VIRGIN ROCK STRESSES VS ROCK MASS STRENGTH IN WESTERN AUSTRALIA'S YILGARN GREENSTONES

Max F Lee and Marnie J Pascoe

Australian Mining Consultants Pty Ltd

Peter A Mikula

Kalgoorlie Consolidated Gold Mines

1 HISTORY

Only five of WA's Yilgarn mines have openings deeper than 1000m below surface. Three of these reached these depths about 20 - 25 years ago; the other two were much earlier. **All of these deep openings were in good competent rock (Achaean greenstones), and at least four of them experienced highly stressed ground, but generally only around small openings[1] mined using airlegs.**

- The older mines involved some level development as well as plats and minor openings associated with the bottoms of shafts. An old miner who had worked at one of these mines commented during a casual conversation; "Yeah, it used to play up a bit, but not quite as bad as this place!".
- Strain bursting occurred during shaft sinking at one of the "younger" mines, but it was successfully managed by simply drilling closely spaced destressing holes in opposite corners of the square shaft. It is understood that this action was taken without any specialist geotechnical input. On-going (possibly periodic?) seismicity is a feature of a particularly brittle rock type (porphyry) exposed near the bottom of this shaft.
- Another "young" mine experienced significant strain bursting from development faces ("dishing") and subsequent time-dependent closure of development in strong stiff gneiss. Very high stresses were eventually measured, but only after numerous technical difficulties and expense. These results were not used to help minimize ground control problems.
- Less "energetic" rocks (dolerite) were intersected at the bottom of the third "young" mine (Mt Charlotte). Rock stresses were measured, but only to confirm depth versus stress predictions based on several earlier shallower measurements. Development openings were oriented and shaped to minimise difficulties due to high surface stresses.

In more recent times, the deepest mining in WA was probably done at the Lancefield Gold Mine, to a depth of about 950m below surface via a decline access. A full suite of geomechanics data was collected (ground conditions, rock properties and rock stress measurements). Numerical modelling was used to understand the cause of a significant and very unusual ground control problem (footwall heave), which was managed by the rigid sizing and sequencing of small panel stopes. Despite the depth, head grade and the inflexible stoping sequence, the mine was reportedly profitable just prior to its closure / sale.

1.1 WA's Stress versus Strength Problem

As WA's Yilgarn mines become deeper, say below 600m, significant and increasing difficulties should be experienced with highly stressed ground (strain bursting, shear bursting, time-dependent yielding / squeezing, pillar failures etc), particularly around the much larger (nominally 5 x 5m) "square" development openings that are now commonly used.

[1] Typically thin "rectangular" openings with high arched backs.

For some mines, it may be difficult to provide both safe places of work and be viable, especially if only current technologies are used:

- Management procedures, risk assessments and well-drilled work practices will be critical to success.

- Timely and appropriate data collection and analysis will be needed for design studies, which should lead into testing, trials and on-going monitoring during mining / stoping.

- Rock stress versus strength issues must be better understood and confidently applied. Preconditioning and destressing techniques may have to be routine.

- To confidently control adverse ground behaviour, more appropriate and well-tested support and reinforcement techniques will also be needed.

The industry needs well-funded, enthusiastic, energetic and optimistic "white knights" (organisations, companies and people) to lead the charge and trial / apply solutions. The no-action alternative with increasing depth will mean costly resupport, redesigns, ongoing changes to schedules and ore losses, with a slow grind to less and less profitable mining. **The industry must get smarter.**

1.2 The Challenge

The devil is always in the detail, but in general, **a much steeper learning curve will be necessary in WA's Yilgarn greenstones in comparison to other previous deep mining areas around the world**:

- **Virgin stresses in WA's Yilgarn are generally higher, more deviatoric and they increase more rapidly with depth**, than in other parts of Australia and generally worldwide.

  High stress concerns will therefore begin at shallower depths in WA (Figure 1 and 2).

- **WA's major and intermediate principal stresses are also often sub-horizontal**.

  This simply means poor ground conditions in backs, ie potentially falls of ground, compared to more easily managed wall slabbing in South African's gold mines, due to their predominately high vertical stresses (**Figure 3**).

- **The strengths of WA's Archaean greenstones vary widely; from weak to very strong (Figure 4).**

  For some rocks, highly stressed ground behaviour could start as shallow as 300m below surface! Ground control problems can also occur when reasonably thick sequences of weak and soft rocks are adjacent to strong and stiff rocks.

- The generally higher production rates of most modern mechanised mines, implies a **faster down-dip advance of stoping, compared with previously**.

  High stress problems will therefore develop more quickly, than previously, and less time will be available to develop appropriate responses.

- **WA's development openings are also generally large (5 x 5m).**

  Rock mass strengths will therefore be "effectively" lower, potentially unstable wedges and slabs can be larger, and more onerous support and reinforcement will be required (compared with smaller development).

- And perhaps the most important issue, there is no longer a socially acceptable accident frequency for the mining industry.

  Despite actual performance, **zero accidents is now the policy and objective of all design, management and work practices / procedures**.

High stress problems in WA's mines will commonly begin to occur at much shallower depths compared with Canadian mines in similar Archaean rocks. They generally have higher stresses, some weak rocks and larger development openings. **Appropriate responses / technologies will need to be developed about twice as quickly as they have in Canada.** Of course they must also be effective, but still allow profitable mining.

Simply testing / trialing of overseas techniques and equipment to manage stress-related ground control problems will not be enough. These will only mean catching up with a few of the world's-best-practices, which to AMC really equates to adopting world's-average-practice!

WA's developing high stress problem will affect us all; companies, financiers, insurers, engineers, the general work force, regulators, teaching institutions, suppliers, consultants, and if we are not diligent the legal profession.

The party is over. Quick and decisive action is required, we may already be behind schedule!

2 ROCK MASS STRENGTH vs ROCK STRESS = GROUND BEHAVIOUR

2.1 Blocky or Structured Rock

For blocky rock masses (Q'< 60; Max Lee's loose definition[2]), or for pre-existing geologic structures (veins, joints, faults, shears and foliation / schistosity), local **shearing and dilation can lead to very poor ground conditions**:

- Time-dependent shearing, loosened ground, load re-distribution and rock noise.
- The development of slabs / wedges, possibly leading to overbreak due to gravity.
- Violent shearing (seismicity), maybe with the ejection of rock and secondary vibration effects, eg overbreak.

The amount of shearing and energy released are a function of:

- Principal stress orientations relative to structures.
- Principal stress magnitudes and their ratios.
- Shear strength and stiffness.
- Degree of freedom for physical shearing to occur.
- The available stored strain energy.
- How quickly shearing occurs, or energy is released.

The mechanics of shearing and energy release is complicated. It is a non-linear process, which means that the end result (stresses and strains) is a function of the load-displacement path. Unlike linear elastic behaviour, shearing is not a fully reversible process.

To simplify things for this workshop, the case of blocky rock is not pursued further. Only the simpler case of the behaviour of good competent "intact", or relatively unstructured rock masses is discussed below.

2.2 Competent Rock Masses

For good competent rock masses (ie Q' > 60), **difficult stress-related ground conditions often begin to occur when surface rock stresses are equal to, or greater than the strength of the intact rock in either compression or tension.**

Depending on the rock type and its texture (ie grain size and fabric), this can mean one or a combination of:

- On-going **time-dependent cracking and deterioration**, ie creep of the intact rock (eg weak talc-chlorite ultramafics) – **Figure 5**.
- **Reasonably benign high stress cracking**, especially around the corners of openings (eg tough unaltered basalts) – **Figure 6**.

[2] For Q' > 60, the rock mass must be better than; RQD = 80; Jn = 4, two well developed joint sets; Jr = 3, rough or irregular, undulating joints; Ja = 1.0, and unaltered joint walls.

- **Energetic high stress cracking / failure (strain bursting)**, possibly with the ejection of surface slabs (eg brittle quartz-rich rocks?) – **Figure 7**.

The behaviour of competent intact rocks is primarily a function of:

- Stress versus strength.
- Rate of crack propagation.
- Loading stiffness and load re-distribution.

Only stress versus strength issues will be discussed at this workshop.

3 ROCK STRENGTH VS ROCK STRESSES

3.1 Mechanical Properties per Rock Type

The mechanical properties of WA's Archaean greenstones are highly variable, particularly intact rock strength; refer to **Table 1.**

All of the individual tests included in **Table 1** have been checked for compliance against ISRM standards; any suspect data was discarded. The quoted values have been standardised to 50mm diameter samples having a length : diameter ratio 2.5 : 1.0. Time limitations in preparing this paper prevented the calculation of standard deviations; it's a large job.

Confidence can only be placed in the average properties, per rock type, which have been calculated using 10 or more tests, the other values are only indicative.

It is AMC's experience that the **local geologic history is critical to understanding the mechanical properties**, and hence the behaviour of WA's various Archaean rock types:

- Be aware that **geologists can use the same name for mechanically very different rocks**.

- **Some of WA's ultramafic rocks were serpentinised (H_2O added) during deposition; others were not**. Some have also been subsequently serpentinised.

  Because the ultramafics are often near the base of the greenstone sequences, it's likely that they helped accommodate large ductile shear movements during folding / faulting, between the older basement granites and the overlying greenstones.

- Most of the Archaean "greenstones" are **variably metamorphosed**, with the development of weak to strong fabrics (ie foliation) which can influence their mechanical properties and behaviour.

- Some rocks have also been **altered**; eg **Na^+ or K^+ metasomatised** near granitic intrusions, **carbonated (CO_2)** and / or **sericitised**. The latter two are often associated with gold mineralisation.

- **A few rocks were intruded about a billion years after the sedimentation and deformation of the Archaean greenstones**, eg some Proterozoic granites, dolerite dykes and possibly lamprophyres.

Although generally interesting, the data in **Table 1** should not be used for important stability assessments. **In order to be confident about the mechanical properties and hence the behaviour of local rocks, there is no other option but to mechanically test suites of all the local rock types, per mine**; to ISRM standards and in sufficient quantities so that properties can be quoted to the required level of accuracy.

3.2 Intact Rock Strength and Failure / Behaviour Criteria

Compressive and tensile intact rock strengths are scale dependent (Figures 8 and 9). This is presumably due to the greater chance, with increasing sample size, of small pre-existing cracks (grain boundaries, imperfections) being present, which assist the propagating of cracks and failure at lower stresses.

Properties from small laboratory tests cannot, therefore, be directly used to predict likely ground behaviour around large openings.

From a practical engineering and stability point of view, the main modes of ground behaviour around openings, which are of interest in good competent rock are surface slabbing, shear failure and rock noise.

These zones can be approximately defined around openings where stress criteria exceed strength criteria, as follows:

- Zones of **surface cracking / slabbing** around underground openings, **due to compressive stresses** can be approximated by the **large-scale unconfined compressive strength** (UCS_{rm}).

  Maximum tangential surface stress > UCS_{rm}

  where $UCS_{rm} = k\ UCS_{50}$

  UCS_{50} = unconfined compressive strength of 50mm diameter specimens
  k ≈ 0.5, (range 0.3 to 0.6).

- Zones of **surface cracking and slabbing due to tensile stresses** can be approximated by the **large-scale tensile strength** (UTS_{rm}).

  Minimum tangential surface stresses < UCS_{rm}

  where $UTS_{rm} = 0.33\ UTS_{50}$

  UTS_{50} = unconfined tensile strength of 50mm diameter Brazilian discs

- The **depth of shear failure** around openings can be approximated by any area where;

  $$UCS_{rm} < \sigma_1 - K\ \sigma_3$$

  where K = (1 + sinϕ) / (1 - sinϕ).

  This zone approximates the zone of unstable crack growth.

  The above relationship is identical to the more traditional Mohr-Coulomb failure criterion using c and ϕ.

- The **locus of rock noise** around openings (unstable crack growth) is also approximately defined by;

  $$UCS_{rm} < \sigma_1 - K\ \sigma_3$$

  but for K = 1.0

- Strain bases failure criteria (ε_{EXT}, defined per rock type) have also been used to predict **zones of compressive and tensile extension cracking.** Cracking occurs within the zone where $\varepsilon_T > \varepsilon_{EXT}$

  where $\varepsilon_T = \{\sigma_3 - \nu(\sigma_1 + \sigma_2)\} / E \cong UTS_{rm} / E$

Ground support designs should consider the extent of these zones; eg the length and stiffness of support elements. Of course the extent of these zones will vary with time as mining induced stresses vary with stoping.

4 ROCK STRESSES

For mining engineering purposes, the rock stresses of interest in the Yilgarn Craton are those on the scale of mineral grains up to stoping blocks, and which are present in the Archaean "greenstones" NOW:

- **Old geologic stress regimes, which have been responsible for multiple episodes of folding and faulting**, over the last 3 billion years, **are of limited interest.**

  They were, however, mainly responsible for the large structures that now intersect the rock mass. These structures probably dictate what local stress fields (magnitudes and orientations) can be sustained due to a variety of external loads, internal forces and elastic reactions.

- **Locked-in stresses and strains**, eg within some deformed minerals (quartz?) and along some grain boundaries, due to previous brittle and ductile deformations, **do not contribute to rock stresses that are of interest to stoping.**

  They may, however, be important to the initiation of cracking (ie rock strength) when rocks are stressed; eg eroded, drilled, tested in the laboratory, blasted, or exposed underground. Locked-in stresses may explain why similar rocks have different strengths, or why rock strengths are so variable.

  A laboratory study by Helmut Bock (at JCUNQ) showed that +/– 30MPa stresses were present in a thin isolated slab of columnar basalt, on the scale of mineral grains.

- **Contemporary rock stresses can be reliably measured using stress-relief (eg CSIRO HI cells) or by hydraulic fracturing techniques**. The main objective is to establish principal stress magnitude and orientation relationships with depth, for consideration in stability assessments, often as input in numerical models.

  It is generally accepted that these stresses are representative of the stress field that should be considered when assessing underground stability. These measurements are, however, **only "point" measurements of local rock stresses** on the scale of about 5×5m. **Measurements should be as close as possible to the area of interest.**

  In most cases, measurements in WA's Yilgarn greenstones are in drained rocks, ie porewater pressure and effective stress principles are not an issue.

  If possible, **measurements should be verified and supplemented with other observations of inferred stress orientations and magnitudes**; eg high stress spalling around raise bored shafts and development openings, shearing on structures etc. Some reality checks are also possible, eg by calculating implied shear strengths on nearby structures.

  Before reasonably reliable inferences can be made about virgin stress fields per stoping block or mine, two things are necessary:

  - **Sufficient site measurements** must be made so that relationships can be developed (eg with depth); say one every fault block / geotechnical domain, or about every 150m depth.

  - It is also very important to **understand the relationship between the local geology and the measured stress field.**

  Investigations at numerous mines have lead to the belief that **existing geologic structures control the local stress field. Most large / continuous structures are at, or near their peak shear strengths before mining (Figure 10).** A consequence of this observation is that it is very easy for minor stress changes, eg due to mining, to initiate significant shear movements, associated rock noise and loosening.

It's AMC's opinion that very few WA mines confidently understand their virgin rock stresses. While rock stress measurement is presently perceived to be expensive by some companies / mines, these people will often quite happily waste considerable resources numerically modelling, using estimates of their rock stresses as input! The results and conclusions from these analyses will be accurate, but maybe wrong!

Given the understanding and confidence that they can give to a mine in terms of the stability of underground openings, especially in potentially highly stressed mines, rock stress measurements are cheap.

- **Virgin rock stresses can, apparently, vary with time.**

  Monitoring of up to four CSIRO HI cells over about 5 years at the bottom of Mt Charlotte (remote from stoping) has shown that virgin stresses can, in fact, vary with time. For Mt Charlotte, a stress drop of about 5MPa (+/– 5MPa) seems to occur every year, but over a 3 month period, often centred on early March (**Figure 11**).

  The concept of varying stresses should be easy to appreciate, but their periodicity is intriguing.

  Over the last 30 years geologists have demonstrated that the earth's lighter continental plates have been constantly colliding and sliding over deeper, more ductile mantle rocks (**Figure 12**). A variety of push-pull mechanisms have been suggested for the motion of the plates, all of which are unlikely to be constant. As a minimum, the plates must buckle and flex, just a little bit, due to variable gravitational attractions from the sun and moon. The classic example of this is the volcanic activity on Io, one of Jupiter's moons.

  Variable stresses (stress drops) could periodically encourage shearing and initiate adverse ground behaviour in highly stressed mines. The mining industry should fund work aimed at monitoring and better defining this problem.

4.1 CSIRO HI Cells – General Discussion

It should be appreciated that it is very difficult to prove that *in situ* rock stress measurements are accurate and that the measured stresses actually exist.

In the case of CSIRO HI cells, it is necessary to rely on the results of a few laboratory tests done by CSIRO[3] and elastic theory. It is very important that measurements are only made in good elastic rock and ideally not too close to any known structures. Care is required during data collection (overcoring and biaxial testing) and standard analysis procedures should be used to calculate site results.

AMC has found, by experience, that CSIRO HI cells reliably measure rock stresses:

- Same level, separated by 120m, different rock type / stiffness, same virgin stresses (**Table 2**).
- Same site, different time (12 years) and measurement scheme, same stresses (**Table 3**).
- Same site, different measurement boreholes, same individual overcore results (**Table 4**).
- Same site, different measurement boreholes / individual overcore results, varible stiffnesses, good site result (**Table 5**).

[3] Most rival stress measurement techniques do not even have this laboratory information; it's not easy to obtain. Often they compare their *in situ* results against data from nearby CSIRO cells.

- Small site, different rock types / stiffnesses across contacts, different stresses (**Table 6**).
- Similar level, same rock type, different fault block / domain, different stresses (**Table 7**).
- Same area, different measurement technique, very different site result (**Table 8**).

Qualitatively rating the accuracy of each site results is important. Results from individual overcored cells are of limited use. They are equivalent to grab samples from ore stockpiles; ie potentially unreliable and misleading. Several cells must be overcored and the results combined to give a site result, plus an indication of the likely variability of stresses at the site (ie errors). Further overcoring (data collection) is not necessary when more data does not significantly alter the average site result. It is usually necessary to overcore 3 CSIRO HI cells.

It is AMC's experience that stresses and elastic rock properties at some sites (on the scale of cells) are inherently more variable than others.

Contrary to popular belief – by the doubting Thomases of this world, and mainly from those who have not had a lot of experience with stress measurement by overcoring **– principal stress orientations are not always parallel to the measurement axis of the borehole**:

- On average, one of the principal stresses should make an angle of about 27 degrees (half a radian) with the measurement borehole, which is about parallel (tongue in cheek)!
- Measurement boreholes are also often drilled sub-horizontal and sub-parallel to the strike of orebodies, or parallel to an ore-controlling structure. Both are often sub-parallel to one of the principal stress directions. This site selection procedure gives maximum sensitivity to the stress components most important to stope design, ie stresses oriented across the stopes. It also leads to the observation that principal stresses are often sub-parallel to the borehole.

4.2 Virgin Stresses

Virgin rock stresses in the Yilgarn Craton are probably a function of the following contributing factors. Other factors can also be important in different geomorphologic and geology environments.

- The **local geology** (variable rock types / stiffnesses and structures). Regionally higher and lower stresses may be possible, eg around the end of stiff "greenstone" belts and adjacent to large shear zone, due to recent movements on these structures.
- The **weight of overburden rocks**.
- **Thermal expansion** as the ambient rock temperatures increases with depth (or contraction as the near surface rocks are eroded / cooled).
- Any **current tectonic component**, due to the present general NNE-SSW motion of the Australian plate, but an analysis of Mt Charlotte's stress field suggests that the local tectonic component at Kalgoorlie is oriented NNW-SSE (**Figure 13**).
- **"Recent near-surface" movements** on shallow dipping structures during erosion.

  Large, open and shallow dipping structures seem to be a feature of WA's mines. They are often "water-courses" and have gypsum infill. It's likely that they are geologically recent structures, possibly due to off-loading of a thick continental ice sheet (about 5km thick), roughly 250million years ago.

  High, sub-horizontal stresses simply cannot be sustained on these structures in near surface environments. They must shear and re-distribute loads, and probably do so progressively during weathering and erosion, or as external tectonic loads vary with time. The mechanism is no different to load redistribution and "arching" around underground openings in blocky / structured rock.

There is strong geological evidence for this mechanism in several Australian mines, and observable styles of geologic shearing match predictions based on good sets of *in situ* rock stress measurements.

The accuracy and validity of some *in situ* rock stress measurements by overcoring has been publicly questioned – again mainly by those doubting Thomases referred to earlier – because stresses appear to rotate with depth, and / or because measured vertical component do not equal the theoretical weight of overburden rocks.

A consequence of these near surface movements is that there is no reason why the vertical stress components should equal the weight of the overburden rocks, especially for old complexly folded and faulted rock masses (**Table 9**). In these rock masses, it's likely that only rock stresses below say 1000m, are truly virgin measurements. **Complex "rotation" of principal stresses, with decreasing depth is also possible and should be expected,** as has also been measured (**Table 10**).

It's disturbing but a fact, that there has been a tendency by some geomechanics specialists and stress measurement gurus to "correct" *in situ* rock stress measurements so that the measured vertical component equals the local theoretical weight of overburden rocks. While I'm sure they did it in good faith, a consequence of this practice is that some and perhaps most, of the old published rock stress measurement data may be "corrected" and therefore wrong. Of course an analysis of this data would tend to prove the idea that the measured vertical stress component does in fact equal the theoretical weight of overburden rocks. **Be wary of old rock stress measurement data, find the raw data and reanalyse site stresses.**

5 ROCK STRESSES IN YILGARN GREENSTONES

Over a number of years, AMC has steadily compiled a confidential database of rock stress measurements and associated site data. While some companies have allowed us to publish this data, others have not. Where there has been an opportunity, measurements done by others has been reviewed, reanalysed (using their raw and AMC's standard procedures) and rated.

Figures 1 and 3 summarise what is presently known about general principal stress magnitudes and orientations in WA's Yilgarn greenstones. These stresses are not representative of any particular mine, nor of any of the individual greenstones pods. It's also possible that average stresses in the Yilgarn Craton, which is mostly a mixture of (very competent?) granite and gneiss, could also be different to the more variable and structured greenstone pods.

Orientations referred to below are with respect to true north.

- **The major principal stress is high, often sub-horizontal (especially with increasing depth) and oriented either NE-SW or NW-SE.**
- The intermediate principal stress is also often sub-horizontal and oriented either NE-SW or NW-SE (opposite to the major principal stress).
- The **minor principal stress is sub-vertical**, and below about 600m depth its magnitude is approximately equal to the weight of overburden rocks.

As mentioned above, the high, deviatoric and sub-horizontal major and intermediate principal stresses promote near-surface shearing on any shallow dipping contacts and structures. Because the main structures in the Yilgarn greenstones dip steeply and strike NNW-SSE and NNE-SSW, the above general major and intermediate principal stress orientations also imply high *in situ* shear stresses on these features. **Both of the above structure types (steep and flat dipping) tend to be on or near the limit of their *in situ* shear strengths.** It is therefore relatively easy for nearby mining to initiate significant shearing.

Compared against data for the rest of Australia and similarly aged rocks in Canada, stresses in WA's Yilgarn greenstones are high, deviatoric and their magnitudes increase more rapidly with depth (**Figure 2**). **The on-set of highly stressed ground behaviour can therefore be expected at shallower depths than in other Australian and similar Canadian mines.**

5.1 Stress Concentrations around Openings

Virgin rock stresses are concentrated (higher and lower) around stopes, and in turn these mining induced stresses are also concentrated around nearby development openings.

Far-field stresses are concentrated, "on-average", by about 1.8 times in the immediate back of approximately square drives mined perpendicular to sub-horizontal stresses. In such situations, significant and important tensile stresses can occur in development walls.

Much higher and lower stress concentrations are possible for differently shaped openings and differently oriented stresses. **Numerical modelling should be used to predict theoretical surface stresses around underground openings.**

5.2 On-set of Highly Stressed Ground in WA

Given the variable strengths of WA's greenstones and the above general stress versus depth relationships, below what depth can highly stressed ground behaviour be expected, versus rock types?

Approximate relationships can be derived between intact rock mass strength (UCS_{50}) and the depth at which high stress cracking / spalling might first occur. **For large square development openings mined perpendicular to a sub-horizontal major principal stress, the depth at which spalling might first be expected in WA's Yilgarn greenstones ≈ 3 x UCS_{50}.**

Figure 15 relates estimated *in situ* "competent" Yilgarn greenstone strengths and WA's major principal stress versus depth. High stress slabbing could begin at the following depths for the following common rock types (nearest 50m):

- Basalts: fresh ≈ 700mm; altered ≈ 350m
- Dolerites: fresh ≈ 750m; altered ≈ 550m
- Felsic / mafic sediments: fresh = 350 - 450m; altered = 400 - 500m; very variable
- Serpentinised talc-carbonates = 200m; ie at very shallow depths
- Porphyries = 750m; some are prone to strain bursting at much shallower depths!
- Proterozoic dolerite dykes = 500m

Casual observations suggest that surface cracking / slabbing around development openings begins at depths as shallow as 300m in weak rocks (eg talc-chlorite ultramafics), and most of the stronger rocks show some evidence of high stress spalling at or very soon after 600m below surface.

6 CONCLUSIONS

- The **worsening rock stress versus strength problem**, with increasing depth, has been defined for WA's Yilgarn greenstones.

- **Do not under-estimate the challenge**; it's perhaps 2 to 3 times as bad as other "highly-stressed" mining areas have / are experiencing around the world.

- **Further work is needed – urgently**; to better define the concern, what it means in terms of ground behaviour, and to develop safe / viable strategies to manage stress versus strength concerns.

- **Site investigations must be thorough**, adequately funded and timely (geology, structures, rock properties, stresses etc). This will mean savings and better profitability, by only having to do jobs once.

- **Mine / stope designs must be well-considered and reviewed. Formal risk assessments and trials are suggested. Monitoring is essential.**

- And if we really do want to mine the "mother lode" to the bottom of the crust, **management and work practices will need to be impeccable.**

Rock Type	Density		Young's Modulus		Poisson's Ratio		Strength			
							UCS50		UTS	
	t/m^3	#	GPa	#		#	MPa	#	MPa	#
FRESH ARCHAEAN (Metamorphosed and some Metasomatised)										
Basalt	2.95	70	81.3	126	0.29	86	230	125	22.5	85
Peridotite	2.99	3	70.8	3	0.20	3	118	3	19.3	3
Black Flag Beds	2.72	5	69.2	7	0.26	7	219	29	21.7	2
Mafic Sediments	2.83	42	72.3	52	0.26	51	158	50	20.0	12
Felsic Sediments	2.57	99	71.1	39	0.25	32	124	81	13.3	59
BIF	3.16	5	92.8	6	0.27	6	230	5		
Cu + Zn Sulphides	4.26	12	132.0	12	0.27	12	182	15		
Gabbro	2.93	13	77.6	25	0.27	25	216	8	13.6	10
Dolerite	3.00	70	88.6	80	0.28	80	254	60	17.6	27
Porphyry	2.70	40	61.7	84	0.24	40	252	105	16.9	73
Dacite	2.74	11	69.5	11	0.26	11	86	11		
Pegmatite	2.71	9	63.6	8	0.24	8	202	9	8.1	13
FRESH PROTEROZOIC (Dykes)										
Dolerite Dyke	2.86	28	74.4	30	0.33	30	175	86	16.6	35
Lamprophyre			70.1	6	0.32	6	127	16	17.4	3
ALTERED - CARBONATED (Au Associated)										
Basalt	2.87	23	64.3	59	0.29	48	116	58	15.9	54
Felsic Sediments	2.81	11	58.8	24	0.28	23	130	25	18.7	23
Sediments	2.59	7	62.8	16	0.25	11	66	15	8.0	8
BIF	3.31	5	64.0	5	0.22	5	152	5	13.6	5
Gabbro	2.88	3	75.7	10	0.29	10	152	3	12.6	3
Dolerite	2.86	34	70.0	11	0.21	11	178	14	14.7	6
Porphyry	2.75	2	66.7	2	0.34	2	118	2	15.3	2
Gneiss			37.0	5	0.31	5	90	28		
Siliceous Veined Ore	2.88	62	65.1	305	0.22	80	180	291	14.1	192
ALTERED - SERICITISED / FOLIATED (Au Associated)										
Mafic	2.81	35	53.0	35	0.25	35	112	35		
Conglomerate	2.75	57	74.0	61	0.24	61	130	13	14.4	30
Grit	2.72	14	68.9	18	0.25	18	161	5	17.3	12
Sandstone	2.78	1	79.2	1	0.20	1				
Felsics	2.75	14	67.5	20	0.28	20	170	14	16.3	8
Porphyry	2.73	30	69.7	25	0.23	24	67	4	18.1	16
ALTERED - SERPENTINISED and CARBONATED (Ni and Au Associated)										
UM Stiff / Strong	3.02	30	75.9	57	0.31	39	163	62	15.1	120
UM Talc - Carbonate	2.82	87	44.0	181	0.33	141	65	271	7.2	199
UM Talc - Chlorite	2.72	25	26.3	20	0.34	16	45	70	4.4	150
Mafics	2.87	6	49.1	6	0.19	6	148	38	15.7	94
Sediments	3.17	5	48.5	5	0.24	4	141	9		
Ni Sulphides	4.78	19	65.6	22	0.19	22	135	23	10.3	9

Table 1: Typical Mechanical Properties of WA's Yilgarn Greenstones

Rock Type	Depth (m)	Borehole Dip/Bearing	Young's Modulus (GPa)	Poisson's Ratio	Site Rating	Sigma 1			Sigma 2			Sigma 3		
						Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)
Brecciated Granite	635	-03/140	48	0.22	Excellent	26.5	16	248	19.0	34	349	13.4	52	137
Felsic Dyke	635	-04/299	75	0.26	Excellent	32.1	10	259	20.5	05	168	12.8	78	052

Dips are positive below the horizontal
Bearings are with respect to True North

Table 2: Same level, separated by 120m, different rock type / stiffness, SAME VIRGIN STRESSES

Date	Boreholes	Overcore Diameter (mm)	Young's Modulus (GPa)	Poisson's Ratio	Site Rating	Sigma 1			Sigma 2			Sigma 3			Vertical Component (MPa)
						Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	
Oct 1985 & May 1986	2 holes; -05/040 and -04/100	143	81	0.42	Good	79.4	10	150	41.1	00	240	30.2	80	330	31.7
September 1997	2 holes; -05/167 and -31/204	72	79	0.31	Excellent	87.6	00	328	45.6	15	058	29.7	75	237	30.8

Dips are positive below the horizontal
Bearings are with respect to Mine North = 38 degrees West of True North

Table 3: Same site, different time (12 years) and measurement scheme, SAME STRESSES

Hole/ Test #	Borehole Dip/Bearing	Young's Modulus (GPa)	Poisson's Ratio	Sigma 1			Sigma 2			Sigma 3		
				Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)
2/1	–05/167	72	0.29	82.4	06	008	47.7	12	100	32.0	76	252
2/2	–05/167	81	0.35	89.0	02	002	46.4	03	092	30.9	86	239
3/1	–31/204	83	0.29	81.1	11	181	41.6	07	090	17.0	77	328

Dips are positive below the horizontal
Bearings are with respect to Mine North = 38 degrees west of True North

Table 4: Same site, different measurement boreholes, SAME INDIVIDUAL OVERCORE RESULTS

Hole/ Test #	Borehole Dip/Bearing	Young's Modulus (GPa)	Poisson's Ratio	Rock Type/ Behaviour	Site Rating	Sigma 1			Sigma 2			Sigma 3		
						Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)
1	**–10/025**	92	0.27	Foliated Dolerite (linear)	Good	**24.1**	**09**	**231**	**10.7**	**00**	**141**	**8.9**	**81**	**051**
2	**–30/330**	49	0.28	Foliated Dolerite (non-linear)	Good	**62.7**	**22**	**154**	**38.6**	**03**	**063**	**24.9**	**67**	**325**
3	**–05/303**	80	0.42	Foliated Dolerite (non-linear)	Good	**47.2**	**06**	**195**	**40.5**	**02**	**105**	**22.7**	**84**	**353**
Site		74	0.32		**Good**	**43.0**	**10**	**194**	**31.5**	**03**	**284**	**19.3**	**80**	**031**

Dips are positive below the horizontal
Bearings are with respect to Mine North = 1 degree east of True North

Table 5: Same site, different measurement boreholes / individual overcore results, variable stiffness, but still a GOOD SITE RESULTS

Rock Type	Borehole Dip/Bearing	Young's Modulus (GPa)	Poisson's Ratio	Site Rating	Sigma 1			Sigma 2			Sigma 3		
					Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)
Basalt	**-05/271**	**86**	0.38	Fair	**36.8**	**17**	**134**	**20.9**	**14**	**040**	**17.5**	**69**	**272**
Serpentinised Ultramafic (talc-carb)	**-07/050**	**55**	0.54	Fair	**43.3**	**04**	**221**	**19.8**	**01**	**322**	**19.0**	**86**	**060**
Porphyry	**-07/050**	**83**	0.35	Fair	**31.3**	**21**	**031**	**22.5**	**21**	**134**	**10.0**	**52**	**252**

Dips are positive below the horizontal
Bearings are with respect to Mine North

Table 6: Small site, different rock types / stiffnesses across contacts, VARIABLE STRESSES

Rock Type	Depth (m)	Young's Modulus (GPa)	Poisson's Ratio	Site Rating	Sigma 1			Sigma 2			Sigma 3			Vertical Component (MPa)
					Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	
Dolerite	322	101	0.30	Good	33.7	08	088	21.1	06	178	10.3	52	304	10.9
Dolerite	382	102	0.25	Good	52.8	08	188	37.0	08	096	19.2	78	324	20.2

Dips are positive below the horizontal
Bearings are with respect to Mine North = 44 degrees of True North

Table 7: Similar level, same rock type, different fault block / domain, DIFFERENT STRESSES

Measurement Technique	Rock Type	Depth (m)	Boreholes	Young's Modulus (GPa)	Poisson's Ratio	Site Rating	Sigma 1			Sigma 2			Sigma 3			Vertical Component (MPa)
							Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	
Borehole Slotter	Massive Sulphide	512	3	111	0.32		23.6	09	074	15.6	05	164	7.2	80	270	7.8
CSIRO HI cells	Massive Suplphide	512	2	111	0.21	Fair	52.6	01	299	18.1	45	209	16.8	45	030	17.5

Dips are positive below the horizontal
Bearings are with respect to Mine North = 10 degrees West of Magnetic North

Table 8: Same area, different measurement technique scheme, VERY DIFFERENT SITE RESULT

Rock Type	Depth	Orebody Dip/Dip Direction	Young's Modulus (GPa)	Poisson's Ratio	Site Rating	Sigma 1			Sigma 2			Sigma 3			Vertical Component (MPa)	
						Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Measured	Excess
Gabbro	596	50/095	85	0.27	Excellent	35.5	33	355	31.9	37	236	14.9	36	113	27.2	10.9
Gabbro	754	37/116	91	0.25	Excellent	50.9	15	213	39.9	22	310	28.0	63	092	31.2	10.5

Dips are positive below the horizontal
Bearings are with respect to Mine North = True North
Implied *in situ* shear strength of orebody (graphite fill): c = 0; ϕ = 11 degrees

Table 9: Different Depth, very different stresses, but same excess vertical component

Depth (m)	Site Rating	Sigma 1			Sigma 2			Sigma 3		
		Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)	Magnitude (MPa)	Dip (°)	Bearing (°)
360	Good	20.03	03	097	16.0	36	189	13.0	54	003
407	Excellent	25.3	01	287	16.0	13	197	11.3	77	020
480	Excellent	26.0	12	076	19.0	57	185	14.0	30	339
555	Good	42.7	06	162	27.1	14	254	22.1	75	051
666	Excellent	36.7	10	185	24.9	15	278	16.1	72	062

All CSIRO cells
Dips are positive below the horizontal
Bearing are with respect to Mine Planning Grid

Table 10: Rotating Stresses with Depth

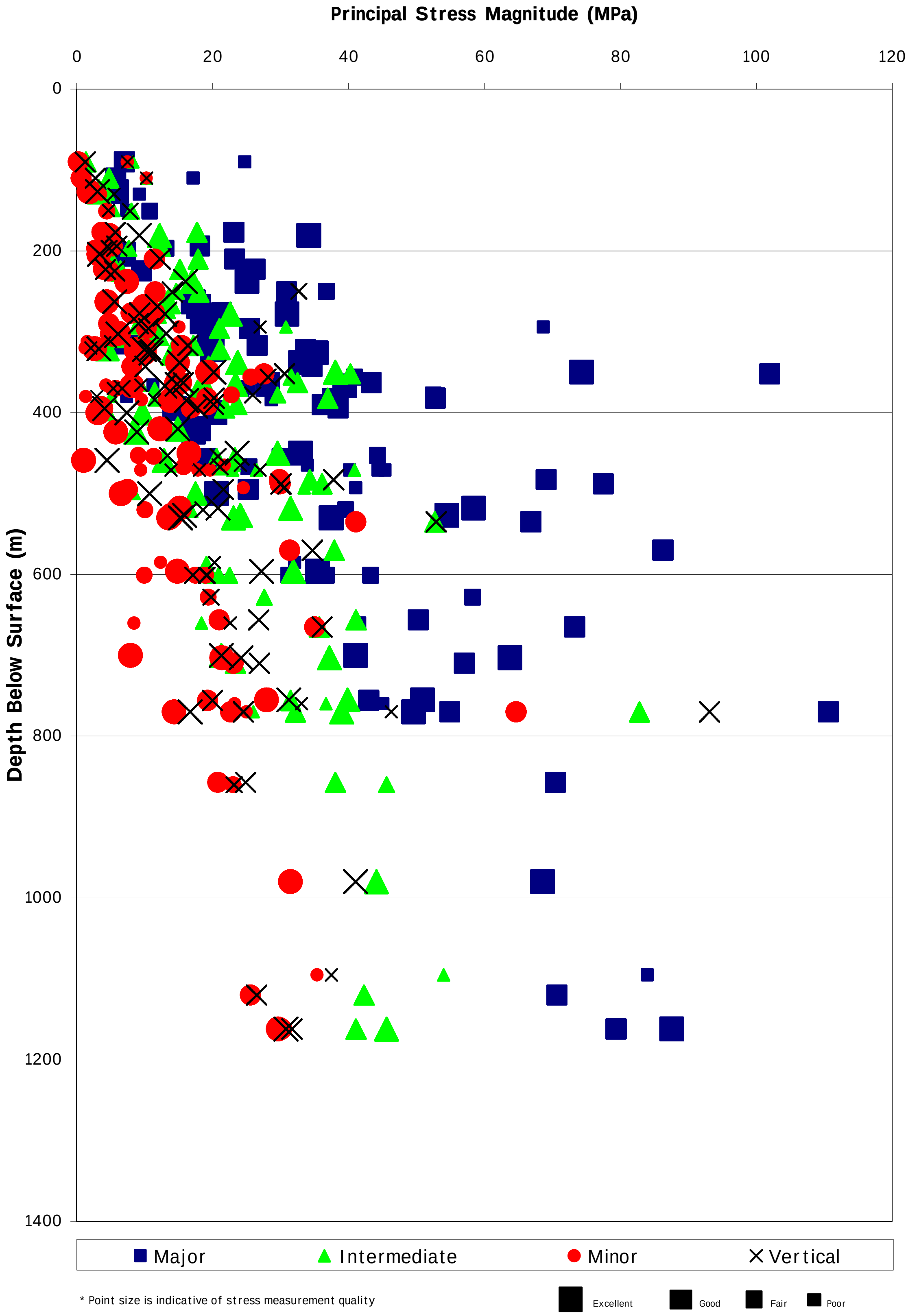


Figure 1: Yilgarn Depth versus Stress Plot (weighted)

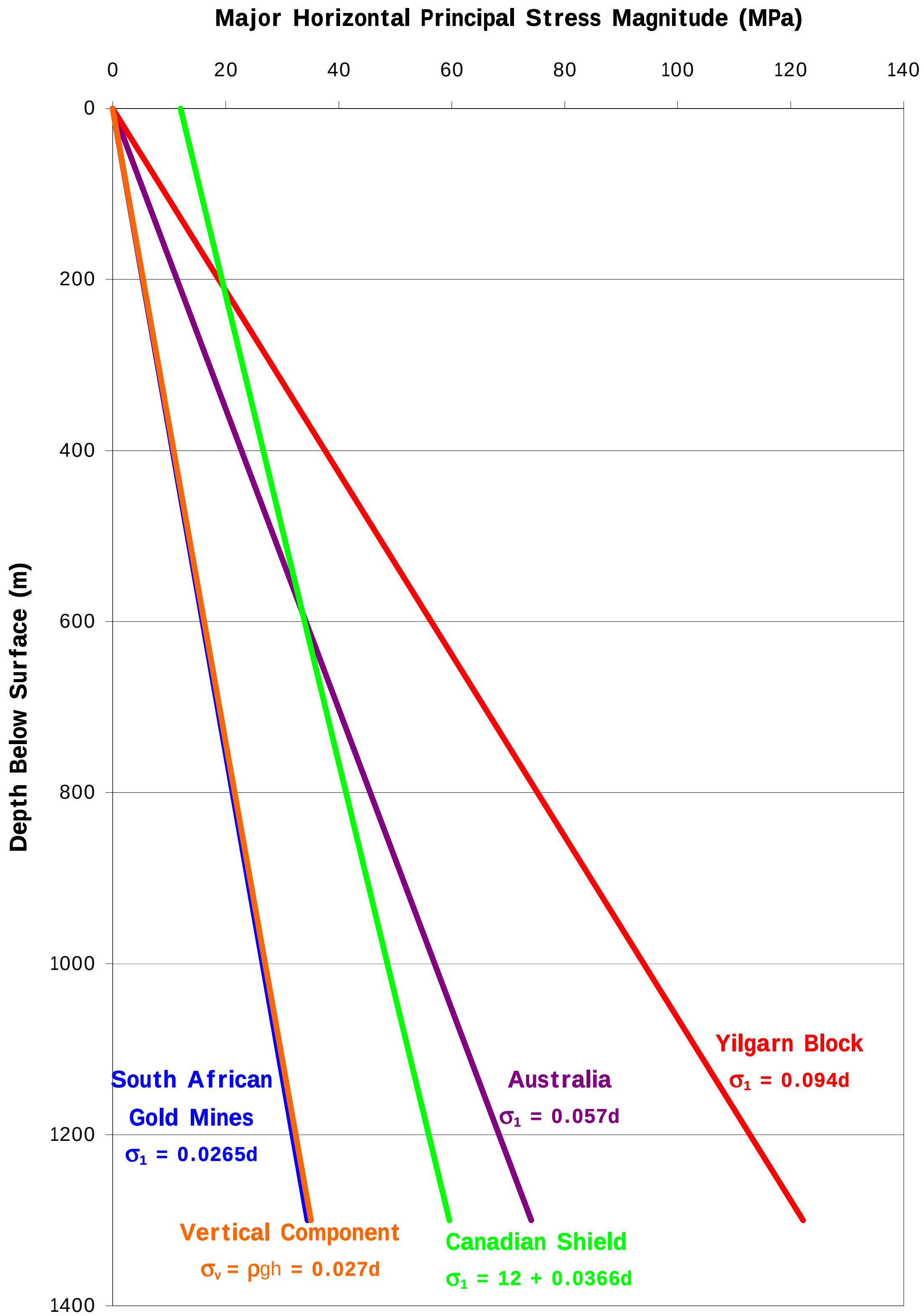


Figure 2: Stress Field Comparison
(Yilgarn vs Other Australian vs Canadian vs South African Gold Mines)

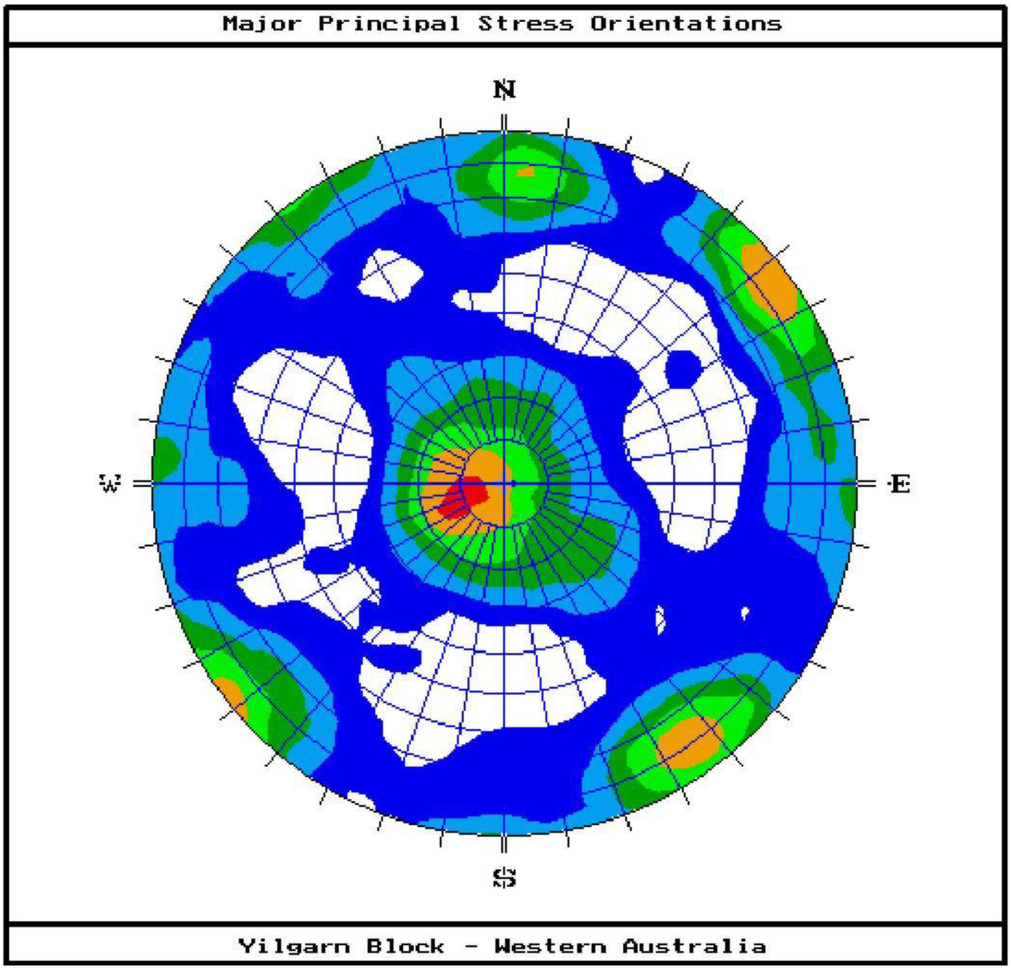


Figure 3: Orientation of Yilgarn Principal Stresses (weighted)

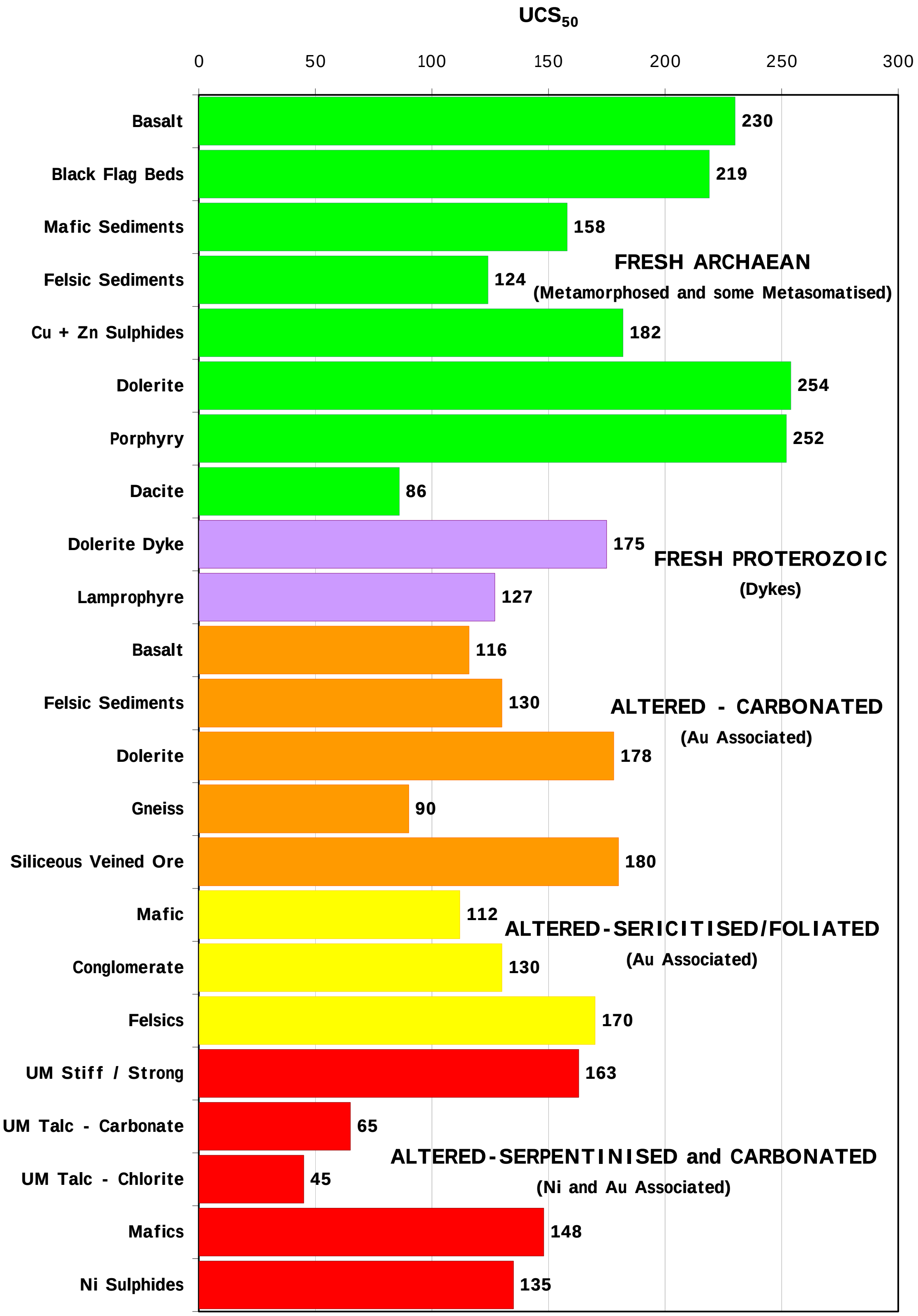
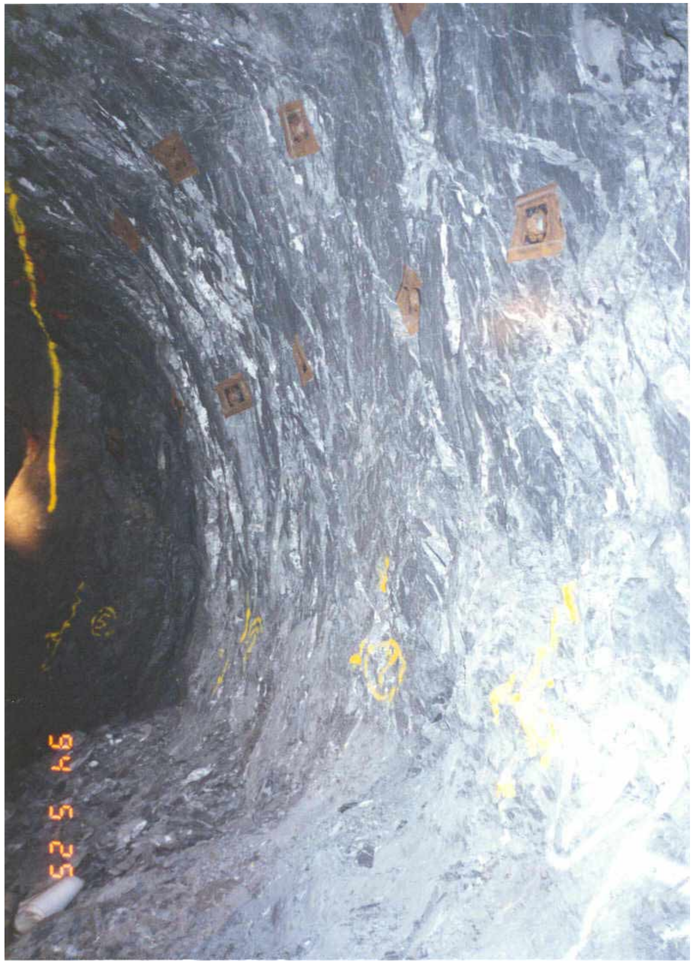


Figure 4: Typical Yilgarn Rock Strengths (MPa)

Figure 5a: Time-Dependent Ground Behaviour – BEFORE: SMALL OPEN STOPE IN TALC–CARBONATE ULTRAMAFICS

Figure 5b: Time-Dependent Ground Behaviour – AFTER : 5 DAYS LATER

Benign Dolerite (high stresses around corner)



Weak Black Shale (wall slabbing)

Figure 6: High Stress Slabbing

Bursting from back and walls in Dolerite (obviously meshed)

Progressive slabbing from a burst-prone porphyry dyke

Figure 7: Strain Bursting

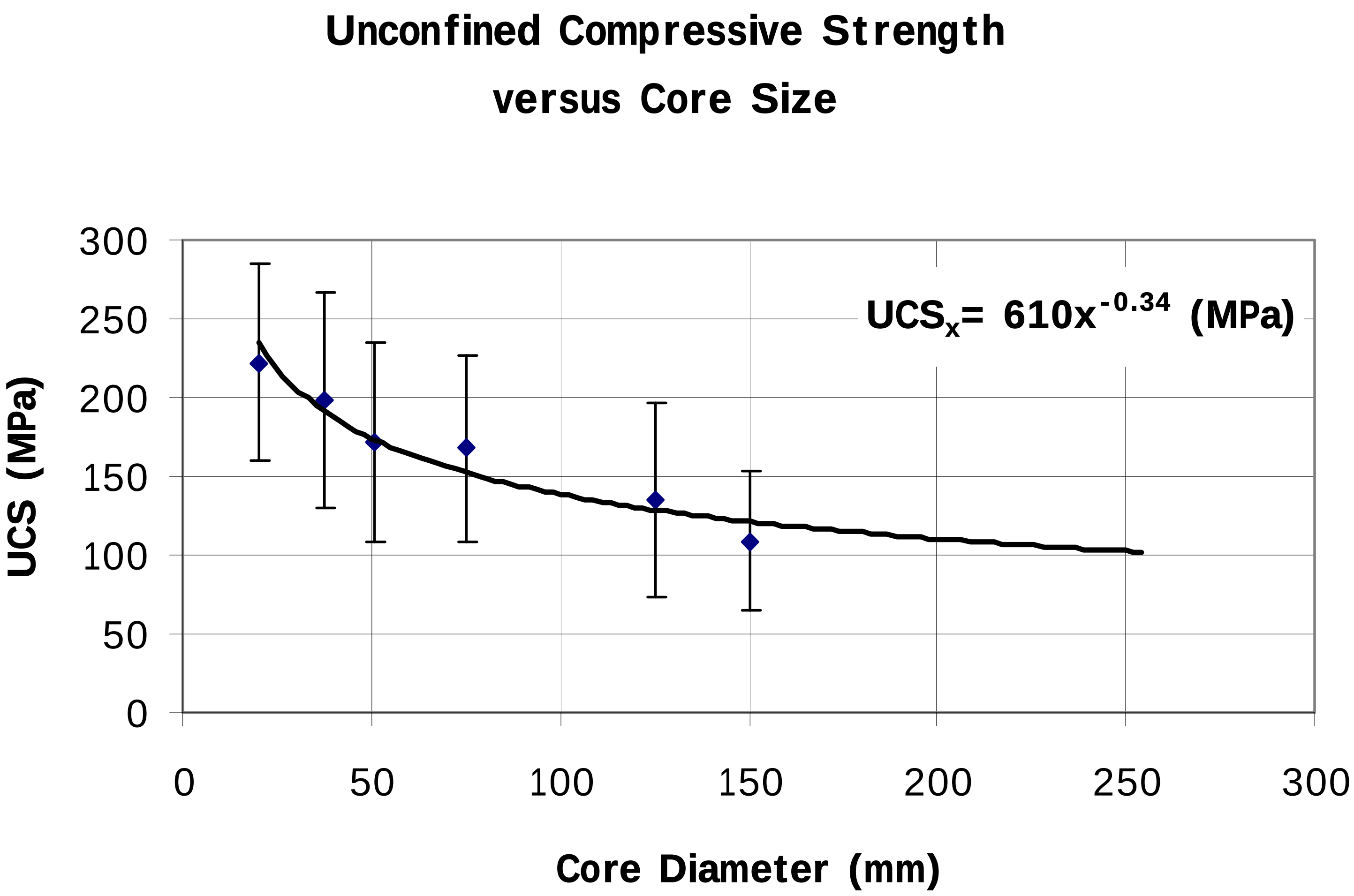


Figure 8: Compressive Strength vs Core Size

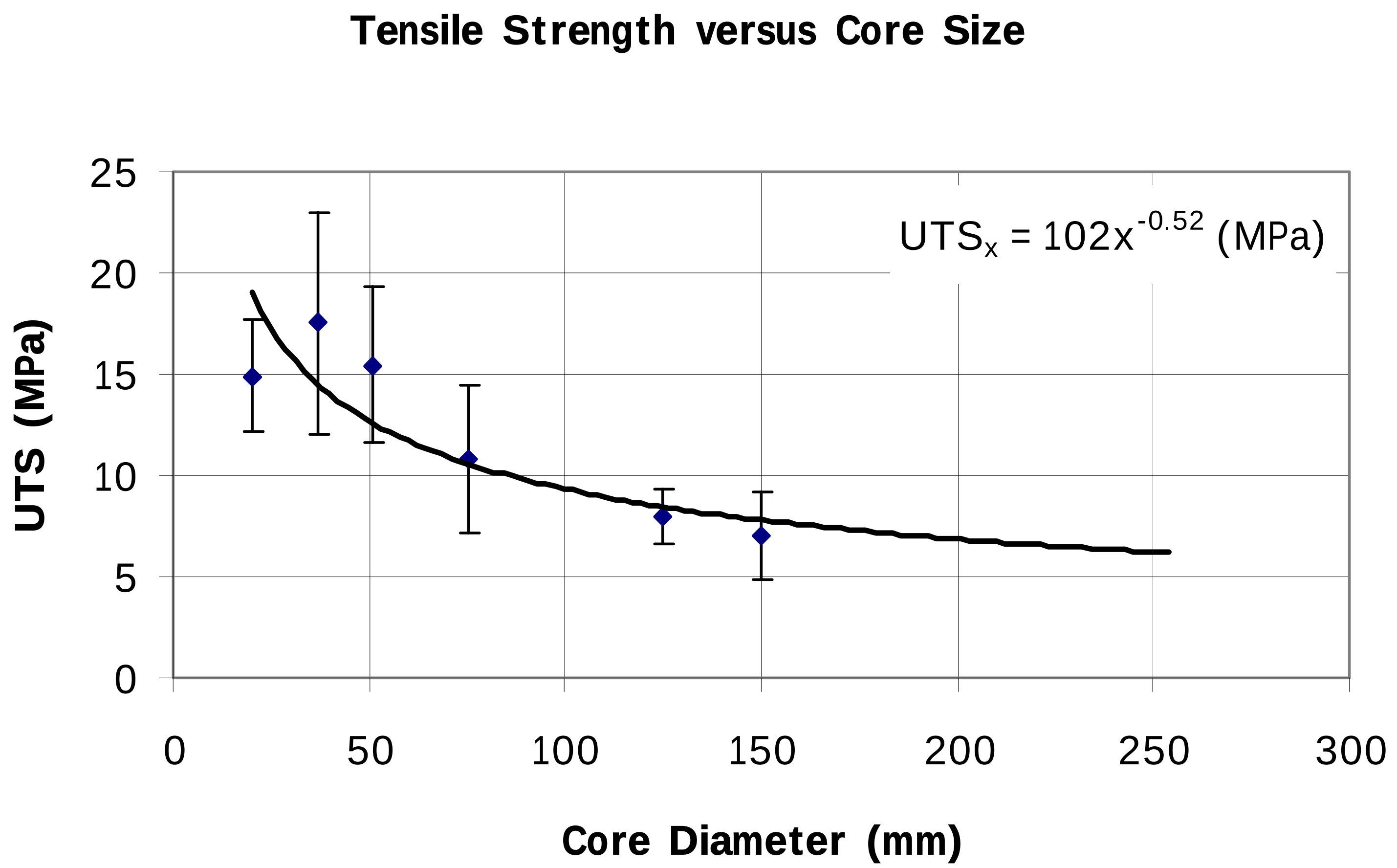


Figure 9: Tensile Strength vs Core Size

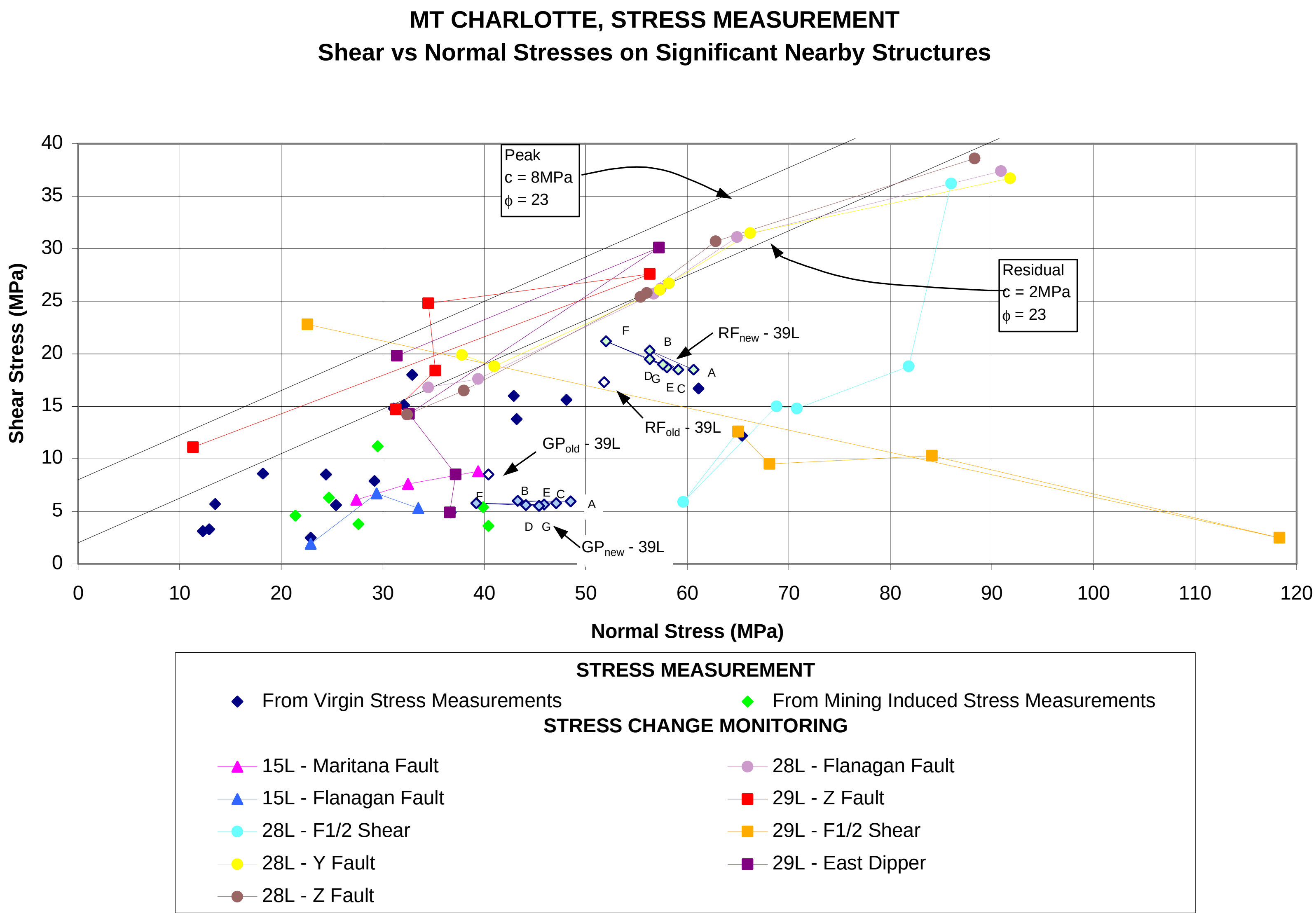


Figure 10: Shear vs Normal Stresses on Mt Charlotte Structures

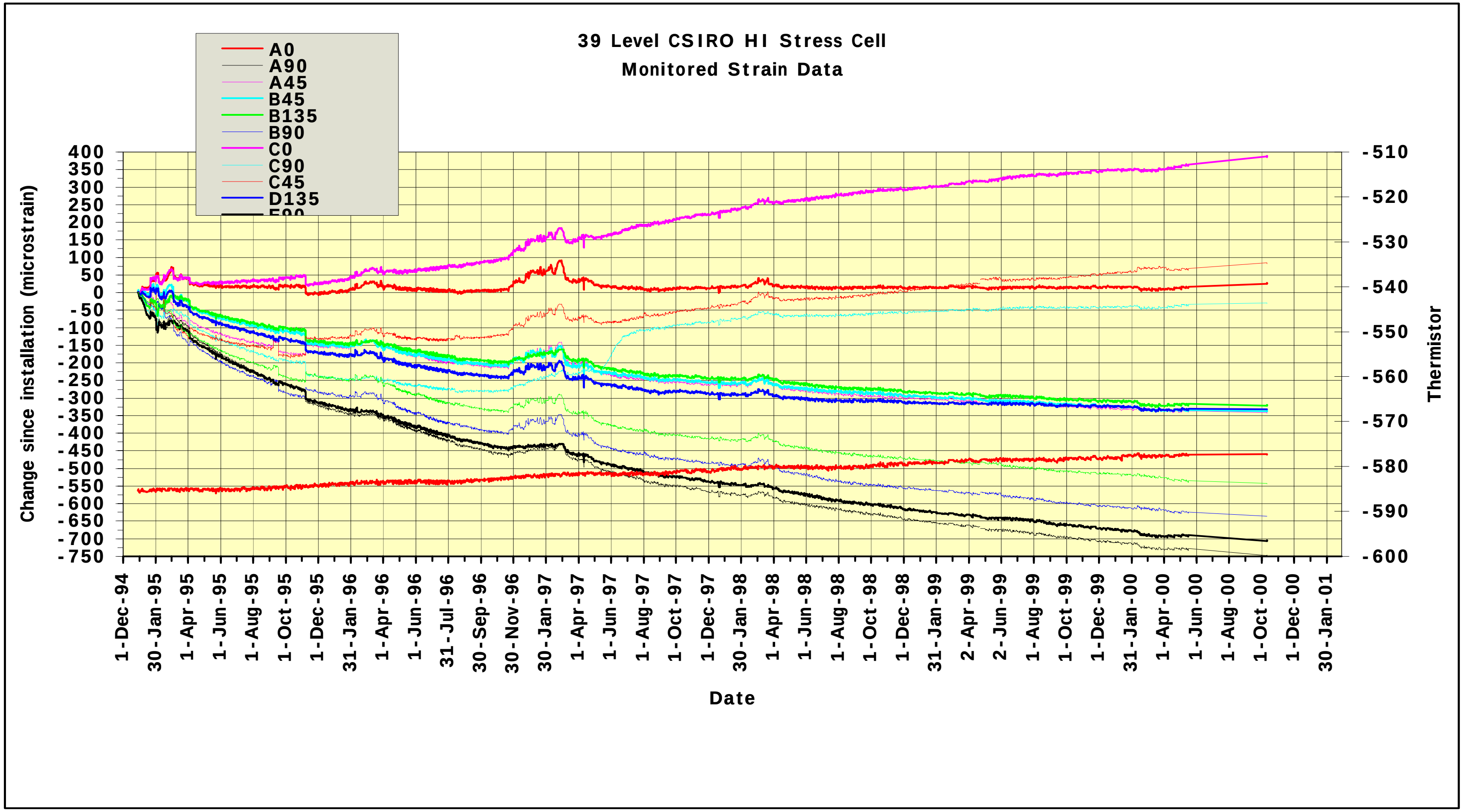


Figure 11: Periodic Stress Dips at Mt Charlotte on 39 Level

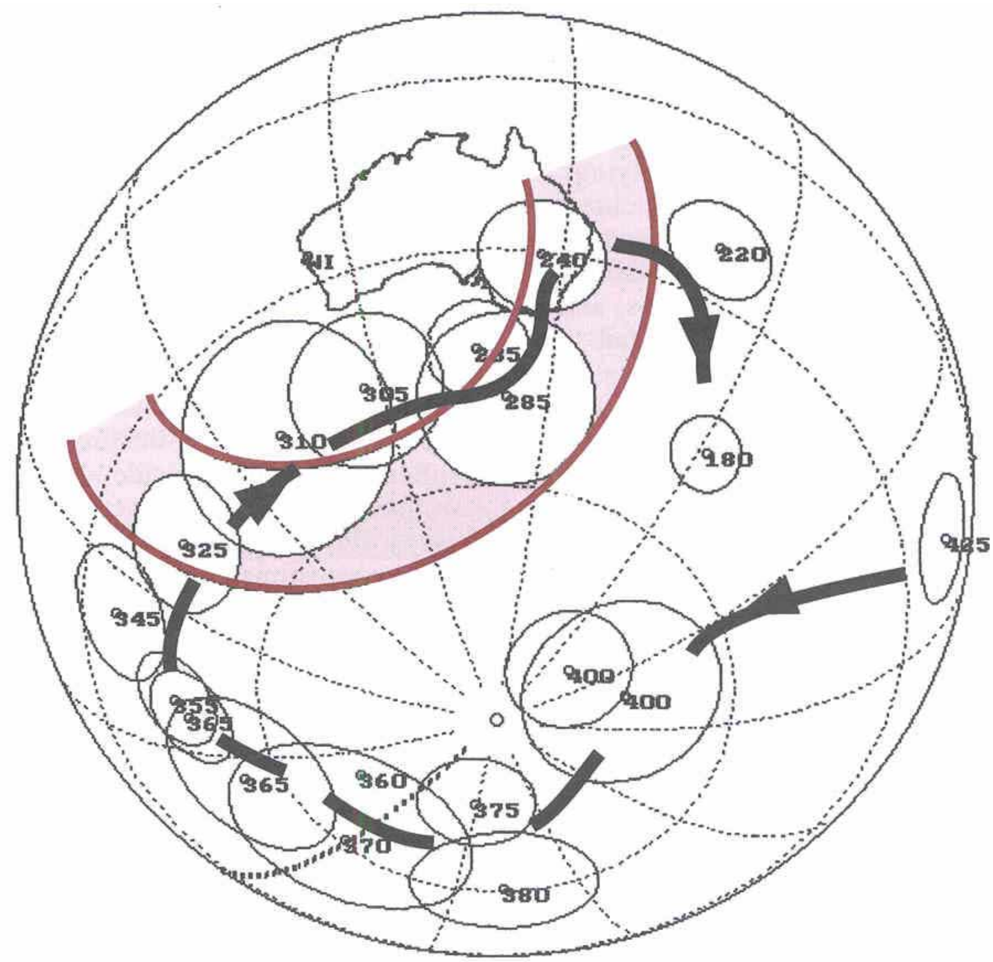


Figure 12: Movement of the Australian Plate – last 425 million years

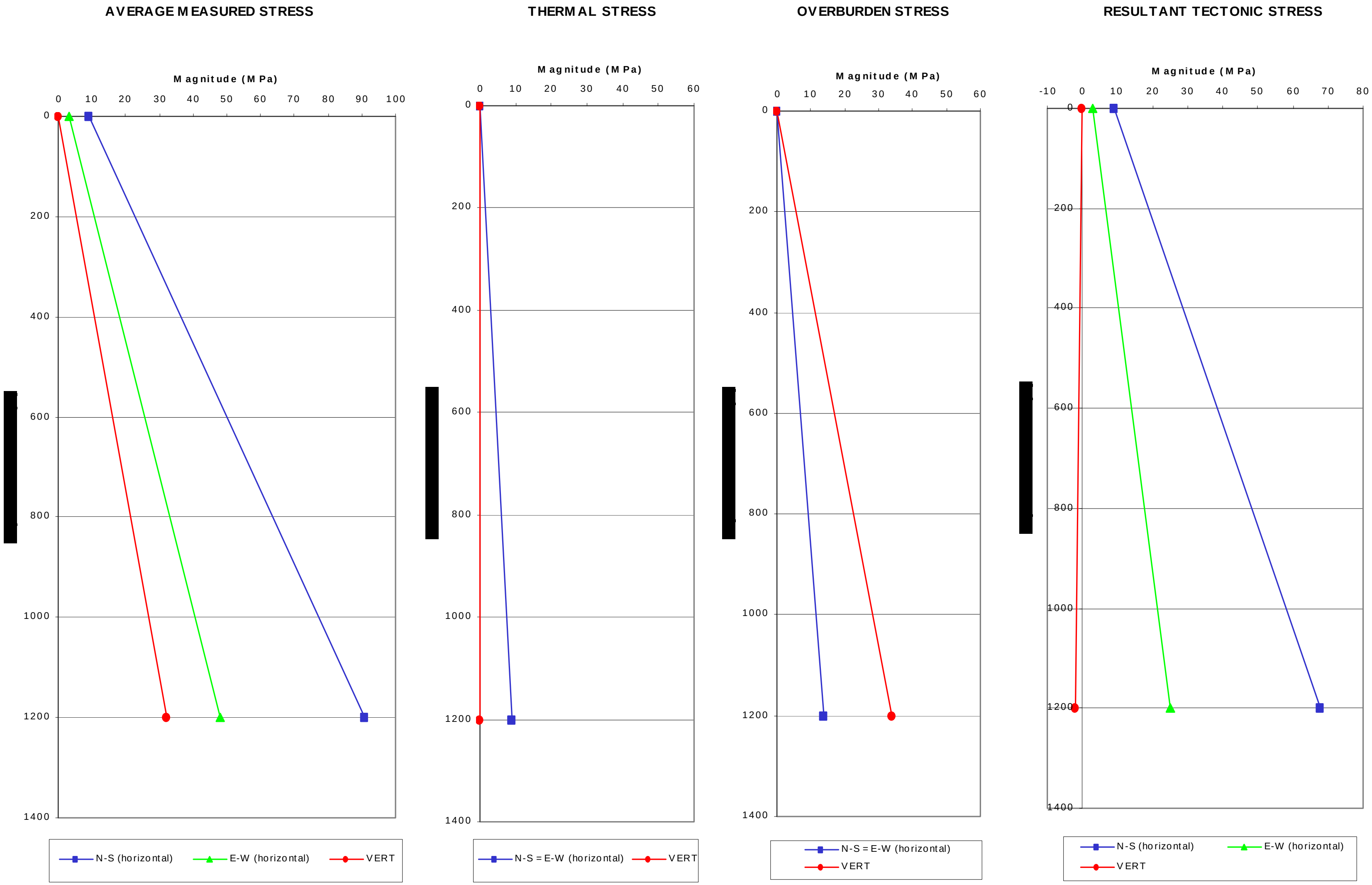


Figure 13: Mt Charlotte Stress Components

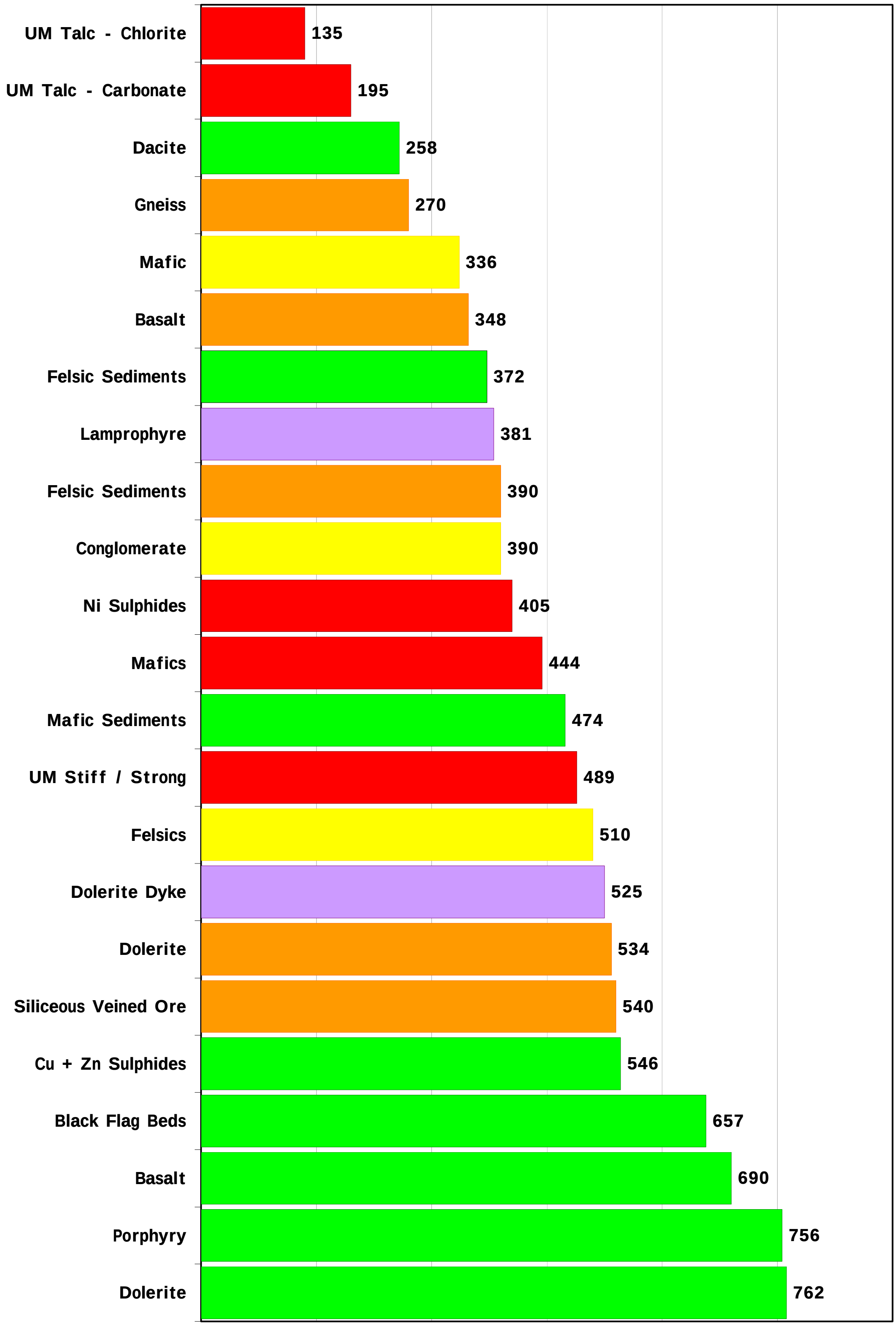
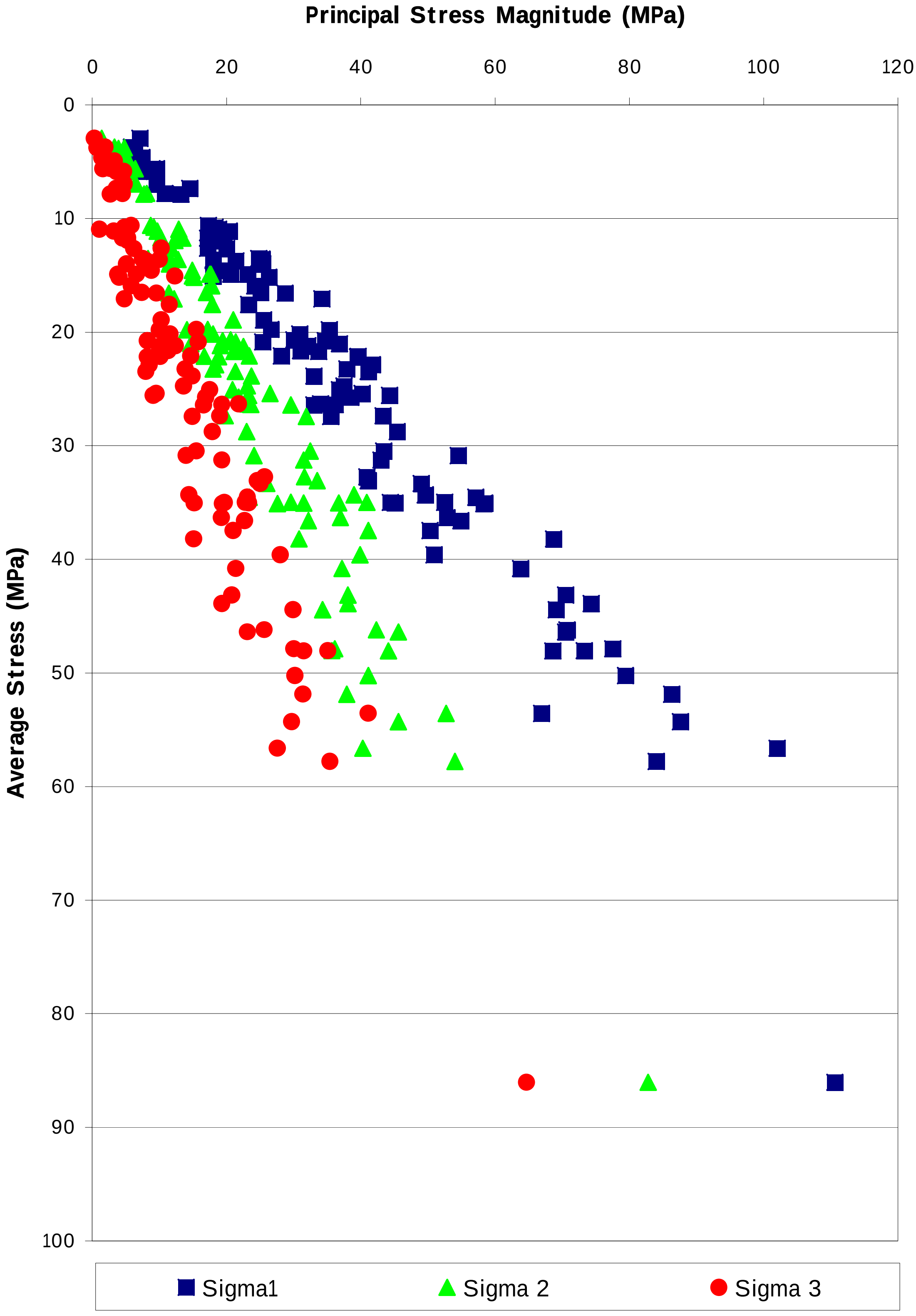


Figure 14: Likely onset of Spalling (depth) vs Rock Type


Principal Stress Magnitude (MPa)
0
20
40
60
80
100
120
Average Stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Sigma1
Sigma 2
Sigma 3