# Stresses in the Australian Continental Tectonic Plate - Variability and Likely Controls

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## Why am I in Ballarat?

**Spying - looking over the fence!!**

**We "miners" have ground control / stability issues associated with seismic events, particularly in deep "highly stresses' underground mines.**

**While we have a range of procedures and techniques for "predicting" and "managing" these events, they do not always work ….**

**So …… what can I find out about your approach to earthquake engineering? ……. and are there equivalent applications to stability issues in mines**

**Exchange information**

**What can I tell you "earth-quakers" about rock stresses, which we "miners" think we know something about, and which should be of fundamental interest to you quakes?**

## Earthquakes

**Definition:**

**SIGNIFICANT SUDDEN PACKAGES OF NATURALLY RELEASED ENERGY – THAT ARE OF SOCIAL AND (CIVIL) ENGINEERING INTEREST**

**Characteristics:**

- Location (longitude, latitude and depth)
- Duration (tens of seconds?)
- Magnitude / Moments
- Frequency
- Focal mechanism
- Associated with shearing on specific and regional geologic features



## Seismic Events

**Definition:**

**SUDDEN PACKAGES OF NATURAL + MINING-INDUCED STRAIN ENERGY – THAT ARE OF SOCIAL AND (MINING + CIVIL) ENGINEERING INTEREST**

**Characteristics:**

- Location (northing, easting, RL)
- Duration (a few seconds – similar to large stope blasts)
- Magnitude / Moments
- Frequency (high to low)
- Focal mechanism (shear, explosive, implosive)
- Associated with specific structures, failure through intact rock and collapse

## Seismic Events in Mines - Underground

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## Seismic Events in Mines - Underground


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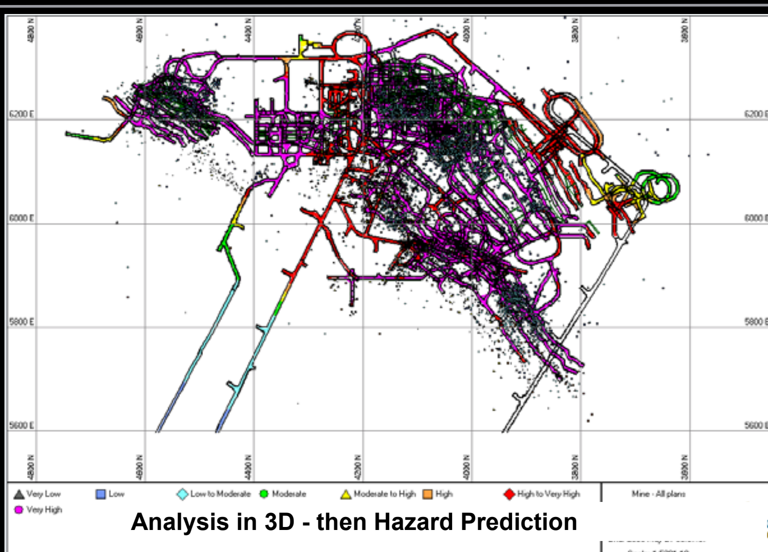
## Surface Damage - also possible

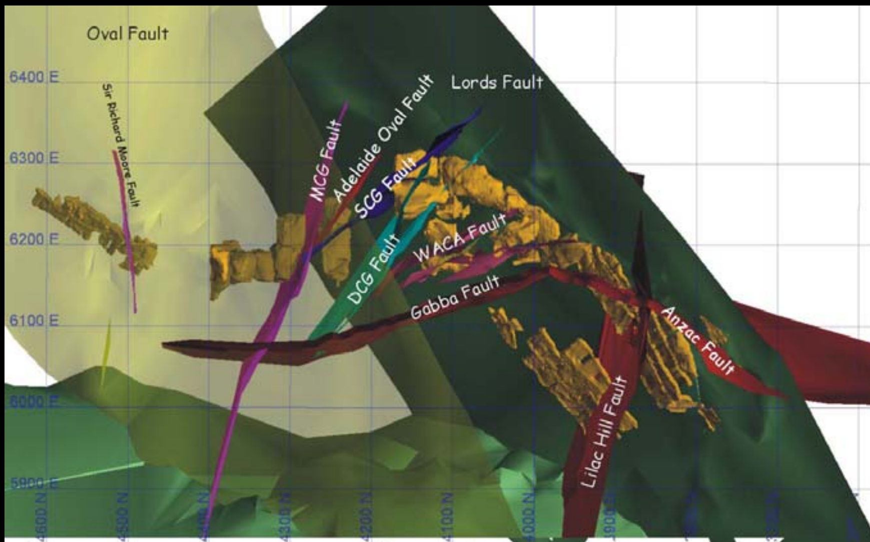


## Seismic Events – Monitoring and Hazard Prediction



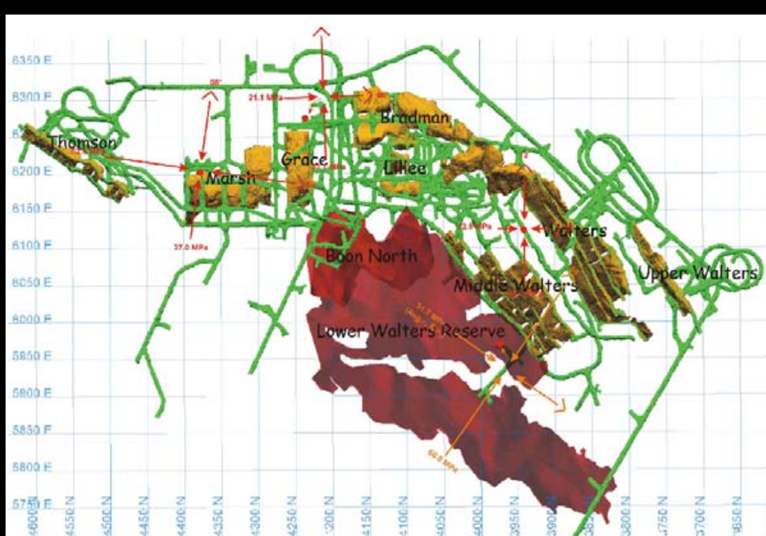

Analysis in 3D - then Hazard Prediction

## Seismic Events – Relationship to Stoping and Structures






## Seismic Events – Relationship to Rock Stresses



## Seismic Event - Prediction

**The following would be nice!!**

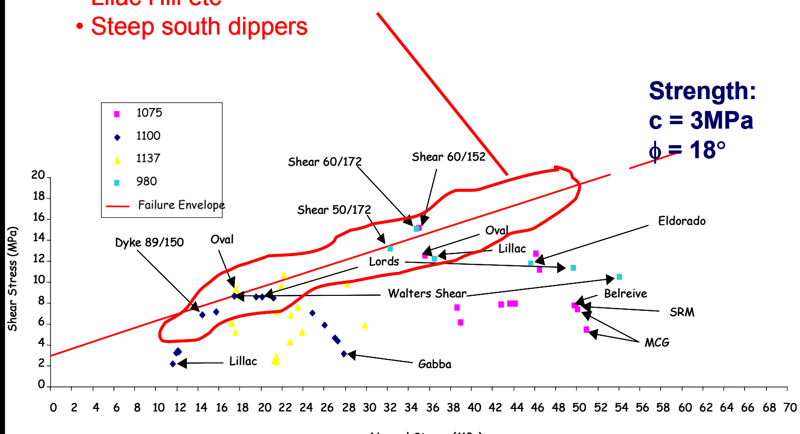
- **Timing - Tuesday 16 at 13.34hrs**
- **Location - 25m below 18 Level @ 5285N, 3456E**
- **Magnitude - 3.5 $M_L$**
- **Frequency - 20 Hz**
- **Duration - 0.3 secs**
- **Mechanism - Shearing on Fault X (dip 75, dip direction 125); maximum of 15mm shear displacement over an area 150m x 50m (strike / dip)**
- **Load Redistribution - To areas X, Y and Z**
- **Are more events possible > 1.0 $M_L$? - No**



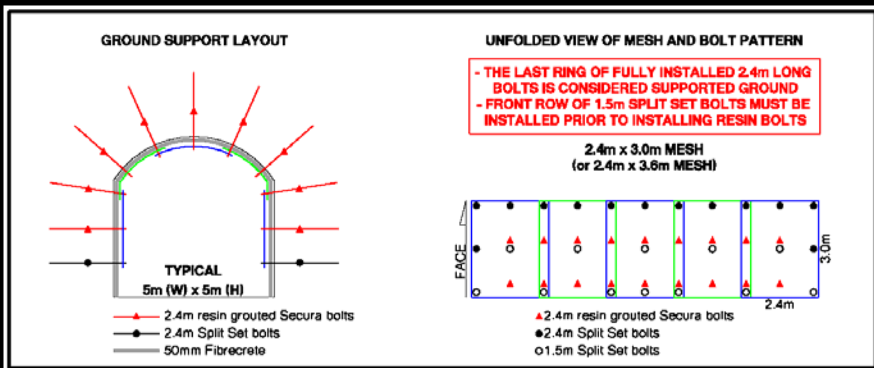
## Seismic Events – Prediction (Mobilised Shear Stress vs Structures)

**Some faults that have a high in situ potential to shear**

- Oval, Lords etc
- Lilac Hill etc
- Steep south dippers



## Seismic Events – Prevention / Standards






## Seismic Events – Prevention / Implementation

## Company Policy – The Driver

No Harm

Everybody goes home safely – every day

Nobody is allowed to work beneath unsupported ground – no exceptions

- Screen +
- Bolts



## Company Policy – Acceptance of Risk

| Likelihood | | Consequence: Insignificant 1 | Minor 2 | Moderate 3 | Major 4 | Catastrophic 5 |
|---|---|---|---|---|---|---|
| A | Almost Certain | 11 | 16 | 20 | 23 | 25 |
| B | Likely | 7 | 12 | 17 | 21 | 24 |
| C | Possible | 4 | 8 | 13 | 18 | 22 |
| D | Unlikely | 2 | 5 | 9 | 14 | 19 |
| E | Rare | 1 | 3 | 6 | 10 | 15 |

Low | Moderate | High | Extreme

**RISK ASSESSMENT LIKELIHOOD DEFINITIONS**

| | |
|---|---|
| Almost Certain | Event is a common or frequent occurrence (daily) |
| Likely | Event is expected to, or has occurred under some conditions (weekly/monthly) |
| Possible | Events will probably occur, or has occurred, under some conditions (yearly) |
| Unlikely | Event could occur at some time, or has happened elsewhere (every 10 years or so) |
| Rare | Event is not expected to occur, but may under exceptional circumstances |

**CONSEQUENCE DEFINITIONS**

| Level | Safety | Environment |
|---|---|---|
| Insignificant | Minor Injury (> $1,000) | Confined to immediate work area, rapid clean up, no damage to environment. |
| Minor | MTI/RWI (> $10,000) | Confined to specific area currently impacted by operations rapid clean up, little damage to environment. |
| Moderate | Lost Time Injury > $100,000 | Impact confined to within lease boundary, local environment naturally recoverable |
| Major | Multi-LTI/ Hospital > $1,000,000 | Major environmental impact, considerable clean up using site and external resources, extends past lease boundary |
| Catastrophic | Fatality/ Disability > $10,000,000 | Severe environmental impact, local species destruction, extensive clean up and long recovery |

## Ongoing Seismicity Investigations

- Monitor events - time, location, magnitude etc etc etc)
- Record mining context and performance of openings
- Accumulate associated data (structures, rock stresses, rock properties)
- Analyse (plot, graph, scratch and drink lotsa coffee!!)
- Fund R&D …. and "look over the fence"



## R&D

- Lots of discussion / papers with Peter Mikula and (lately) Stephen Fraser
- R&D undertaken by the Australian Centre for Geomechanics (ACG)
- The odd chats with Gary Gibson
- Seminars (2) on Earthquake Building Codes
- 2008, Ballarat - rock stresses
- Future?

  Special Eastern Australian Ground Control Ground (EAGCG) meeting?

## Background - Max

Qualifications - Geology (BSc Hons) + Civil Engineering (MSc)

Profession - Geotechnical Engineer (34 yrs; Mt Isa Mine, CSIRO, AMC)

Interests:

- Geology
- Structural Geology
- Ground Behaviour
- Rock Stresses
- Rock Properties
- Tectonics



## Rock Stresses

- Old Engineering Theory
- Indicators
- Measurements

## Old Theory

**Just due to the weight of overburden rocks??**

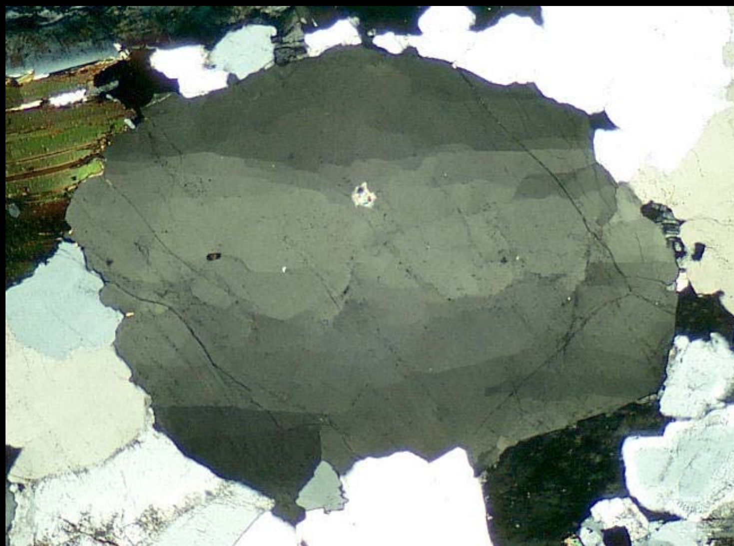
- **Vertical component = σV = major principal stress = ρ g Depth**
- **Horizontal components = σH and σh = [ν / (1 – ν)] ρ g Depth**



## Indicators

- **Geological – grains, folding and faulting**
- **Boreholes - breakout and drilling induced fractures**
- **Underground Openings - high stress spalling**
- **Mining-induced Seismicity – shearing (new and pre-existing structures)**

## Geological – Grain Size

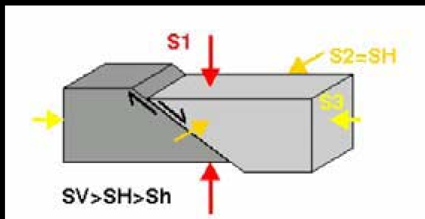




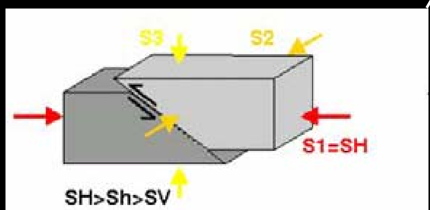
## Geological - Folding

## Geological - New Fault (rare)

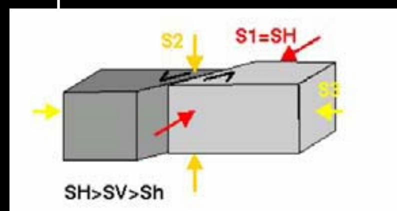
Normal Faulting




Thrust Faulting



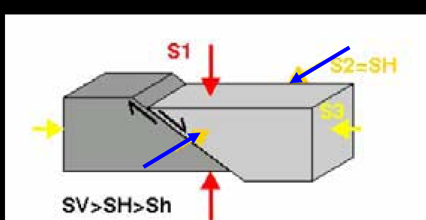

Strike-slip Faulting






## Geological – Shearing on Pre-existing Structure (common)

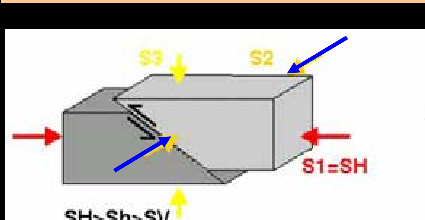
Normal Faulting

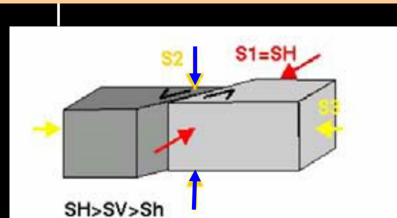



Thrust Faulting

Strike-slip Faulting

**THE DIRECTION OF THE SHEAR DISPLACEMENT – EG DURING AN EARTHQUAKE - DOES NOT HAVE TO BE PARALLEL TO THE LOCAL MAJOR PRINCIPAL STRESS!!**

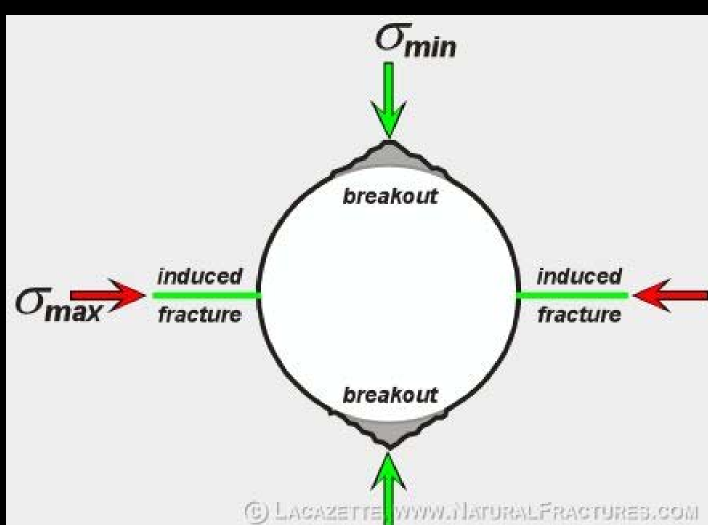


## Boreholes - Breakout




## Boreholes - Breakout + Drilling Included Fracturing



## Borehole – core discing



## Underground Openings - High Stress Spalling

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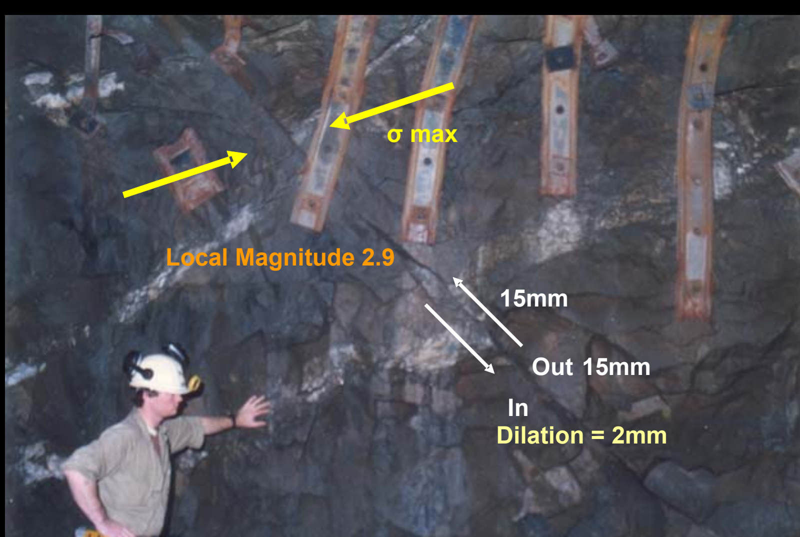
## Mining-induced Seismicity – Sudden Shearing

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## Mining-induced Seismicity – Sudden Shearing / Bursting




## Insitu Rock Stress Measurements - Australia

- 40+ years
- 1000+ in situ measurement sites (hydraulic fracturing, overcoring etc) – mostly at mines and civil engineering projects
- Depths up to 1.6km – cf ≈ 35Km thick continental crust (SHALLOW!!)

"What's does the data tell us?

## Insitu Rock Stress Measurement
## Drilling, Installation, Overcoring and Biaxial Testing



## Rock Stress Measurement
## Overcoring using CSIRO HI Cells

## Measurement Specification: CSIRO HI Cells

**Elastic isotropic** rock

Holes oriented to **avoid undesirable high stress effects** - borehole breakout, discing, tensile stresses, excessive strains etc

Overcore at least **1.5 “diameters”** away from opening

Various overcore sizes: 6 inch (142mm) and 74mm

To collect sufficient data, typically **3 successfully overcores per site**

**Measure strains to within 1° of ambient rock temperature**, or correct - 1° ≈ 1MPa

**Good rock property data is just as important as good overcore strain data**

**Analyse data in a consistent manner** - after Worotnicki (1993)

**Fully document results**

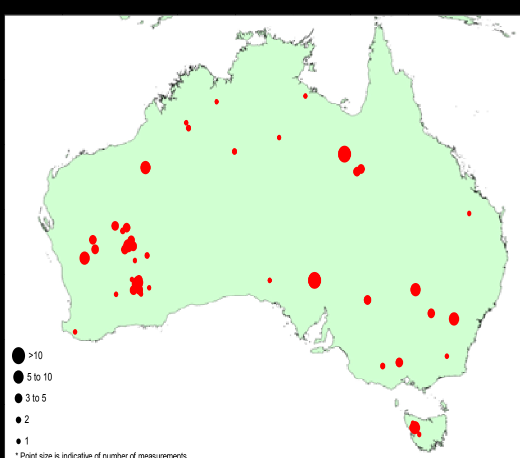
**Qualitatively rate** the confidence that can be placed in each overcore and **site result**

**Expect variability - after all it’s rock!!**

**Overcoring not an appropriate measurement technique for some situations**



## Rock Stress Measurement - Oz Distribution




- **Accepted methods (overcore and hydraulic fracturing)**
- **3D**
- **Rating ≥ Fair**
- **258 site measurements**
- **145 deeper than 500m**
- **No coal, no civil**
- **Scattered**
- **Representative sample stresses in the Australian continental plate?**

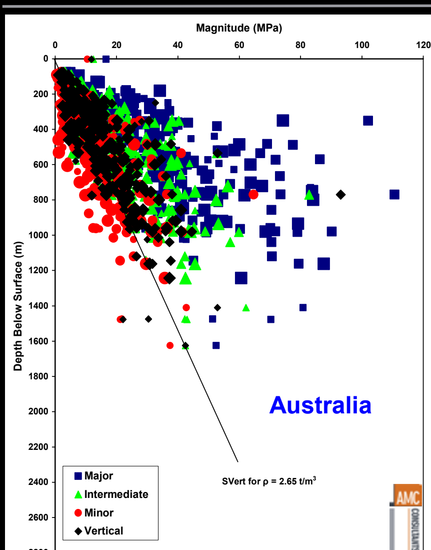
## All Rock Stress Measurements are NOT Equal

Qualitative Rating depends on;

- Technique; Stress Relief (CSIRO HI cell, ANZI cell, CSIR cell, USBM cell, Door-stoppers, Borre cell, Borehole slotter, Flat Jacks etc), Hydraulic Fracturing, Acoustic Emission, Displacement Rate Analysis etc
- Experimental difficulties / procedures; poor rock, electrical, mechanical, thermal etc
- Amount of data collected; strains and rock properties ($\sigma = E\ \varepsilon$)
- Assumptions; rock is NOT always a perfectly homogeneous, isotropic and linearly elastic material !!
- Data analysis; assumptions of result per cell, result per site



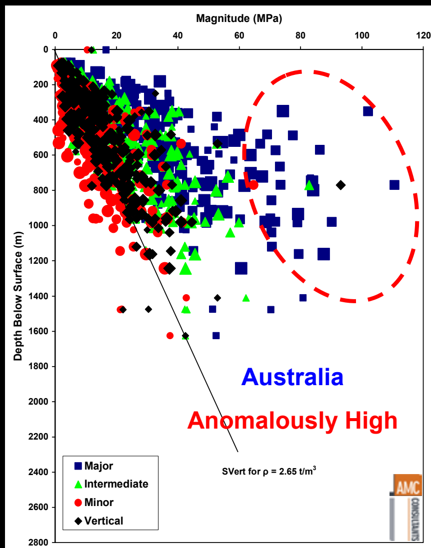
## Principal Stress Magnitudes vs Depth

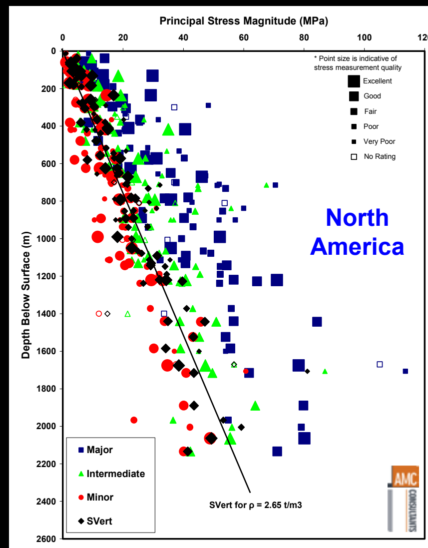



Mess ??

No simple depth vs stress relationship

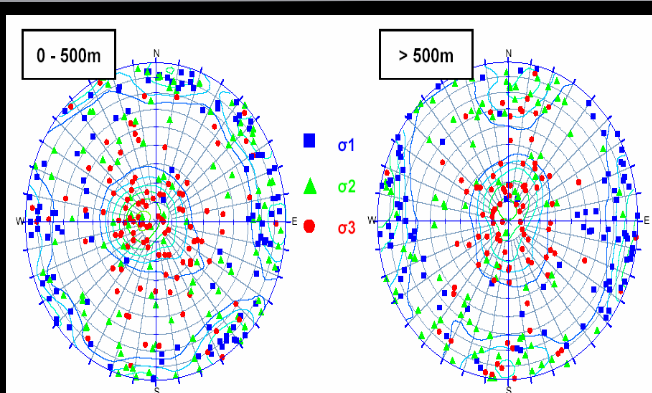
## Principal Stress Magnitudes vs Depth






## Principal Stress Orientations vs Depth

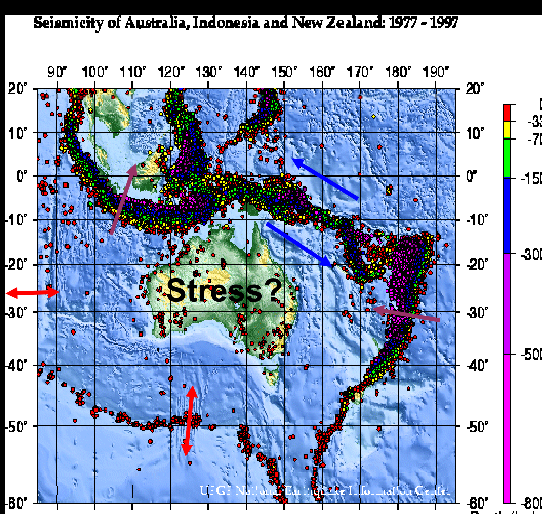



- σ3 mostly, but not always sub-vertical
- No preferred σ1 direction
- More scatter stresses < 500m

## Maximum Horizontal Stresses vs Tectonic Zones Orientations and Magnitudes @ 1000m

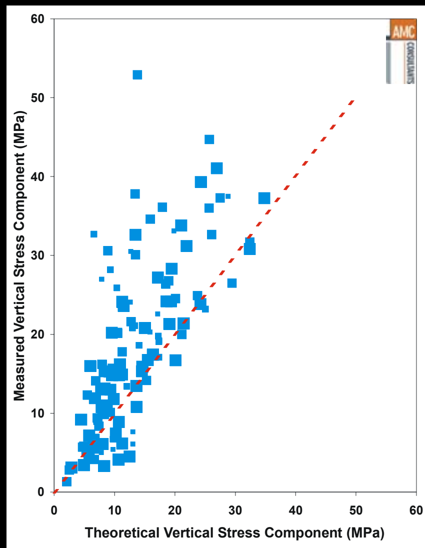



## Plate Stresses vs Plate Motion



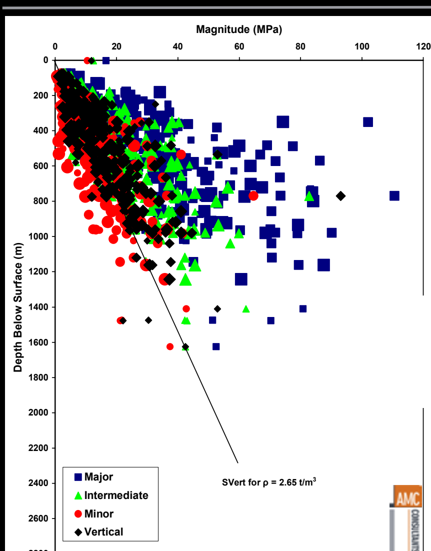

- NOT related to plate motion
- FUNCTION of interactions with other tectonic plates
  - Shearing - thrusting (subduction) and strike slip
  - Normal Load – rifting (normal faulting?) and tractions
- FUNCTION of plate thickness?

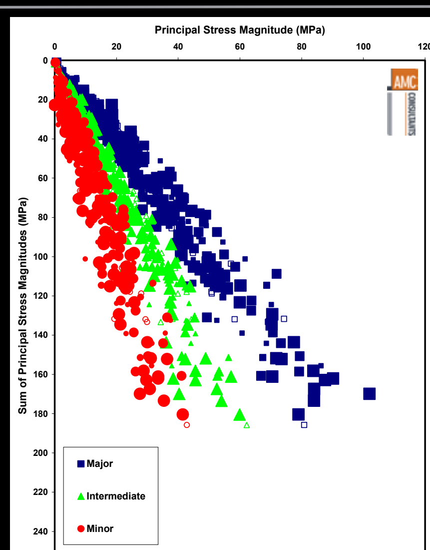
# Vertical Component – Measured > Theoretical in Yilgarn



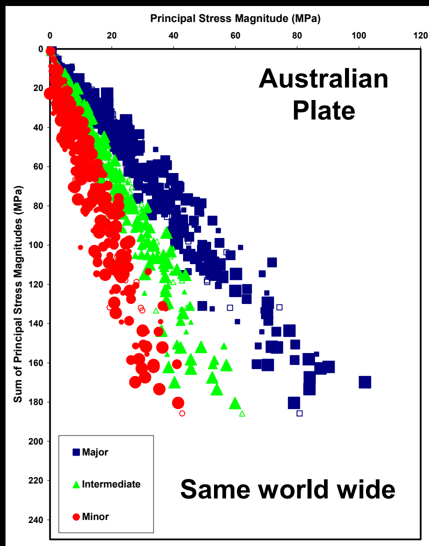


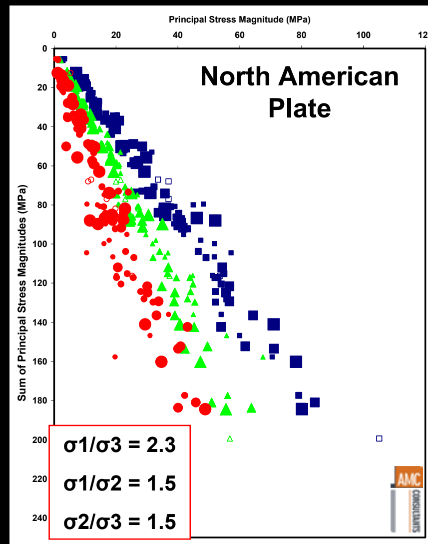

# Principal Stress vs 1st Invariant



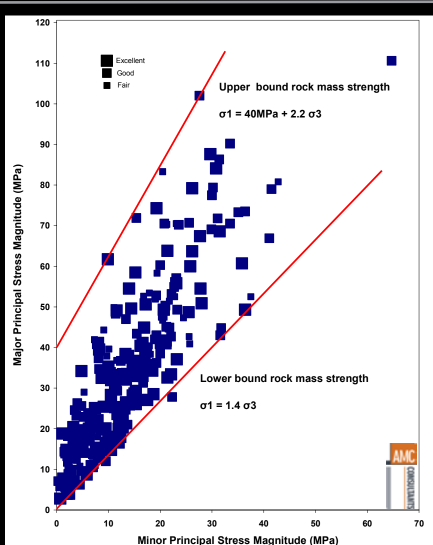
## Principal Stress vs 1st Invariant – rock is rock is rock!!





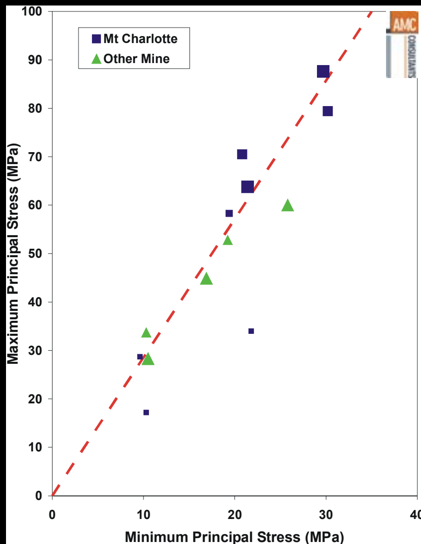

## Rock Mass Strength (σ1 vs σ3)




Back analysed insitu shear strengths of typical Yilgarn structures (for high normal loads):

- Graphitic: C = 2MPa, $\phi$ = 12°
- Talc-rich: C = 2MPa, $\phi$ = 18°
- Chloritic: C = 2MPa, $\phi$ = 23°

## Similar Rock Mass = Similar Structure Characteristics

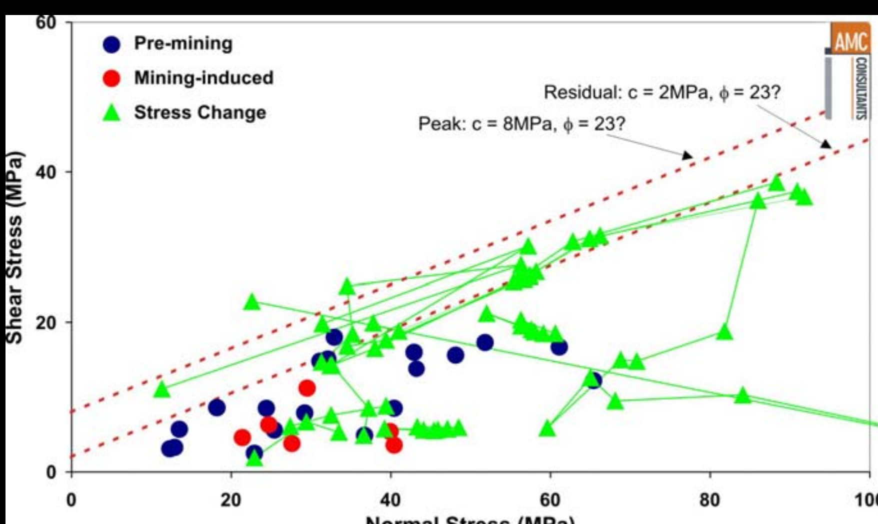



**Same Shear Strength**

**C = 2MPa, $\phi$ = 23°**



## Pre-mining + Mining Induced + Stress Change Monitoring

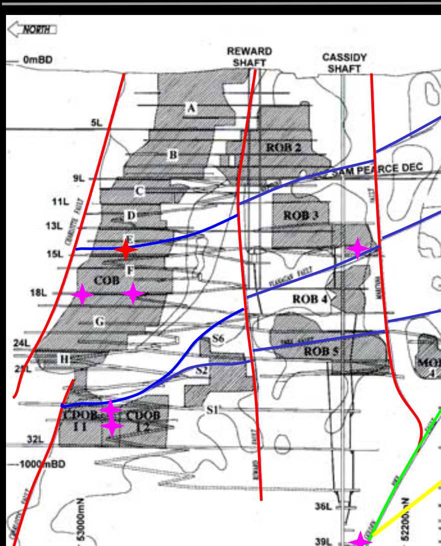


## Conclusion

- At any location - a few local structures (orientation and shear strength) dictate the local rock stresses (principal stress orientations and ratios)
- The mobilised shear stress on these “stress-controlling-structures” is - typically - on / near their (large scale) shear strength
- Stress changes (eg reductions in normal load – nearby mining) = shearing (eg plastic - creep; brittle - seismicity / earthquakes)
- **A detailed knowledge of structures + stresses should lead to forward earthquake “prediction”**

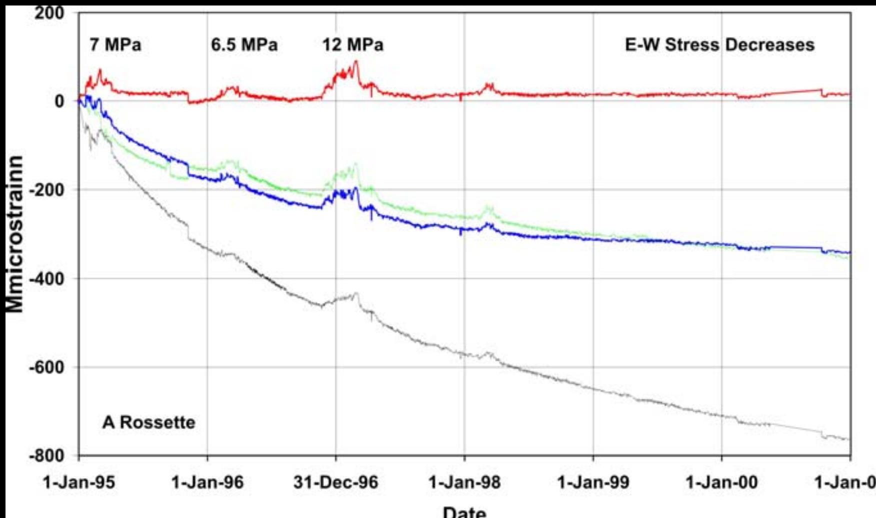


## There’s more!!



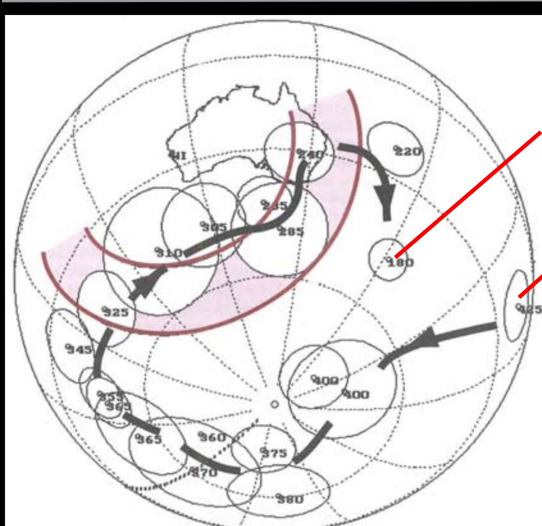

Stress change monitoring cells

## Periodic Stress Decreases – horizontal NE-SW






## Australian Plate Motion vs Time



**Cretaceous - End of the dinosaurs**

**Devonian - Au in Ballarat**

- Don't expect plate stresses to be constant!!
- Expect on-going shearing on pre-exiting structures

## Shear, Load Re-distribution, Stress Change -
Shear, Load Re-distribution, Stress Change -