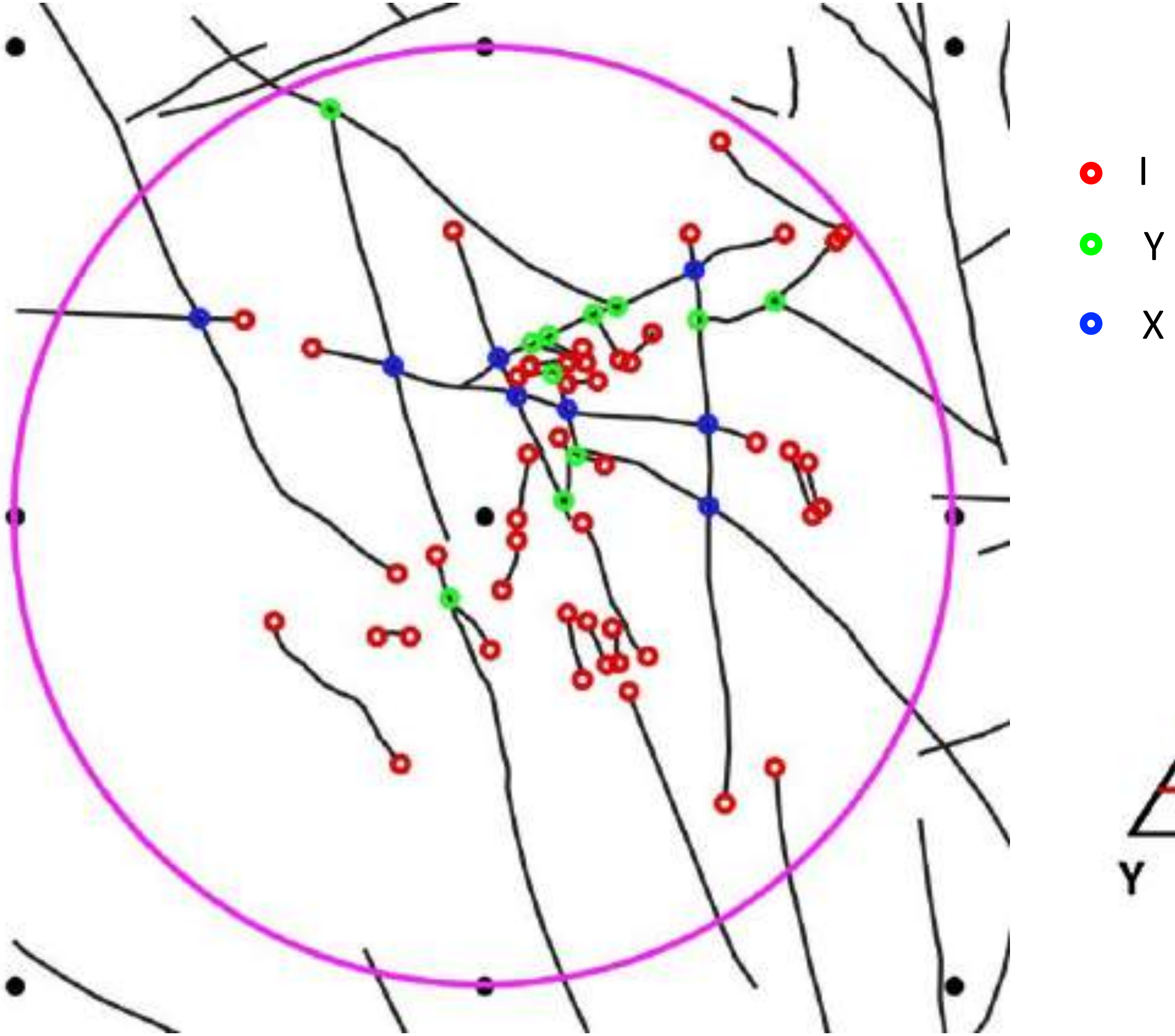
Network analysis

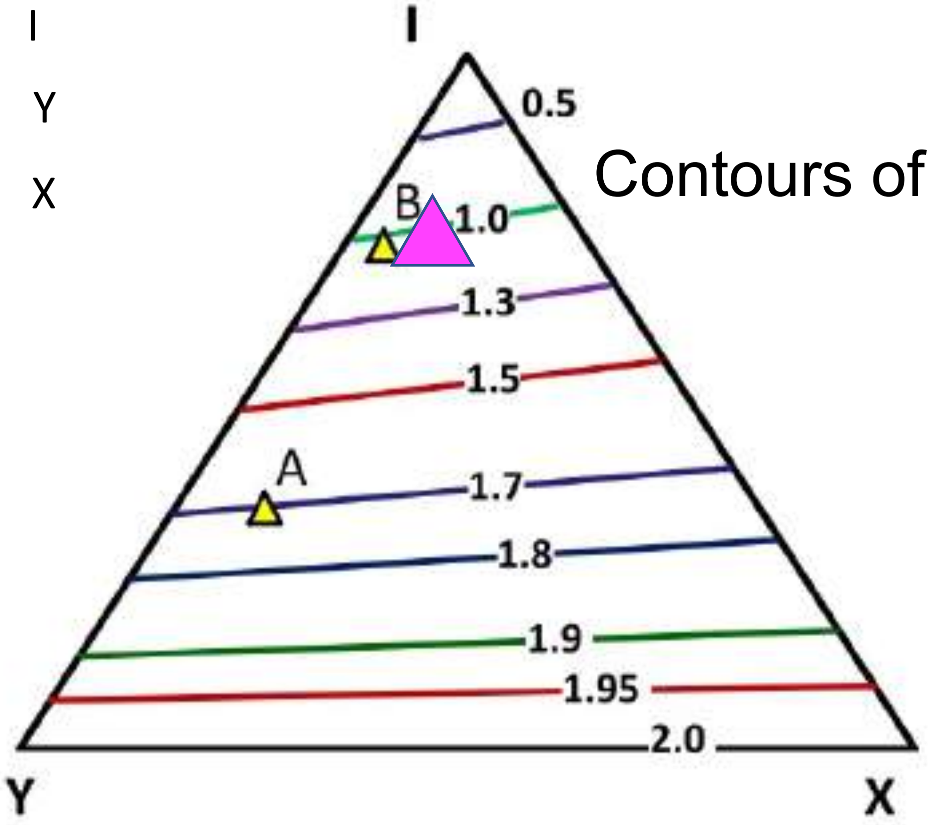
Intensity of Branches = n/4r

Connectivity of Branches,

CB = (NY + 4NX)/NB

= 2(NY + 4NX) /(NI+3NY+4NX)





Contours of CB

Sanderson and Nixon 2015

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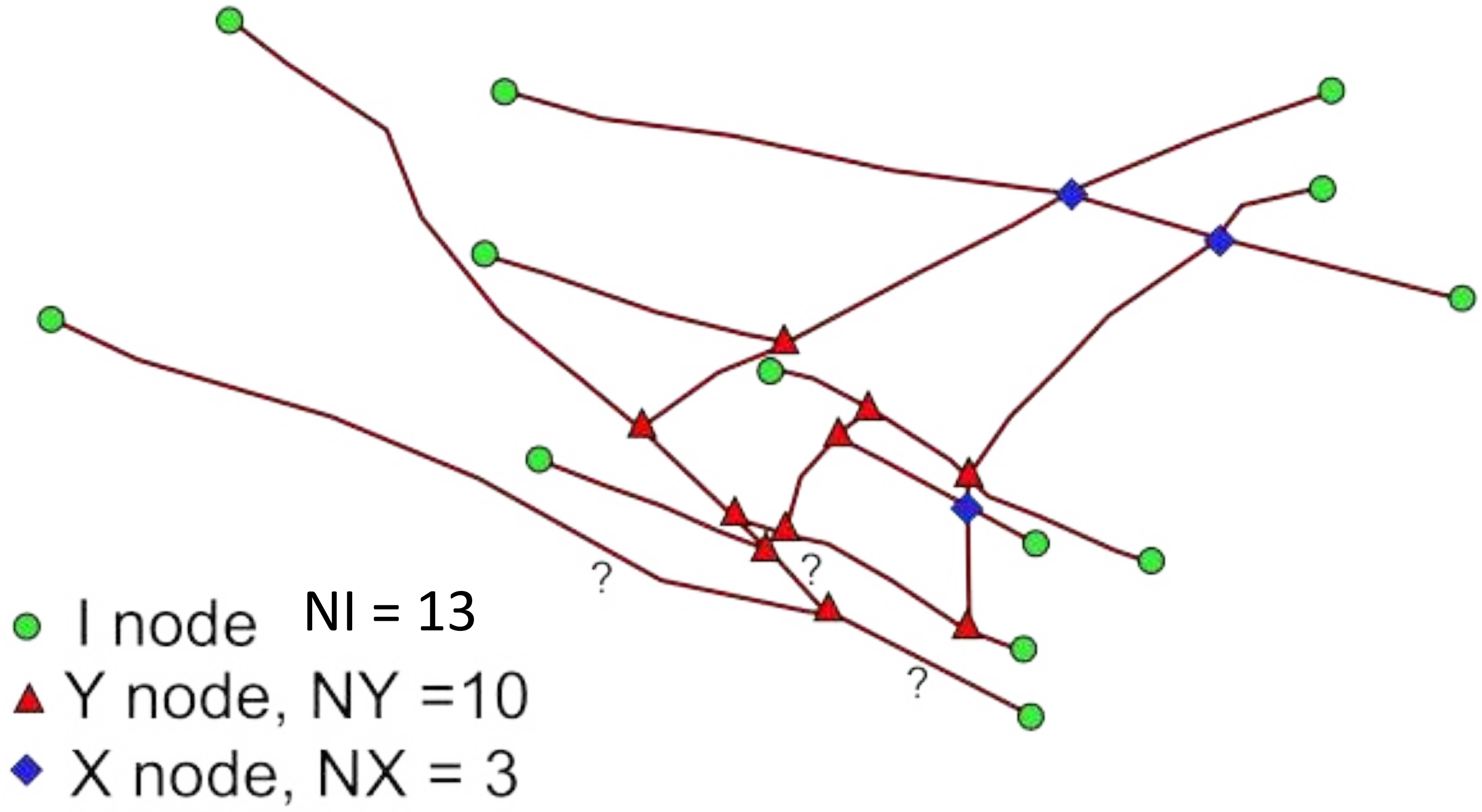
Geometry Network analysis

Example from Sunrise Dam Gold Mine, WA

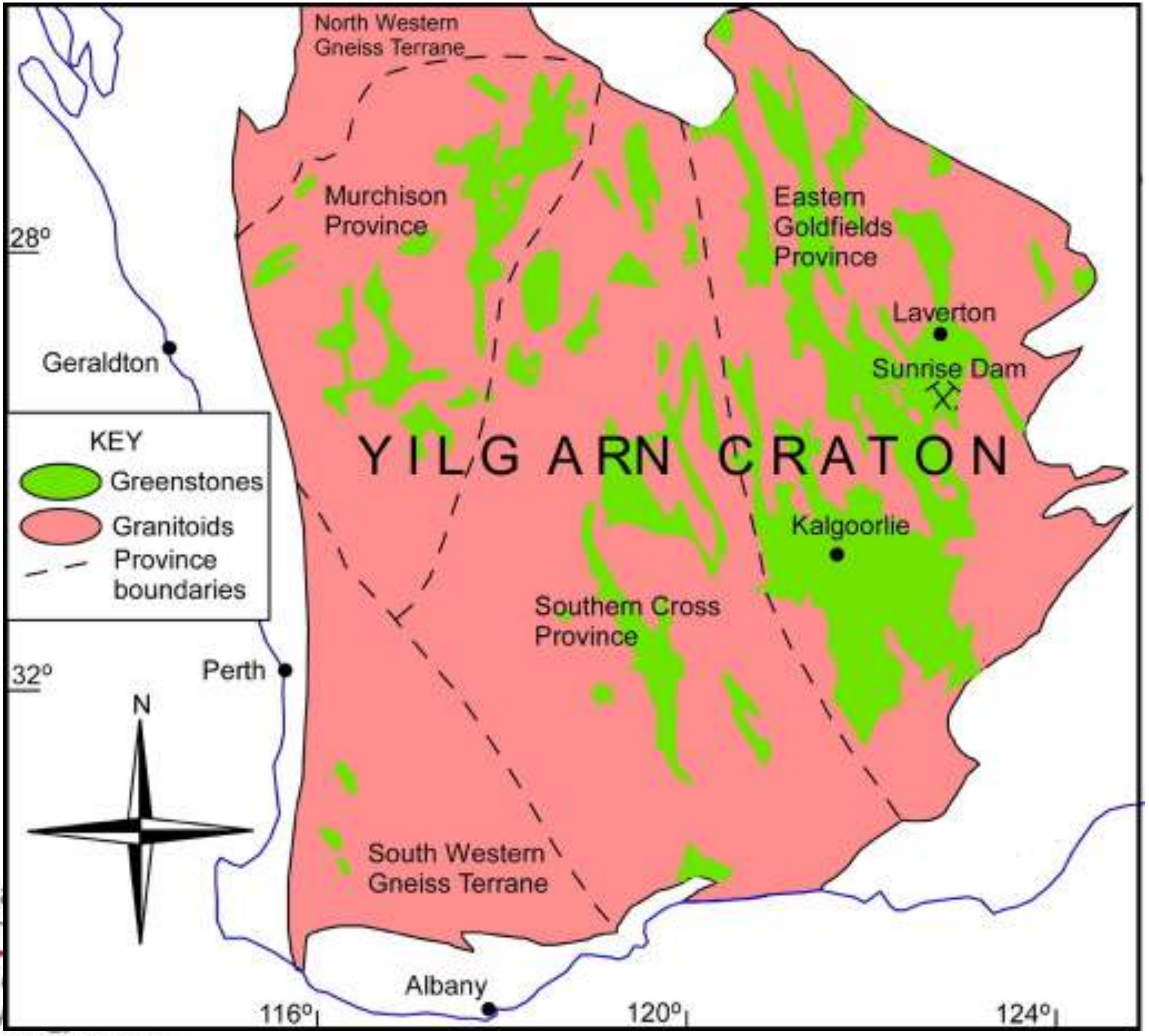


CB = (NY + 4NX)/NB
= 2(NY + 4NX) /(NI+3NY+4NX)
= 2(10+3)/(13+3*10+4*3)
=26/55
=0.47

Sanderson and Nixon 2015

Geometry

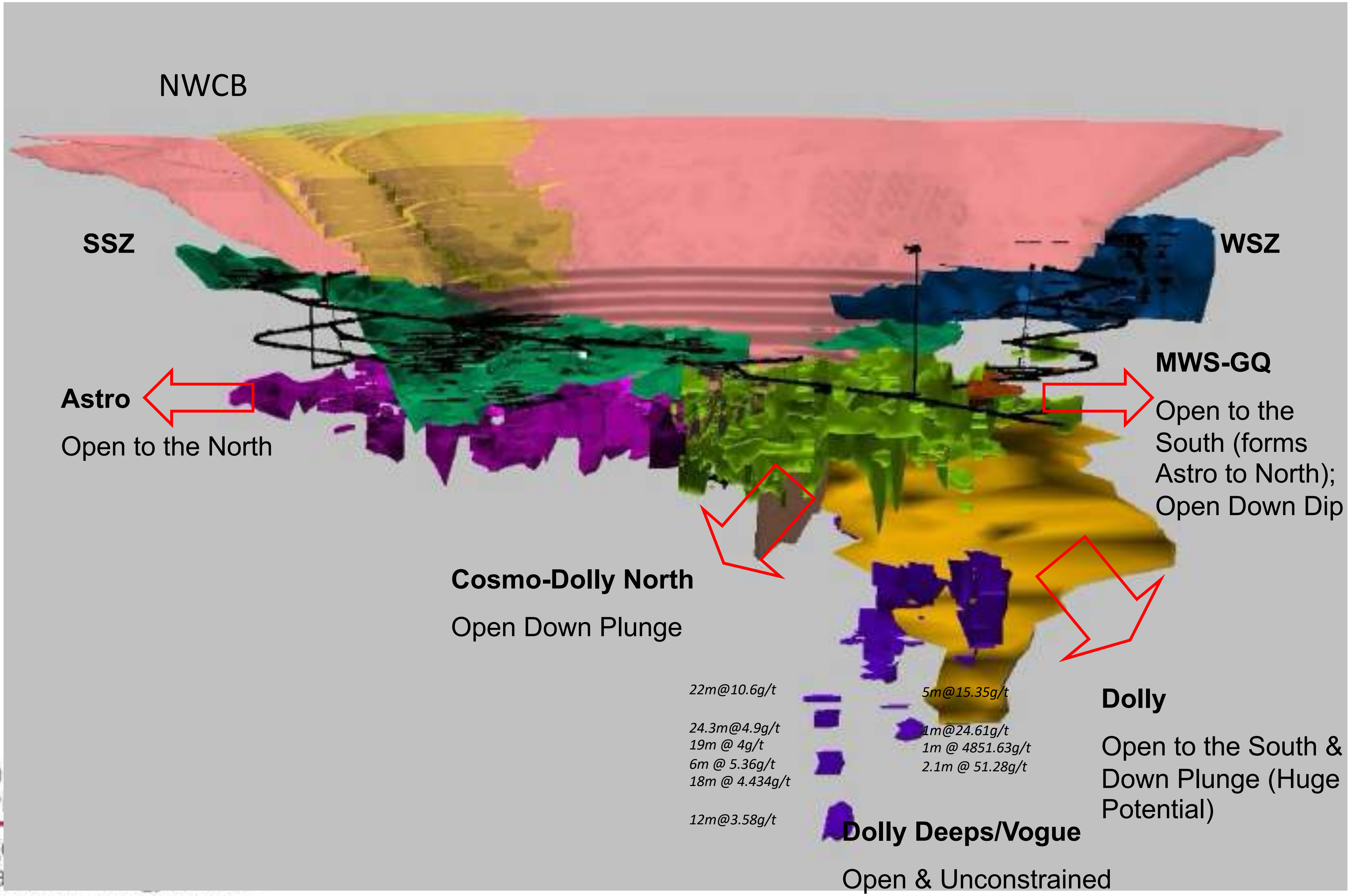
Sunrise Dam Gold Mine

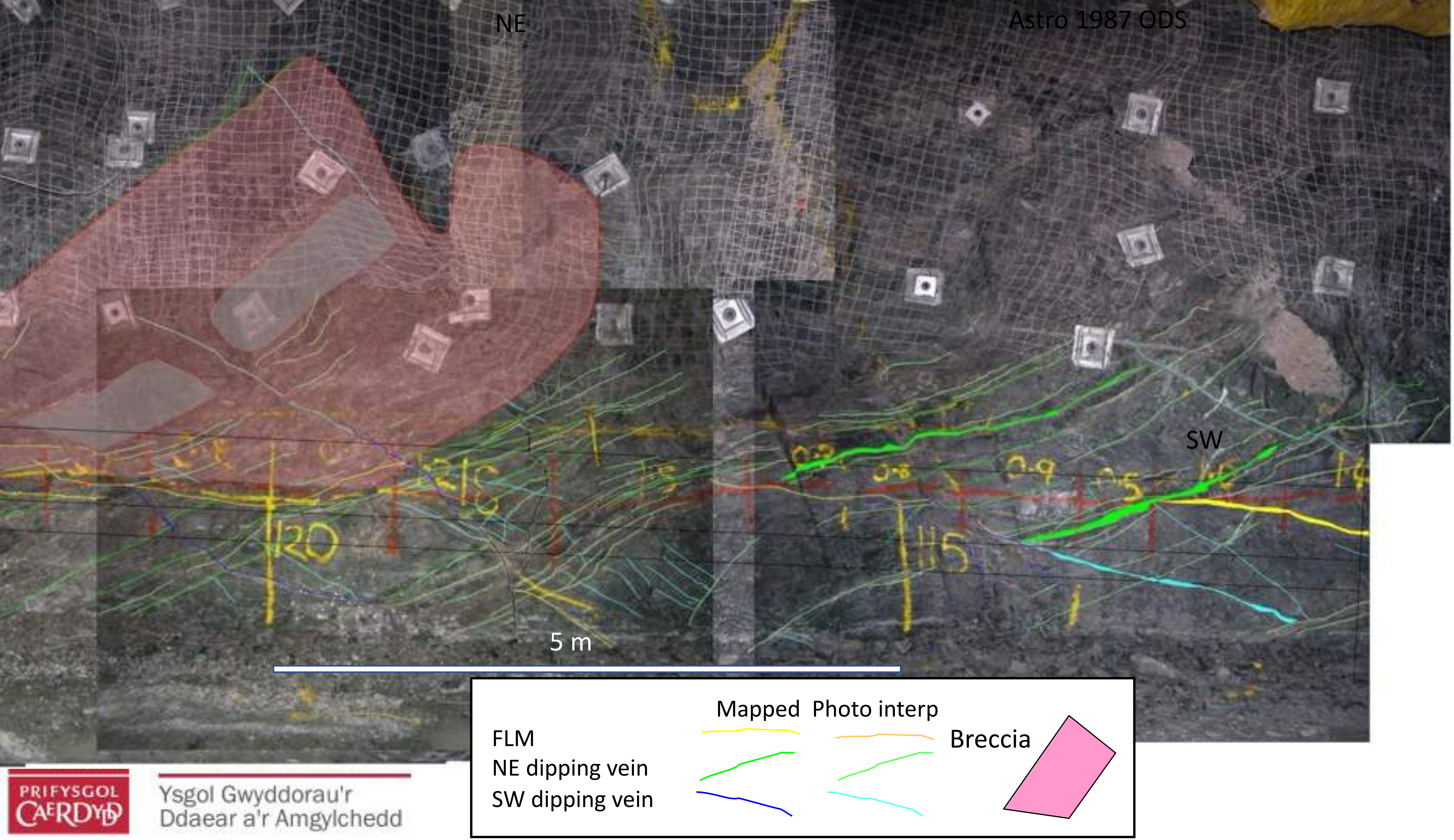


Resource
4 Moz

Geometry

Sunrise Dam Gold UG Lodes





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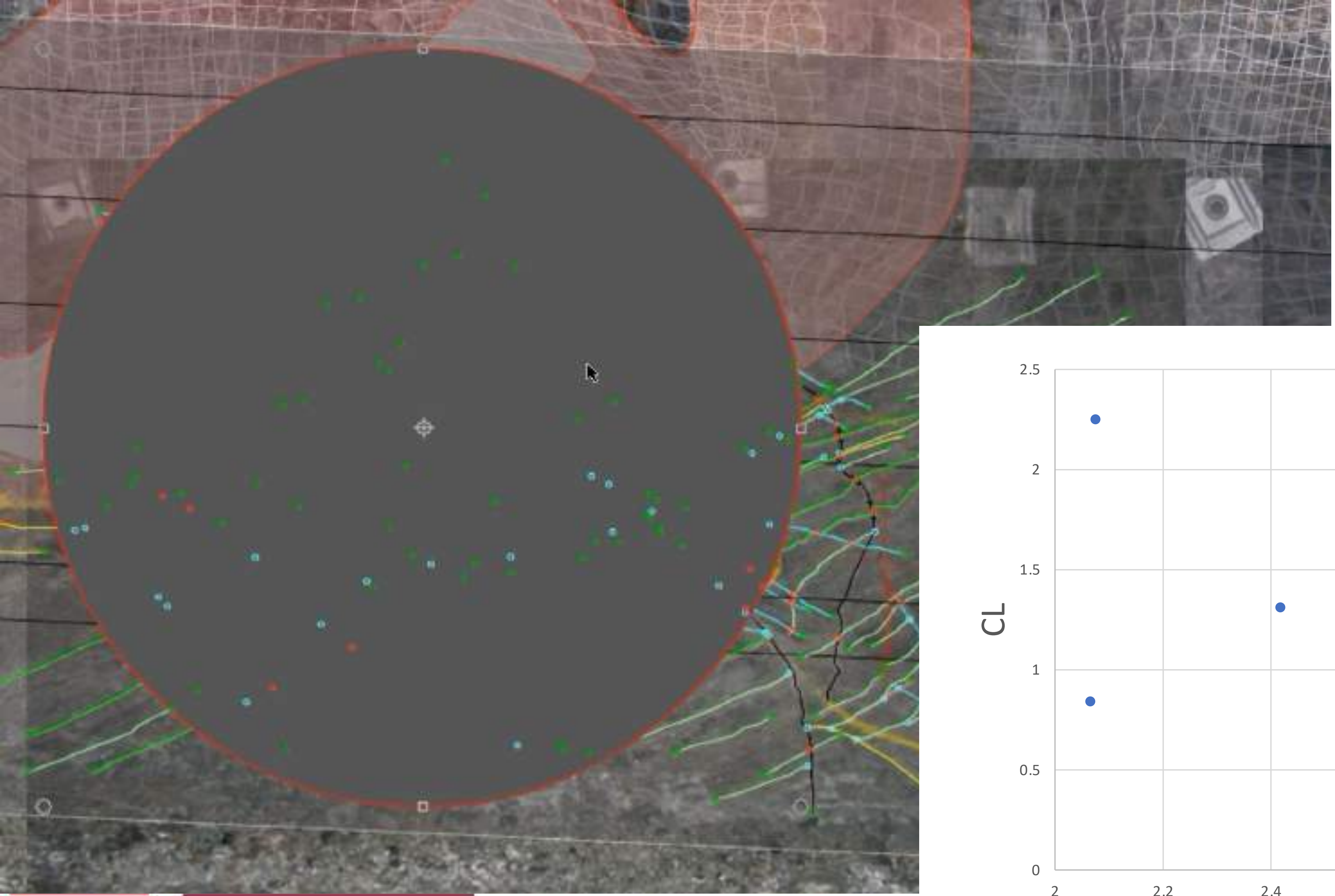
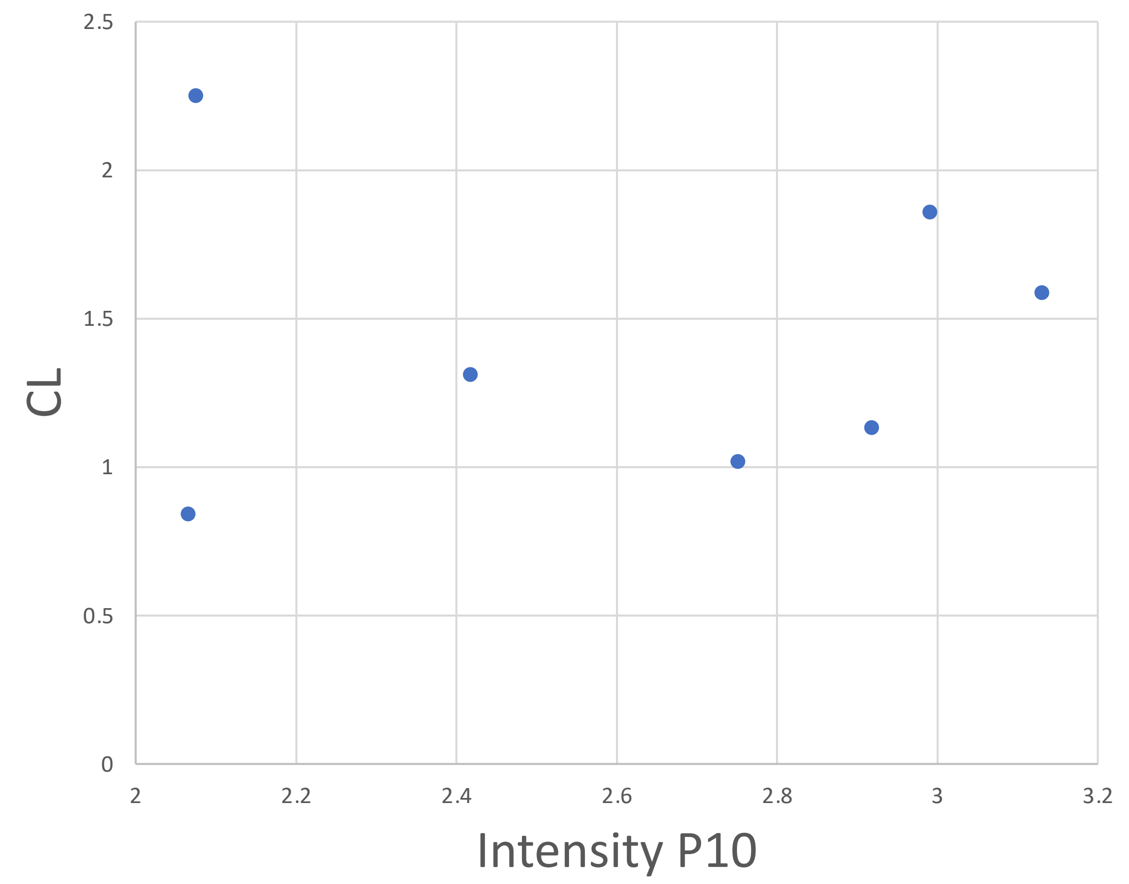
Sunrise Dam Gold Mine





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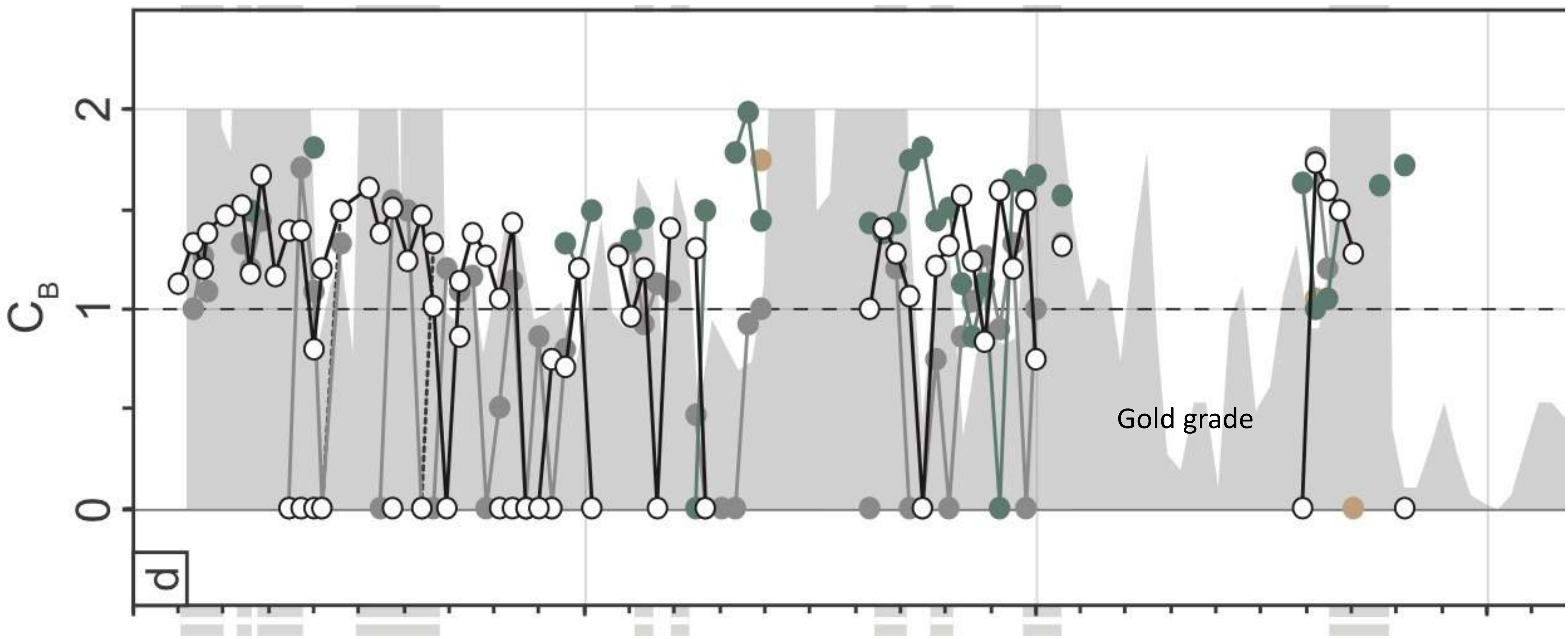

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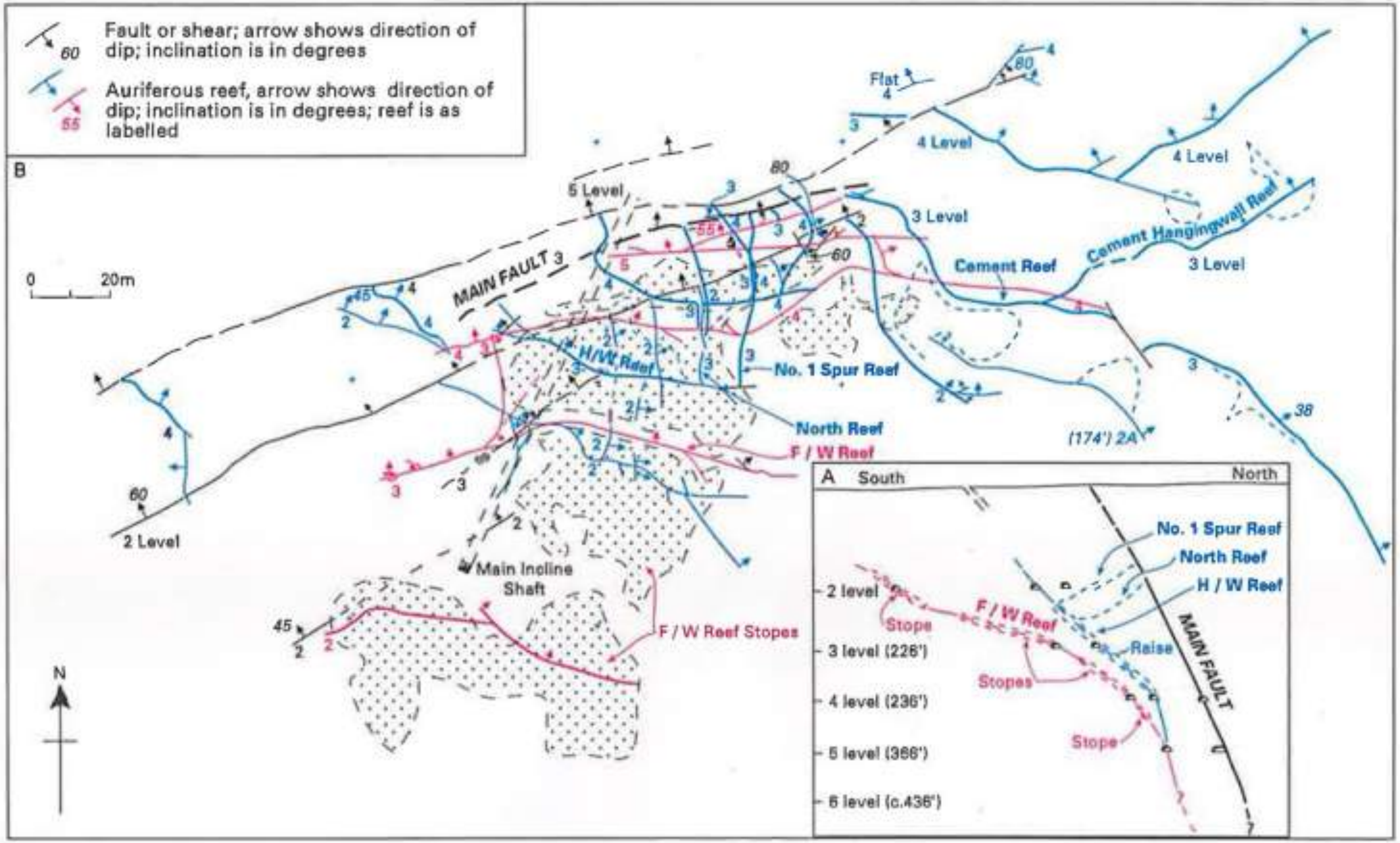
Turlin et al. 2019. Cheechoo gold deposit Eeyou Istchee James Bay area of Quebec

Techniques: Connectivity analysis

- Hopefield Mine, Harare Greenstone Belt



Conductivity *Qf* through a fracture of length *L*, aperture *a*

$$Qf = \frac{a^3 L\Delta p}{12\mu}$$

Δp = pressure drop
μ = viscosity

Conductivity *Qp* through a pipe of length *L*, radius *r*

$$Qp = \frac{\pi r^4 L\Delta p}{8\mu}$$

$$\Rightarrow \frac{Qp}{Qf} = \frac{1.5L}{a}$$

*L*ength/*a*perture relationships for veins and dykes

Host Rock	***L-a* relationship**	***L/a***	**Reference**
Quartzites Calcarenites Calcsilicates S M C	Power Law	20 - 2000	Johnston & McCaffrey 1996
L			
T			
E			
Basalt Dykes		1000	
Linear Elastic Fracture Mechanics	Linear	25-100000	Pollard 1987

Pipe flow is 1 -5 orders of magnitude more conductive than fracture flow

Conclusions

- Geometric analysis of structures, networks, and orebodies is the most basic step in analyzing hydrothermal gold deposits. Geometric analysis can include network topology.
- Faults are characterized by a core and damage zones
- Bends and Jogs are key structures for localizing ore bodies
- Contractional jogs and bends are just as potentially important as dilational jogs and bends
- Faults may form multiple sets rather than conjugates
- Deposits are related to major deformation zones
- However, they are commonly at some distance from the major deformation zone itself
- Faults from networks, for which connectivity can be evaluated.

Kupol epithermal gold mine, Russia

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Blenkinsop, T., Oliver, N., Dirks, P., Nugus, M., Tripp, G., & Sanislav, I. (2020). Structural geology applied to the evaluation of hydrothermal gold deposits. In *Reviews in Economic Geology, v.21* (pp. 1–23). https://doi.org/10.5382/rev.21.01

Fault slip data

Field/Seismological measurements
4 items:

- Dip of fault
- Dip bearing of fault,
- Pitch or Rake of slickenline
- Slip sense

Apartment building in La Guaira, Venezuela, on June 22, and on June 25 2026 after the earthquakes.Satellite image ©2026 Vantor

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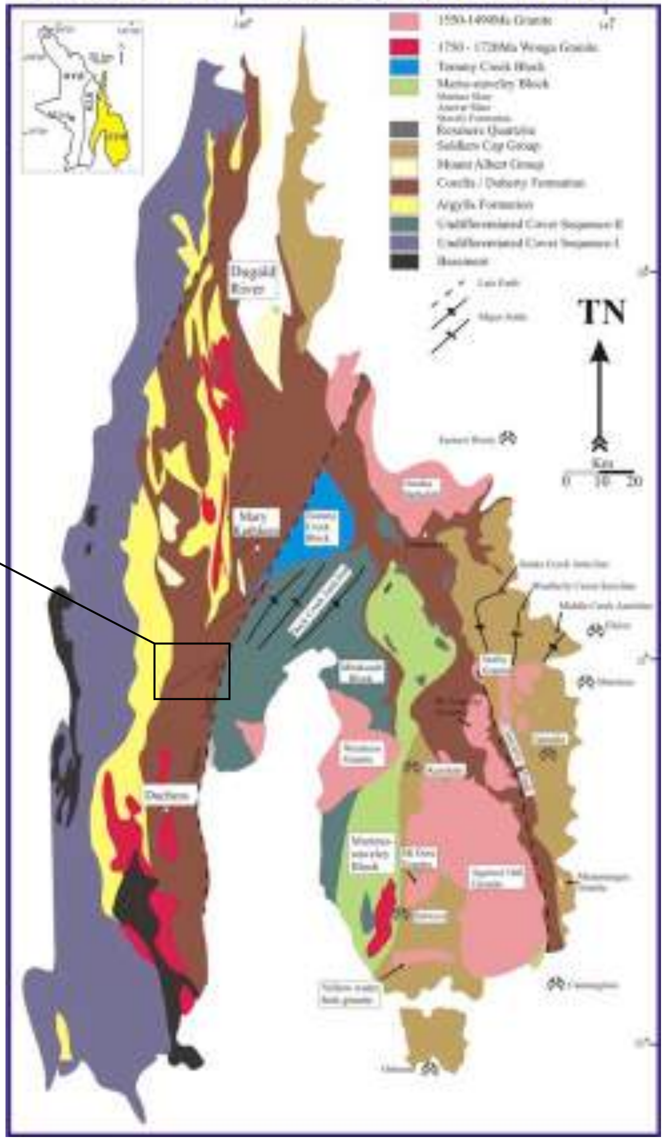
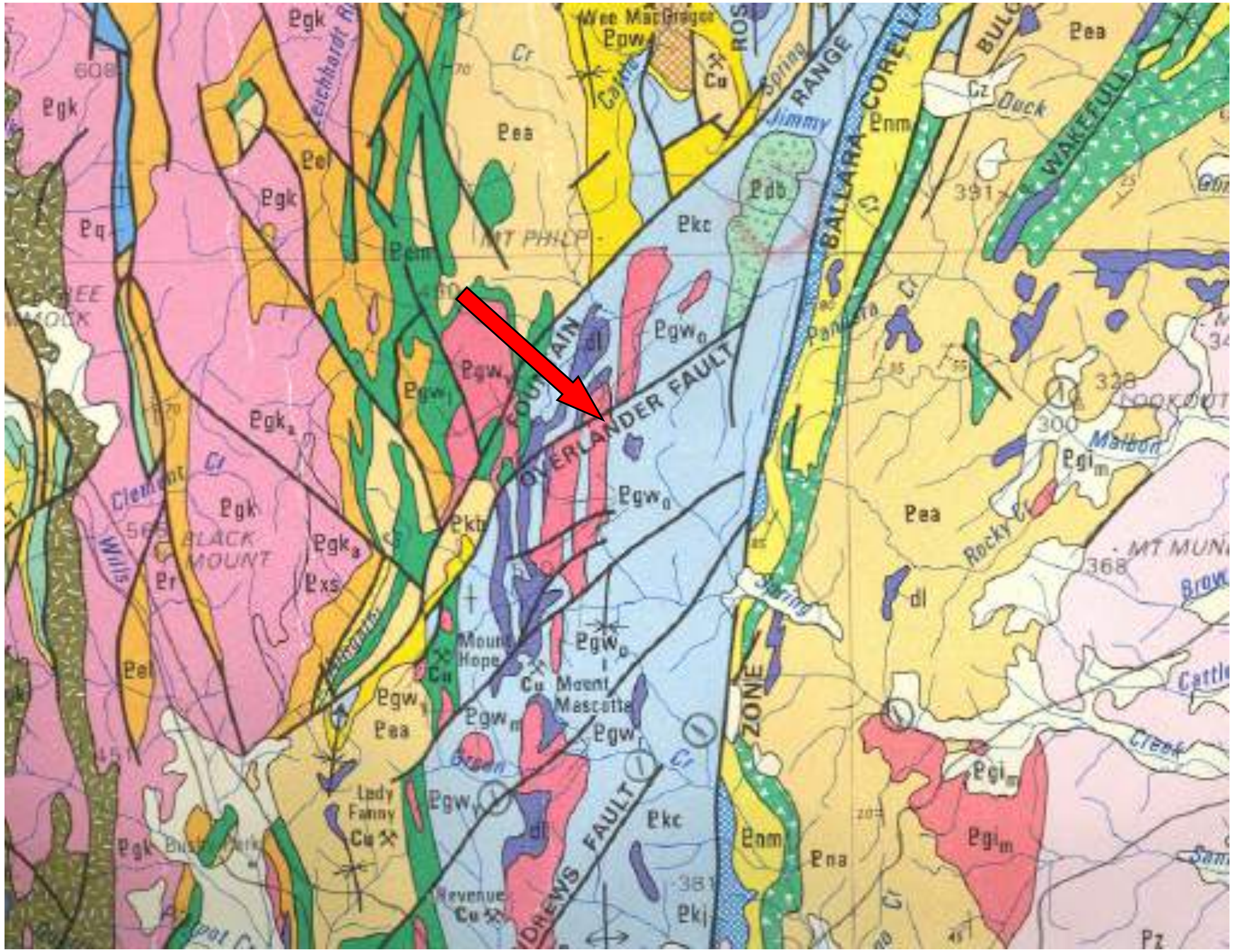
Example from the Overlander Fault, Mt Isa inlier

Eastern Succession, Mt Isa Inlier





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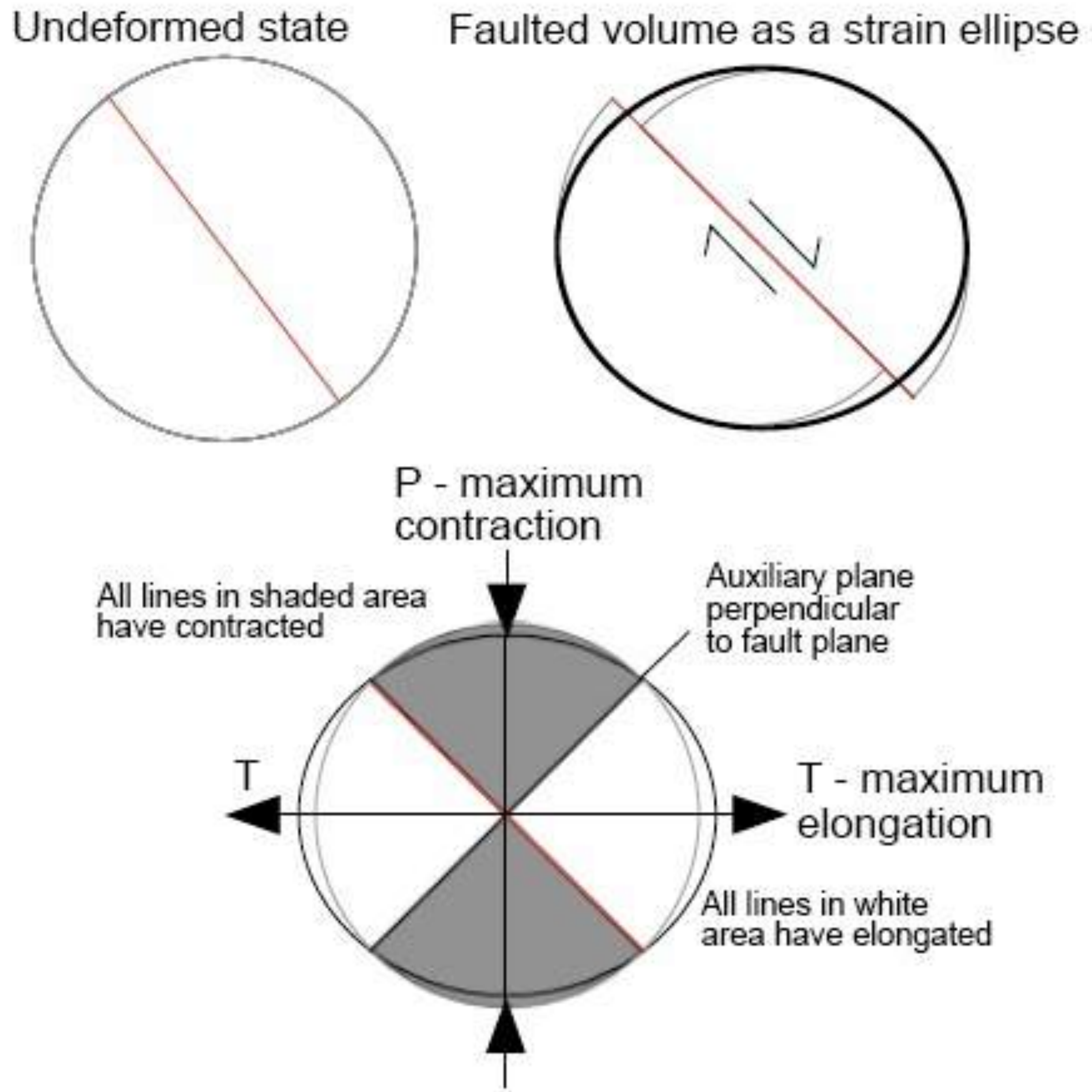
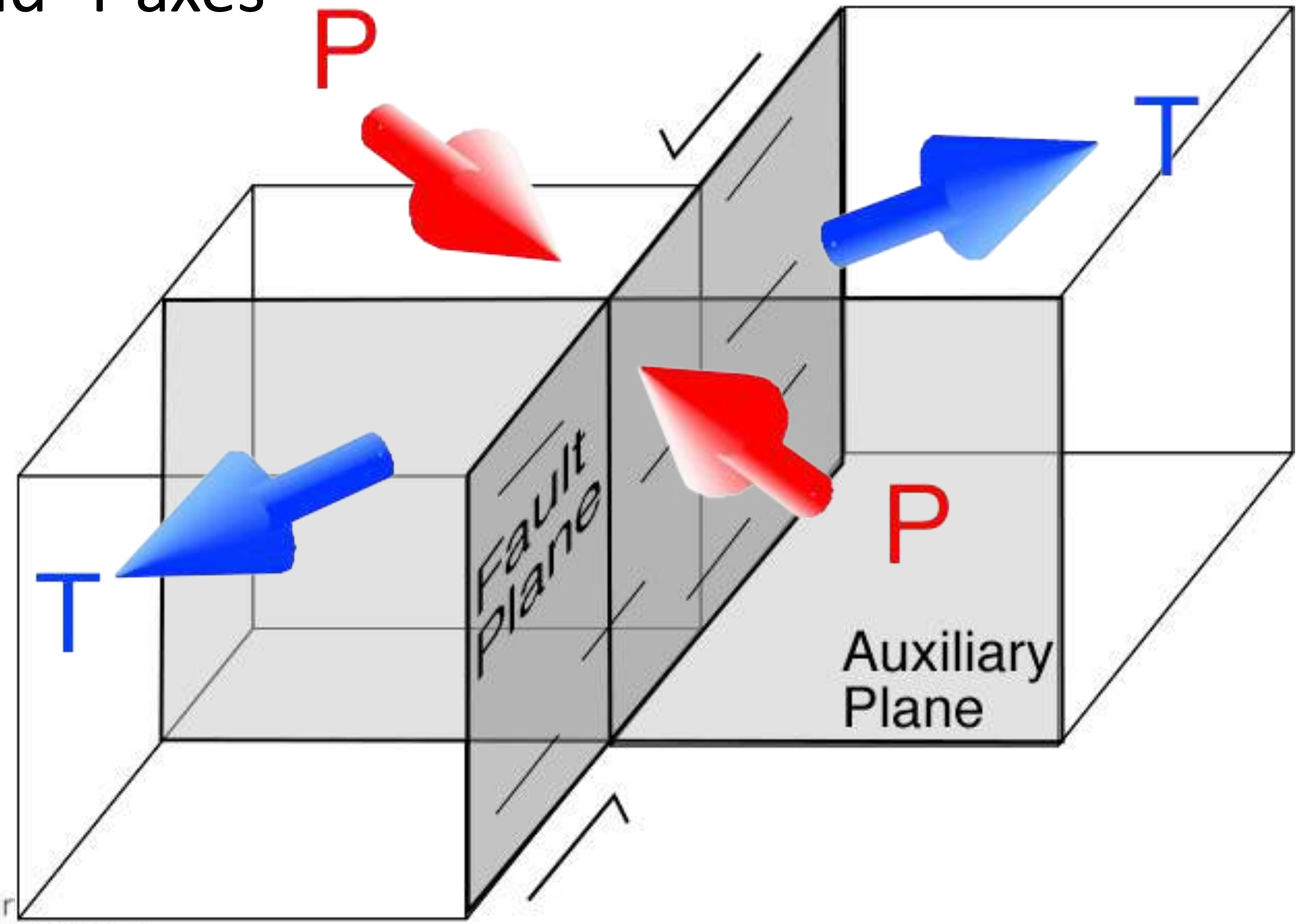
Method	Result
Fault Plane Solution = Moment Tensor Summation (linked Bingham axes = eigenvectors of PT) *Kinematic Analysis*	Principal Incremental strains, ε_3 and ε_1 (Extension positive)
Right Dihedra/ Trihedra *Dynamic Analysis*	Principal Stress Orientations of σ_1 and σ_3 (Compression positive)
Stress Inversion *Dynamic Analysis*	Reduced Stress tensor: Orientations of σ_1-σ_3, ϕ

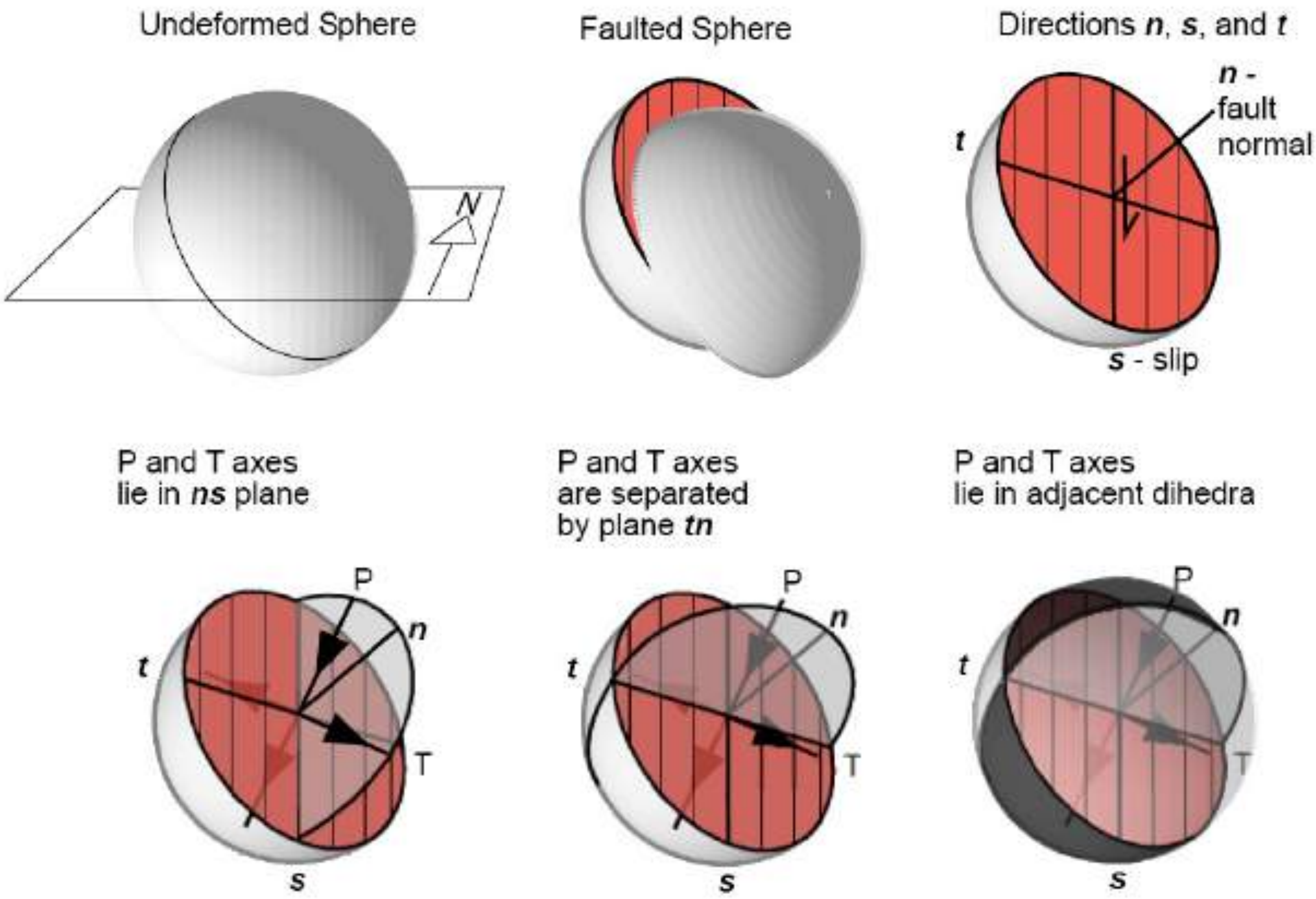
Principal strain axes of a fault in two dimensions



P and T axes



Principal infinitessimal strain axes of a fault in three dimensions



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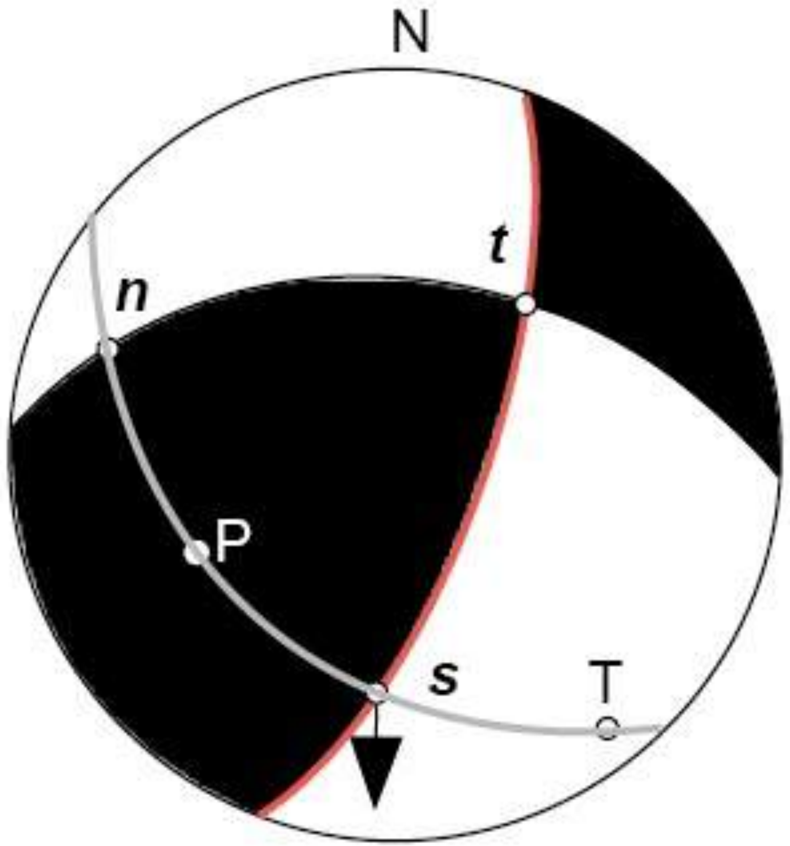
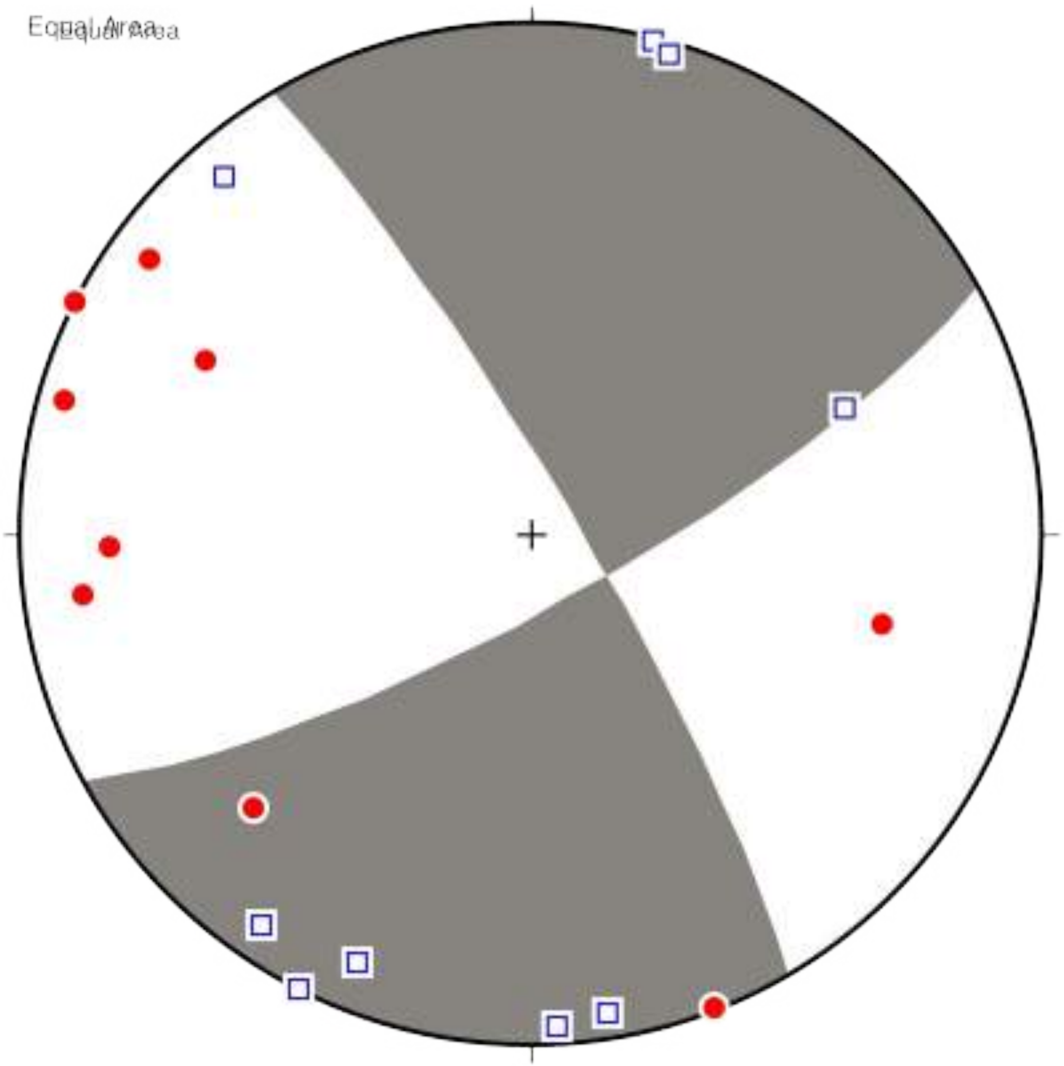


Lower hemisphere equal area stereoplot of P dihedra (black) and T dihedra (white). P and T axes lie in ***ns*** plane and bisect ***n*** and ***s***

P and T axis Plot   Fault Plane Solution (Beach Ball)



Overlander fault N = 9 subset

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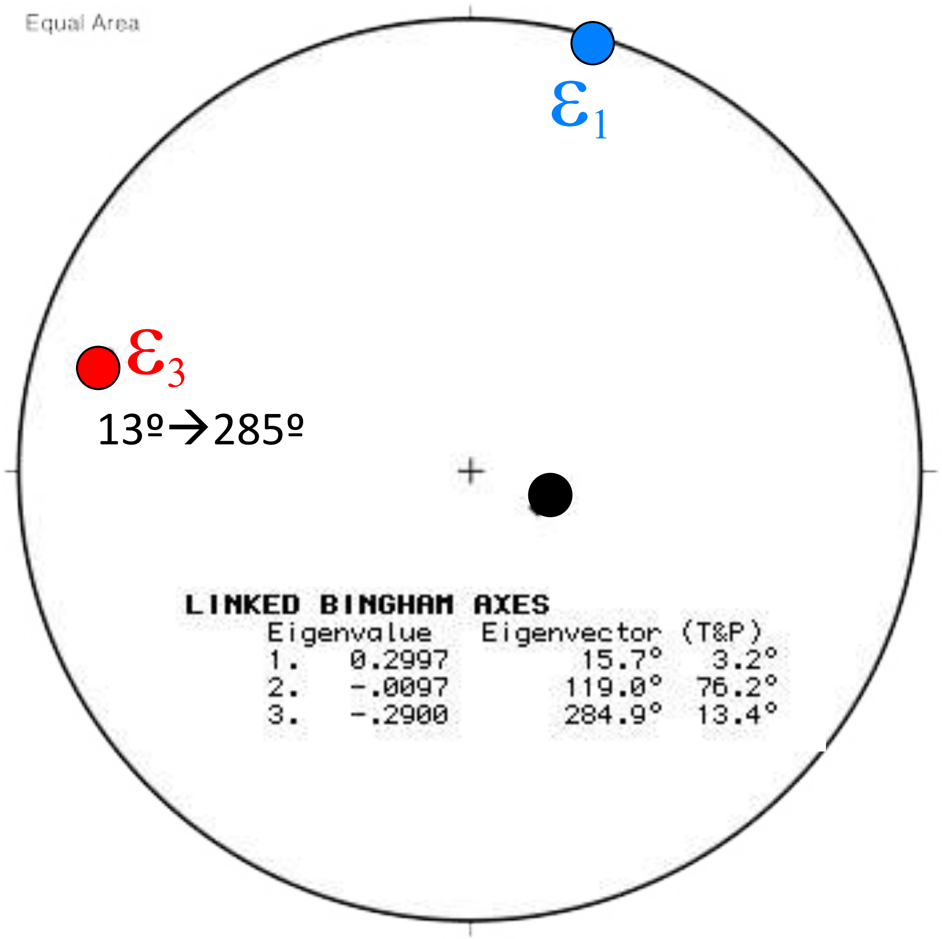
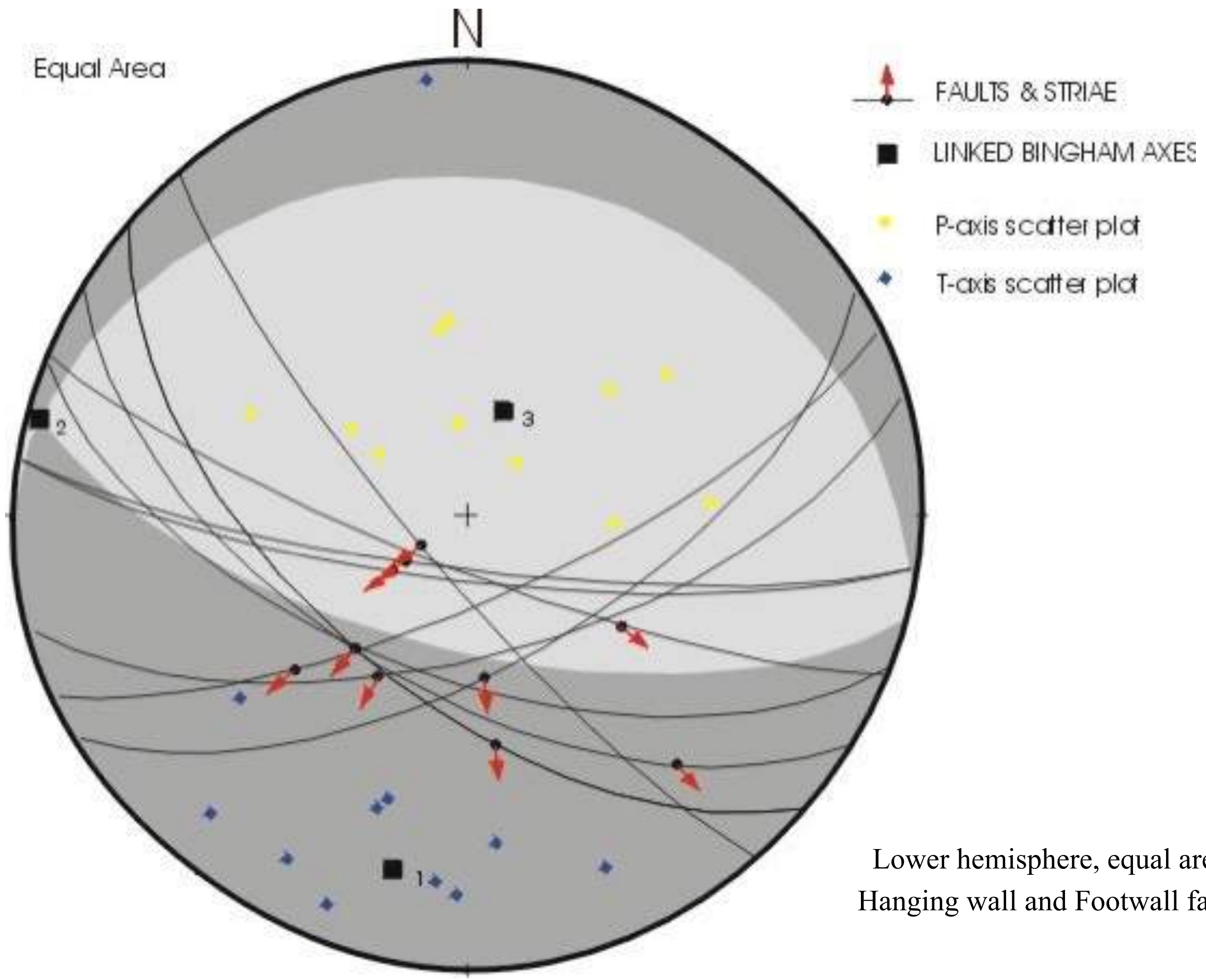
Moment Tensor Sum



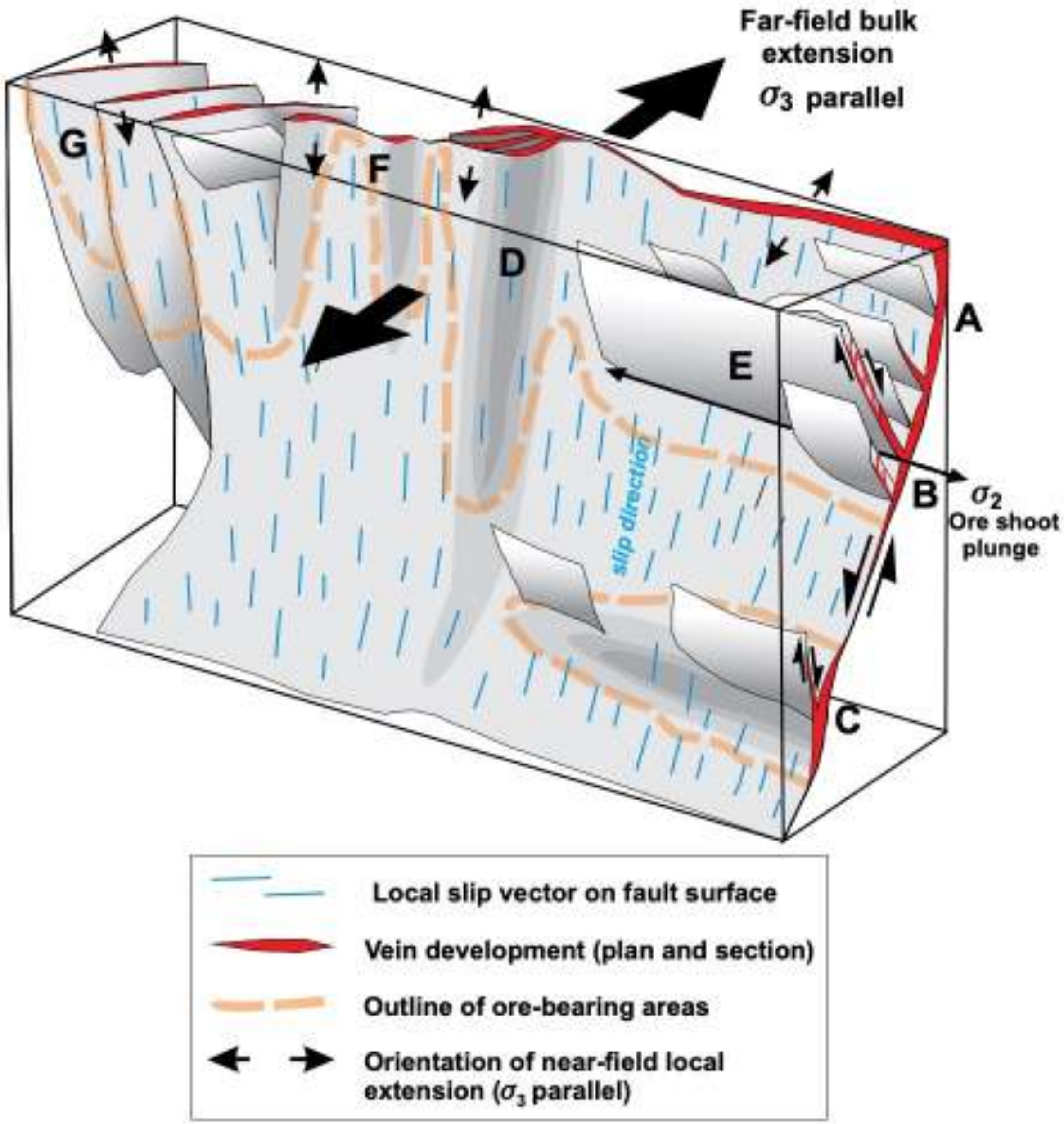
Overlander fault N = 9 subset

Moment Tensor Sum: Pajingo mine example

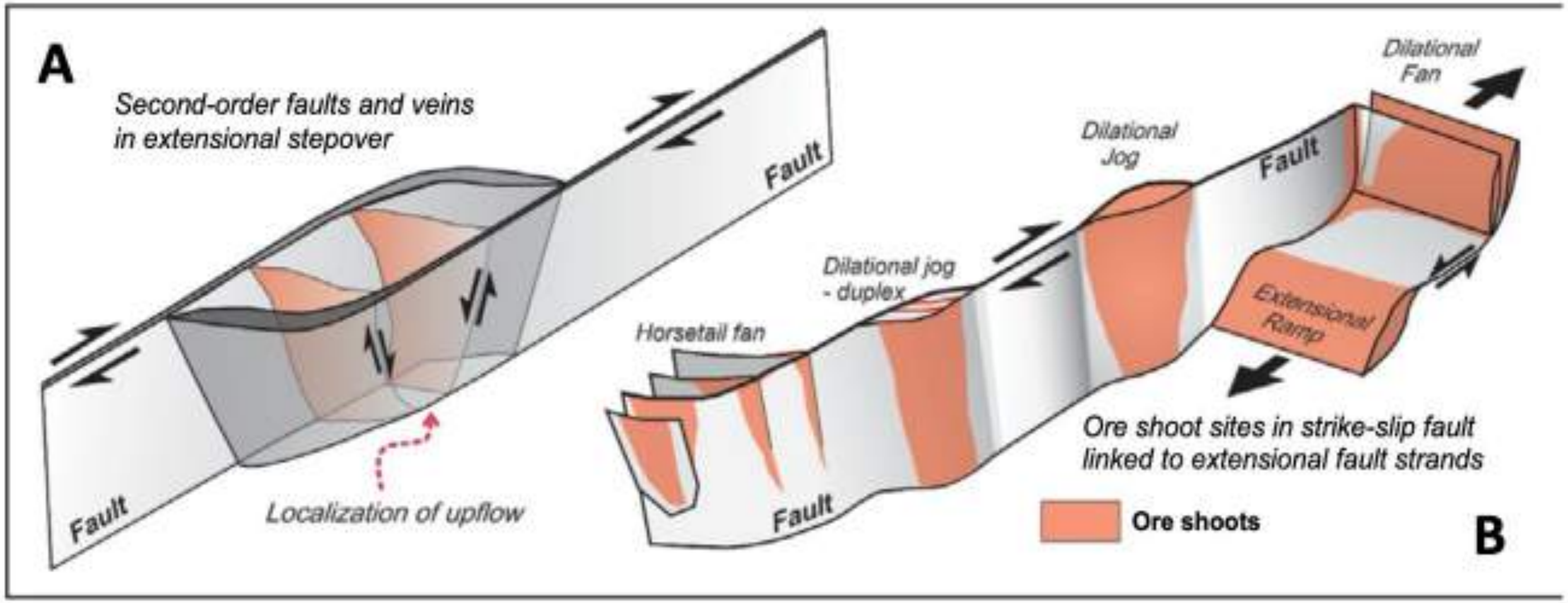


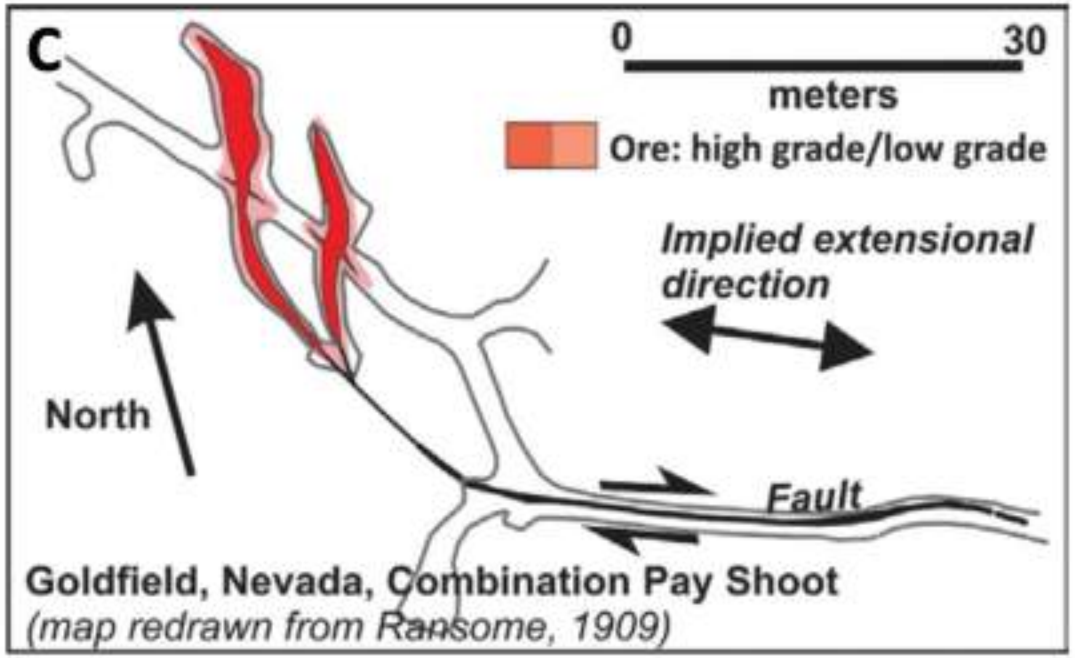
Lower hemisphere, equal area stereoplot for the Hanging wall and Footwall faults. N = 11

Epithermal Deposits



Rhys, David A., Peter D. Lewis, and Julie V. Rowland. 'Structural Controls on Ore Localization in Epithermal Gold-Silver Deposits: A Mineral Systems Approach'. In *Applied Structural Geologyof Ore-Forming Hydrothermal Systems*. Society of Economic Geologists, 2020. https://doi.org/10.5382/rev.21.03.





Rhys et al. 2020
Transtension

Summary

- Kinematic analysis means finding P and T axes for faults or small shear zones
- Fault and slip orientation and sense are needed
- The Moment Tensor Sum is the best fit to the P and T axes
- The P and T axes can be interpreted as the principal strain axes for the faulting event
- These can be used to understand the boundary conditions for deformation and fluid flow

References

Blenkinsop, T. G. (2004). Orebody geometry in lode gold deposits from Zimbabwe: implications for fluid flow, deformation and mineralization. *Journal of Structural Geology*, *26*(6–7), 1293–1301. https://doi.org/10.1016/j.jsg.2003.11.010

Blenkinsop, T.G., and Kadzviti, S., 2006, Fluid flow in shear zones: Insights from the geometry and evolution of ore bodies at Renco gold mine, Zimbabwe: Geofluids, v. 6, p. 334–345.

Blenkinsop, T. G., Dirks, P. G. H. M., Nugus, M., Tripp, G., & Sanislav, I. (n.d.). Structural geology applied to the evaluation of hydrothermal gold deposits. *Reviews in Economic Geology*. https://doi.org/10.5382/rev.00.00

Carvell, J., Blenkinsop, T., Clarke, G., and Tonelli, M., 2014, Scaling, kinemat- ics and evolution of a polymodal fault system: Hail Creek mine, NE Aus- tralia: Tectonophysics, v. 632, p. 138–150, doi:10.1016/j.tecto.2014.06.003.

Healy, D., Blenkinsop, T. G., Timms, N. E., Meredith, P. G., Mitchell, T. M., & Cooke, M. L. (2015). Polymodal faulting: Time for a new angle on shear failure. *Journal of Structural Geology*, *80*. https://doi.org/10.1016/j.jsg.2015.08.013

Kisters, A. F. ., Kolb, J., Meyer, F. M., & Hoernes, S. (2000). Hydrologic segmentation of high-temperature shear zones: structural, geochemical and isotopic evidence from auriferous mylonites of the Renco mine, Zimbabwe. *Journal of Structural Geology*, *22*(6), 811–829. https://doi.org/10.1016/S0191-8141(00)00006-7

Sanderson, D.J., and Nixon, C.W., 2015, The use of topology in fracture network characterization: Journal of Structural Geology, v. 72, p. 55–66, doi:10.1016/j.jsg.2015.01.005.