

EXPERIENCE OF OVERCORING THE ANZI STRAIN CELL IN HQ EXPLORATION BOREHOLES TO DETERMINE THE THREE DIMENSIONAL IN SITU STRESSES AT DEPTHS APPROACHING 1KM

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This paper describes recent use of the ANZI (Australia, New Zealand Inflatable) strain cell and the overcoring method of stress relief in an HQ exploration borehole at depths approaching 1km to determine the three dimensional in situ stress field in a one-day operation. The stages of a routine overcoring operation are presented to illustrate each step of the process. The results from a European metalliferous mining site are presented to illustrate the process of characterising the three dimensional in situ stress environment when multiple high confidence measurements are achieved.

The ANZI strain cell is an instrument system that uses the overcoring method of stress relief to determine the three dimensional in situ stresses in rock. The instrument has been used successfully for over three decades in numerous underground mining and civil projects but technical advances over the last decade have allowed the system to be deployed routinely in surface exploration boreholes. Recent development of a downhole electronic data logger, a wireline enabled drilling system and an instrument deployment system has simplified the process of obtaining three dimensional overcore measurements at previously inaccessible depths remote to any underground excavation.

The capability to deploy ANZI strain cells from surface exploration boreholes represents a significant breakthrough for the design of underground civil structures. High confidence characterisation of the in situ stresses at design stage provides the opportunity to design key infrastructure to take advantage of the in situ stress field from the outset before any excavation and construction activity even begins. Understanding the three dimensional in situ stress field not only provides a measure of the magnitude and direction of loads acting within the rock mass, it is also provided insight into the mechanics of the all the various processes driving ground deformations.

Keywords: overcore measurement, ANZI Strain Cell, three dimensional in situ stress.

1 INTRODUCTION

The overcoring method of stress relief is a method for determining three dimensional in situ stresses in rock. Overcoring the ANZI strain cell provides determination of the three dimensional in situ stress field, several independent estimates of the mechanical properties of the rock at a range of confining pressures, and importantly, an indication of the confidence that can be placed in each measurement.

A brief overview of the history of the ANZI cell is provided for context. The operation of the instrument and the various stages of testing used to provide confidence in the integrity of each measurement are described. Recent advances in the ANZI overcore system to enable measurements in surface exploration boreholes to depths approached 1km are also presented. These include:

- wireline enabled drilling techniques to prepare the pilot hole
- modular instrument deployment and pressurisation system
- high precision downhole strain, pressure and temperature logging
- increase in the number of axial gauges to measure axial strain variations.

Overcore measurements made in an underground European metalliferous mine illustrate the spatial and vertical variability in the stress field that can occur at the local and mine scale.

2 STRESS MEASUREMENT TECHNOLOGY AND LIMITATIONS

The concept of stress is a convenient engineering construct to link displacements and their derivative strain with forces through idealised models of material behaviour. Displacements and strain changes can be measured, but stresses cannot be measured directly. Changes in stress can be calculated from changes in strain by assuming a continuous, homogeneous, isotropic, linear elastic (CHILE) model of material behaviour.

To determine the in situ stress requires:

- a change in loading conditions, ideally from in situ conditions to conditions of zero stress
- the measurement of changes in six independent strains during stress relief
- an assumed material behaviour that relates stress to strain.

This relatively involved process means that in situ stresses determined from overcoring are in practice an estimate based on imperfect strain measurements and idealised rock behaviour. Although the term “stress measurement” is widely adopted, the limitations of the terminology should be recognised.

The overcoring process used with the ANZI strain cell allows a stress change in the rock, from the in situ state of stress at the start of overcoring to a zero state of stress at the end of overcoring. The strain changes measured by the ANZI strain cell during this process allow for the full three dimensional stress tensor to be determined based on an assumption of CHILE material behaviour. In practice, there are a variety of influences that are found to complicate this process, including drilling induced effects described by (Mills et al 2016), material behaviours that are not captured by the CHILE model described by (Mills and Gale 2016).

3 DEVELOPMENT OF DOWNHOLE OVERCORING USING THE ANZI STRAIN CELL

Mills and Puller (2017) provide a brief history of the overcoring method of stress relief from its beginnings by Lieurance (1933) in the 1930's, through to the use of strain gauged techniques in single boreholes from the 1950's onward. In the 1970's, Hiltcher et al (1979) developed an overcoring method for use in deep boreholes, where the pilot hole could be drilled without the need to withdraw drilling rods. This method is reported by Hallbjorn (1986) to have been successfully used to measure in situ stresses in exploration boreholes to depths of 500m. The ANZI overcoring system is similar to the method described by Hiltcher et al. (1979).

In 2014, a 48mm diameter (reduced from 58mm) version of the ANZI strain cell was developed to allow overcoring with a standard HQ coring bit. This version of the instrument was initially monitored using a data cable that ran to a logging system on the surface. Solid installation rods were initially used but these limited the installation depth to less than about 100m. These were replaced with a system using two cables deployed on a mechanised cable drum through the drill pipe. The first cable was connected to the instrument and monitored at the surface for the duration of the overcoring. The second cable was used to pressurise the instrument during installation and initial testing and then disconnected and withdrawn prior to overcoring. This approach was still somewhat cumbersome at depths greater than about 100m.

These various limitations were overcome with the development of:

- a drive sub installed behind the core barrel that provides for a wireline deployable downhole drilling system similar to the approach described by Hiltcher et al (1979)
- a high precision downhole data logging system fixed to the back of the ANZI strain cell
- a wireline enabled deployment system for the instrument and data logger
- an instrument pressurisation system that uses the drill pipe.

Mills and Puller (2017) describe in detail how these revised drilling, installation and data logging systems now enable routine overcore measurements at depths of 850m within a 12 hour shift.

4 OPERATION OF THE ANZI STRAIN CELL

The design of the ANZI strain cell is focused on providing systems to allow the confidence in each point measurement to be assessed. The confidence that can be placed in each estimate of the in situ stress varies for a range of reasons. The key is to be able to differentiate those as well as having sufficient duplication of measurement for rock behaviour to be characterised and departures from CHILE behaviour compensated for.

Figure 1 shows a photograph of the 48mm diameter version of the ANZI Strain Cell with the data logger attached prior to installation and one instrument after overcoring. The instrument has an inflatable polyurethane membrane with 18 electrical resistance strain gauges exposed on its outer surface. When the membrane is covered in epoxy cement and inflated during installation, the electrical resistance strain gauges become directly bonded to the wall of the pilot hole allowing direct measurement of strain changes in the rock as it is overcored. Further detail on the ANZI Strain Cell and its operation are provided in Mills (1997) and its specific application to overcoring in deep exploration boreholes is described in Mills and Puller (2017).

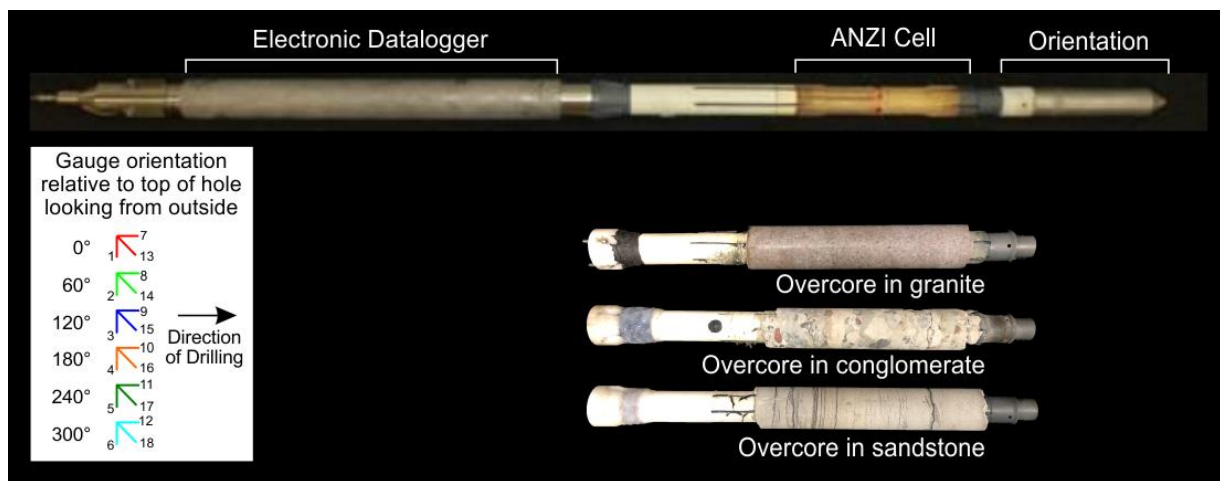


Figure 1: 48mm ANZI Strain Cell and downhole data logger prior to installation and recovered overcore, the result of which are used as examples throughout this report

There are six stages in the standard overcoring test procedure using the ANZI strain cell: preparation of the hole, installation, in situ pressure test, overcoring stress relief, biaxial pressure test and laboratory testing of the core recovered from the pilot hole. The following sections provide an overview of each of these stages.

5 BOREHOLE PREPARATION

A borehole is drilled to the measurement depth using standard drilling procedures. The borehole is commonly HQ size. A casing advancer drive sub is installed behind the core barrel. The end of the hole is prepared so that the HQ core stub is ground away and a centralising conical indentation is formed at the end of the hole. A small diameter pilot hole is then drilled concentrically from the end of the conical indentation in the end of the HQ hole, for a distance of 1m. The core from this pilot hole is inspected to determine the ideal horizon for instrument installation. The core from the pilot hole is retained for material testing in the laboratory.

6 INSTALLATION

Figure 2 shows a photograph of the instrument during installation. The outer surface of the ANZI strain cell is coated with a bespoke epoxy cement and deployed into the drill pipe on the wireline overshot with dry-release. Once the installation assembly is released from the overshot upon striking water, it floats downward until seating on the landing ring in the back of the core barrel. The pre-determined distance from the landing ring to the strain gauges positions the ANZI cell in the pilot hole at the target depth.



Figure 2: ANZI strain cell, data logger and installation assembly being readied for deployment in an inclined hole drilled to a depth of 740m. The collar of the hole is approximately 1340m below the ground surface.

Pressure is applied internally to the ANZI cell membrane by generating a positive pressure differential between the inside and the outside of the drill pipe. This pressure causes the strain gauges to be pressed directly against the pilot hole wall. Most of the epoxy cement coating is extruded away from the strain gauges and membrane under the pressure applied during installation. The membrane profile is designed to facilitate this process and leave a very thin (0.3-0.5mm) layer of cement between the gauges and the rock. When the cement has cured, typically 3-4 hours after installation depending on rock temperature, the strain gauges are bonded directly to the rock.

7 IN SITU PRESSURE TEST

Once the cement has cured, the internal pressure is varied to conduct a pressure test using the instrument as a dilatometer or pressuremeter. This test is used to:

- confirm that the strain gauges are well bonded to the rock
- provide an estimate of the in situ elastic properties of the rock under plane strain conditions prior to any disturbance that may be caused by drilling during the overcoring process
- provide, under some circumstances, independent confirmation of the in situ stress direction based in variation in elastic modulus around the borehole following the technique described by Mills and Gale (2016).

Figure 3 shows an example of a pressure test. The six circumferential gauges show the largest strain change. The six axial gauges show almost no change or a slight stretching consistent with the almost plane strain conditions at the centre of the pressurised length of borehole. The 45° gauges show a strain change midway between the circumferential gauges and axial gauges.

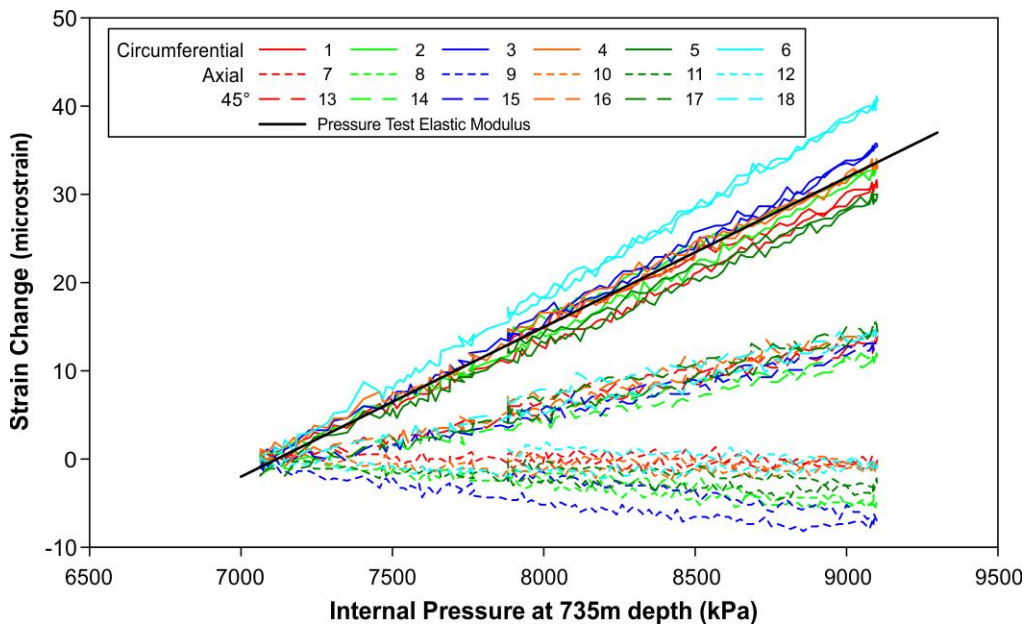


Figure 3: In situ pressure test result for ANZI instrument EMM5

8 OVERCORING

The ANZI strain cell overcoring operation is conducted in much the same way as for other instruments that use the overcoring stress relief method. Figure 4 shows an example of an ANZI overcoring result with the strain changes plotted relative to borehole depth/drilling distance. The final strains on all gauges are tensile, consistent with the relief of the compressive in situ stresses.

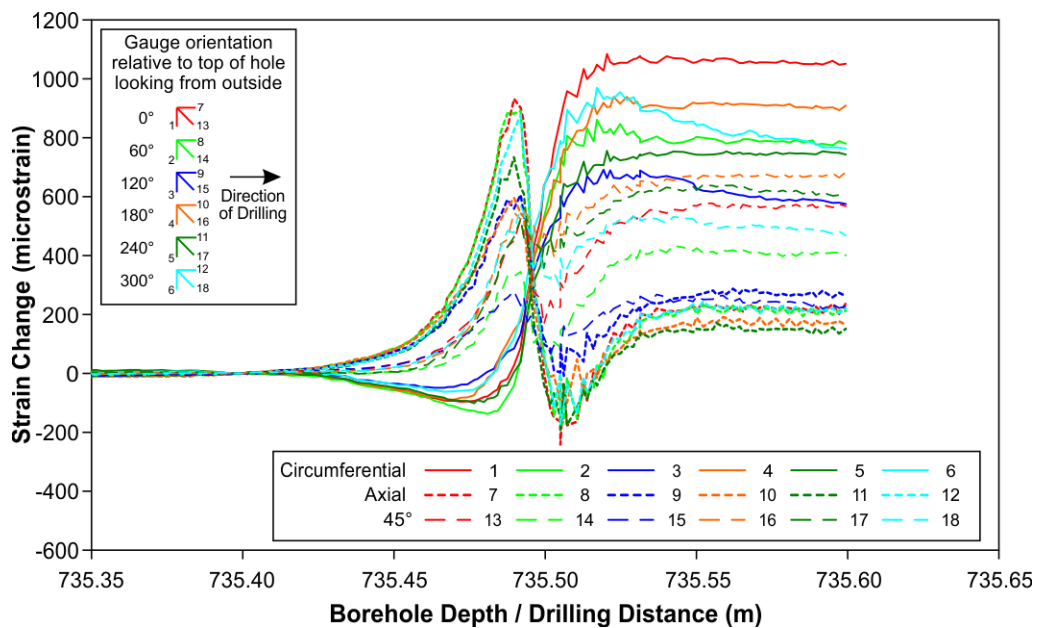


Figure 4: Strain changes observed during overcoring for ANZI instrument EMM5

The logger records strain, pressure and temperature every few seconds commencing before the instrument is deployed until it is recovered. The general form of the overcoring strain changes can be used as a basis to identify rosettes of strain gauges that may be behaving irregularly and should be ignored in the final analysis. Correlation of strains between opposing gauges and by the six independent measurements of axial strain provides an insight into rock behaviour during stress relief and an immediate indication of the level of confidence that can be placed in the strain data.

9 BIAXIAL PRESSURE TEST

A biaxial pressure test is conducted after the overcore is recovered. External pressure is applied incrementally to the outside of the rock annulus recovered when the pilot hole has been overcored with the instrument inside it. The elastic modulus and Poisson's ratio of the rock material can be estimated from this test at a range of different pressures. The strain changes measured provide not only an estimate of the CHILE rock properties but are also useful as an indicator of non-CHILE behaviour that may have been caused for example by permanent deformation during the overcoring process.

Figure 5 shows an example of a biaxial test result. The circumferential gauges show compressive strain changes consistent with the application of external pressure to the outside of the overcored rock annulus. The axial gauges show tensile going strain changes due to the Poisson's ratio effect of the external pressure being applied to the rock annulus.

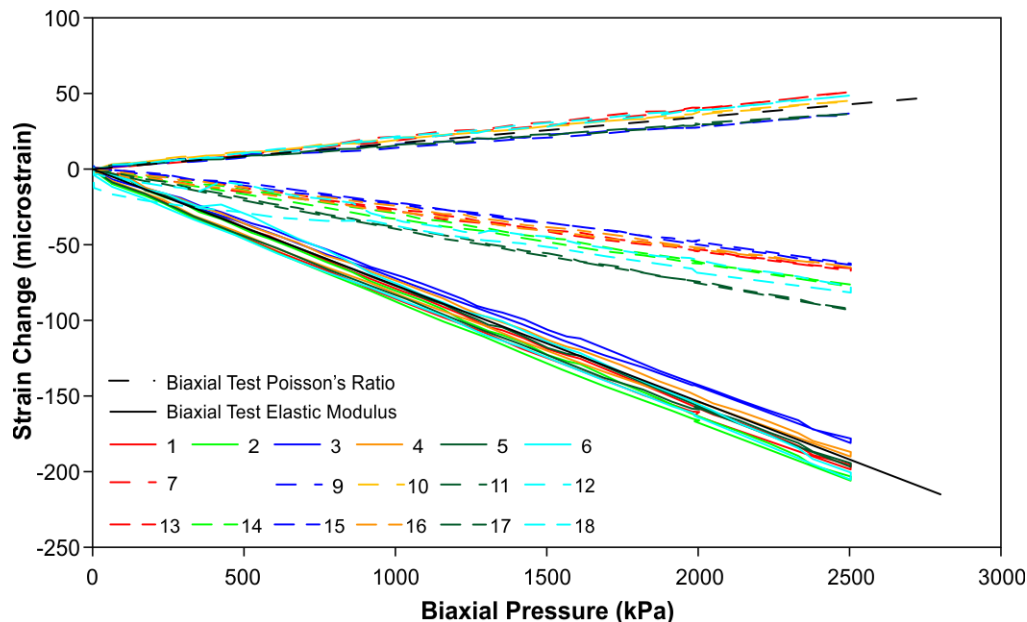


Figure 5: Biaxial test result for ANZI instrument EMM5

10 LABORATORY TESTING

Core recovered from the pilot hole at the location of the strain measurements is tested in a multi-stage uniaxial compression test to further confirm the elastic properties of the rock material. Axial and circumferential strain gauges and the load/displacement records of the compression test all the elastic properties of the rock to be estimated during three or more load/unload cycles up to failure in uniaxial compression.

11 ASSESSMENT OF ELASTIC PROPERTIES

The elastic properties of the rock are determined in three separate tests:

- in situ pressure test conducted prior to overcoring
- biaxial pressure test conducted after overcoring
- laboratory test on core recovered from the pilot hole.

These three tests are conducted on the rock at various stages of the measurement process and various confining stresses. In a CHILE material all three tests would indicate the same values of elastic properties but in practice there are commonly variations. These different conditions provide insight into the rock behaviour and the impact of drilling on the rock as it is unloaded and recovered from the hole.

Variations in elastic properties are commonly observed and these variations have provided useful insights into the processes that occur at the tip of a borehole during drilling and a range of factors that affect the behaviour of rock materials. Figure 6 shows an example of the elastic modulus variation at different confining pressures. The confining pressure is represented in Figure 6 as the first stress invariant which is the sum of the three principal stresses. A single value of elastic modulus is required to estimate the in situ stresses from the measured strains. Given the variation typically observed, an elastic modulus midway between the first stress invariant of the in situ stresses (pre-overcoring stress state) and zero (post-overcore stress state) is used in the analysis.

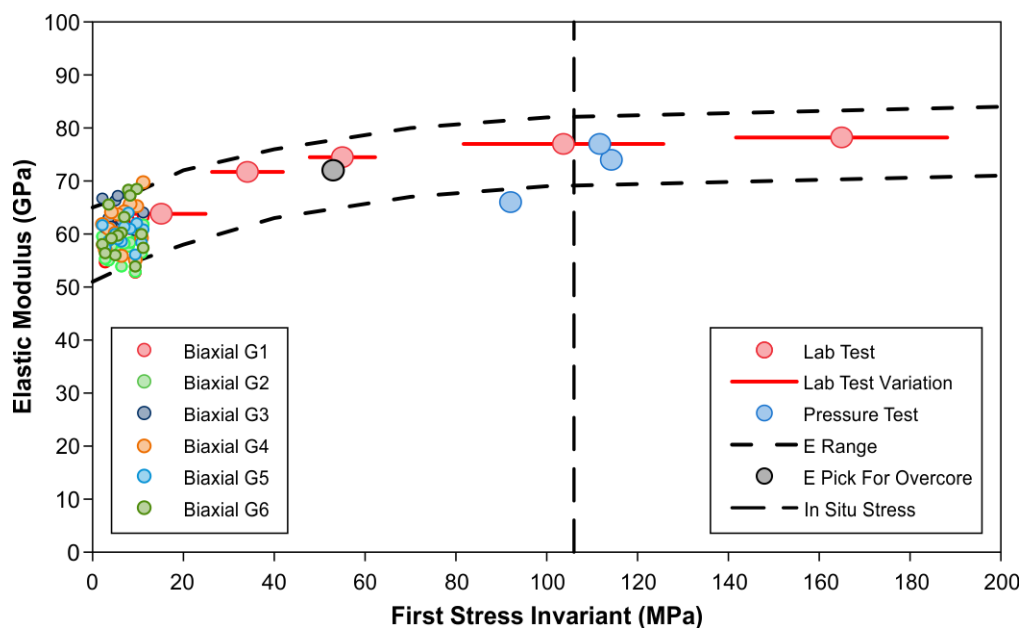


Figure 6: Variation of elastic modulus with first stress invariant (sum of the three principal stresses) for ANZI instrument EMM5

12 CASE STUDY OVERCORING AT A DEPTH OF 2050M BELOW SURFACE IN A METALLIFEROUS MINE

A single HQ borehole was collared from at 1340m below surface in an underground European metalliferous mine and drilled to a depth of 740m. The borehole dipped at an angle of 81°. Three campaigns of overcore measurements were conducted at depths in the borehole of approximately 50m, 350m and 740m. Two high confidence point measurements were made at each of the three measurement horizons. The stress field at this site was characterised using the results from these overcore measurements.

The interpreted in situ stress results from these six overcore measurements are summarised in Figure 7. There is close agreement of the in situ stresses indicating a stress field that is consistent in orientation over the length of the hole.

Four of the measurements also show close agreement in magnitude with the major principal stress having a well constrained magnitude of 53MPa, dipping 30° at a bearing of 195°. The other two overcore measurements, EMM4 and EMM5, indicate stresses that are consistent with the overall stress field in terms of orientation but show stress magnitudes that have been locally reduced at the point of measurement. These two measurements indicate the north-south major principal stress is 12MPa to 24MPa lower than the other point measurements, including those that are only 6m away. The cause of this variability is not known but anisotropy and differences in material properties of the rock between overcore locations are comparatively small and not thought to be responsible for stress reductions observed.

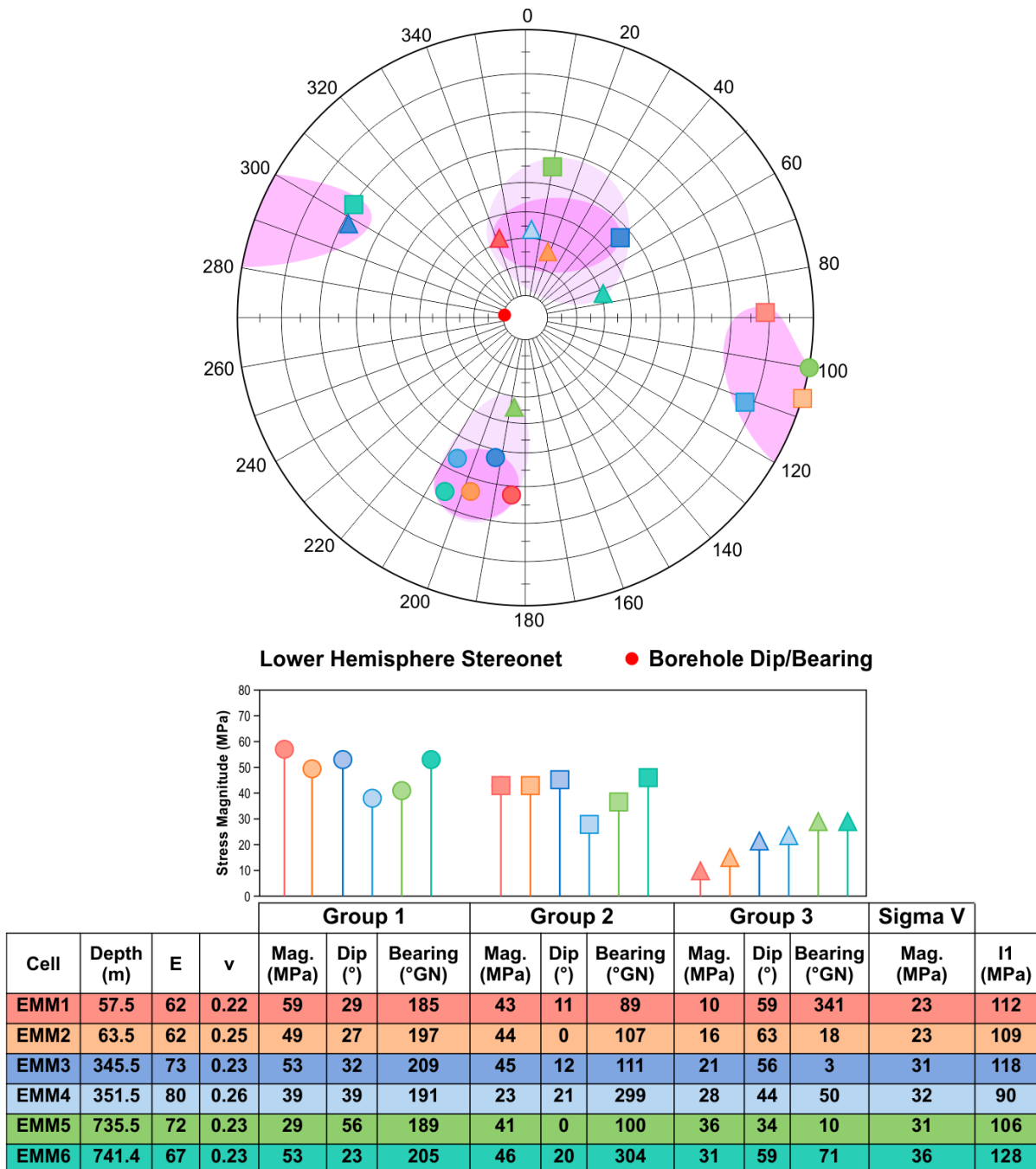


Figure 7: Stress measurement results from a European metalliferous mine

Figure 8 shows the depth/stress magnitude relationship for the principal stresses and for the first stress invariant. When EMM4 and EMM5 are ignored, the magnitudes of σ_1 and σ_2 are approximately constant at 53MPa and 44MPa respectively over the length of the borehole. The minor principal stress shows an approximately linear trend of increasing with depth consistent with increasing weight of overburden rock.

The ratio of σ_1 and σ_2 (i.e. the north-south and east-west stresses) is consistent with depth and averages approximately 1.2. This ratio is low when compared to other locations SCT have conducted overcoring measurements.

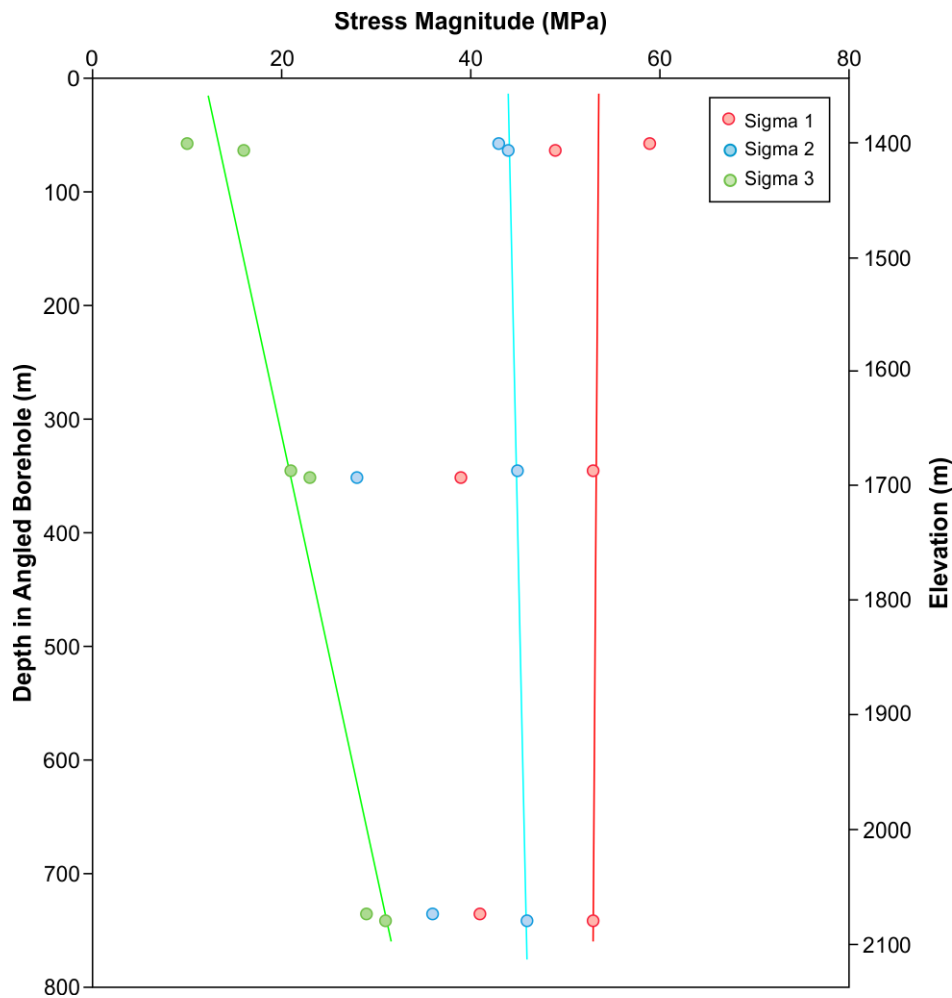


Figure 8: Depth/stress relationship for the three principal stresses and first stress invariant at a European metalliferous mine

13 CONCLUSIONS

The capability to deploy ANZI strain cells in exploration boreholes represents a significant technological breakthrough for the design of underground mines and underground excavations generally. Being able to obtain high confidence measurements of the three dimensional in situ stresses at the planning stage of any underground construction activity provides the opportunity to take advantage of these stresses in design of underground structures. Not only does it become possible to protect key infrastructure by locating it away from areas of stress concentration, advantage can be taken of the major stresses to promote caving through appropriate design.

The high levels of redundancy in both the instrument and the measurement technique are designed to provide an indication of the confidence that can be placed in each result and to enhance the understanding of material behaviour at the point of measurement and ground behaviour at the site more generally.

The ability to characterise the three dimensional in situ stresses at a site by making multiple point measurements is demonstrated. Understanding the spatial and depth related variability in the stress field at a local and mine scale becomes possible when multiple high confidence measurements are achieved.

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