Stress measurements at great depth at Craig-Onaping Mines, Sudbury Canada

E. Villaescusa, L. Machuca & C. Windsor
CRC Mining, Western Australian School of Mines, Kalgoorlie, WA, Australia

B. Simser & S. Carlisle
Xstrata Nickel, Onaping Ontario Canada

ABSTRACT: Reliable estimation of in situ stress is a major step in the analysis and design of underground excavations in rock, particularly for evaluating the stability of underground structures to prevent failure or collapse. In the last ten years, the Western Australian School of Mines (WASM) has studied and developed an AE stress measurement technique using orientated core named the WASM AE method. It allows the determination of a representative and detailed knowledge of the in situ stress field during the early stages of a project (such as mine feasibility studies), even in areas where development access is not yet available. The method has been used for in situ stress measurement at more than 80 mine sites worldwide with over 200 individual stress measurements carried out to date. This paper describes the sample collection, sample testing and reconciliation of results for very deep measurements carried out at the Craig-Onaping mine complex in Sudbury Canada. The results constitute the deepest measurements undertaken to date at the WA School of Mines and indicate that the main principal stress is horizontal and oriented parallel to a common regional sub trend in a NE/SW direction.

1 INTRODUCTION

Effective planning, design and operation of deep underground mines requires a good understanding of the geological environment. In essence, knowledge of large scale structures, rock mass strength and deformability, as well as *in-situ* stress is required prior to the start of the mining operations. These data are required as input to numerical models of the planned extraction sequences in order to predict the performance of excavations and to design appropriate ground support schemes. Over the last ten years researchers at the Western Australian School of Mines (WASM) have developed techniques for measuring *in-situ* stress from oriented core, obtained from remote locations well in advance of mining development (Villaescusa et al,2002; 2003). This information can be used to estimate the mobilized shear stress on large scale structures that are likely to cause failure, seismicity or influence the overall rock mass behaviour at a global mine scale (Windsor et al, 2007).

2 MINE LOCATION

The Craig-Onaping Mine is located in the Onaping-Levack region on the Northwest rim of the Sudbury Igneous Complex, roughly 45 minutes from downtown Sudbury (see Figure 1). It is in close proximity to the Fraser Mine and the Strathcona Mill. The Onaping mine was amalgamated with Craig to form one mine in 1997. Activity at the Onaping shaft has since decreased to providing a few services including second egress for Craig. The Craig Mine's shaft is currently 1500m deep and blasthole/longhole and cut & fill stoping are the major mining methods used. Longhole/blasthole stoping accounts for about 70% of the mining that occurs while Cut-and-fill is used for the remaining 30%. Where geometry and continuity permit, blasthole mining

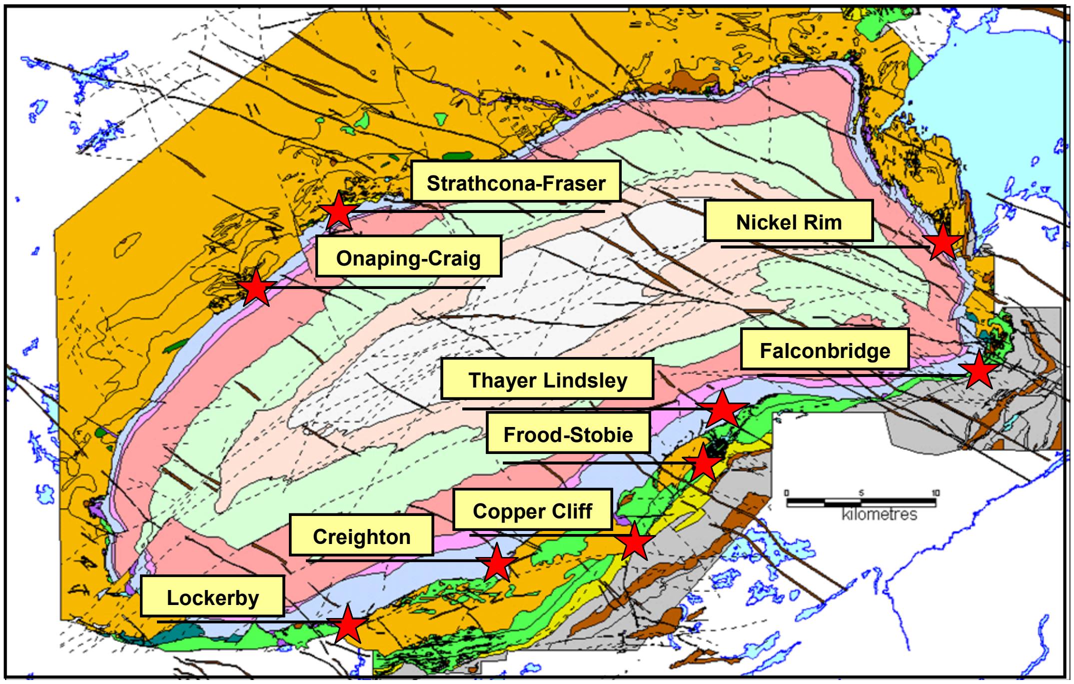

Figure 1. General illustration of the Sudbury basin area (MAP249 - Ontario Geological Survey).

is the method of choice; where the ore is more erratic and 'poddy' in nature, cut-and-fill is selected for mining. Cut-and-fill has, to date, been utilized for the greater percentage of the mining at Craig (~80%). If possible, the waste rock is placed in mined stopes so that it does not need to be hoisted to surface for disposal.

The combined mineral reserves plus past production totals 16.6 million tonnes grading 1.86% Ni and 0.67% Cu (as of Dec 31, 2006). The Craig deposit consists of nine discrete zones striking over a strike length of 1000m and lying between 800 and 1900 m below surface. The Onaping deposit lies about 1000m west of the Craig deposit and consists of three discrete zones striking over a strike length of 800m and lying between 550 and 1800m below surface (see Figure 2). The ore zones are quite variable in dimension and attitude but generally strike north to northeast and dip 40 to 45 degrees to the southeast. A distinct southeast plunge is common to most zones and a secondary northeast plunge is also evident.

3 EXTRACTION SEQUENCES

The overall mining sequence at Craig mine is based on the chosen mining methods, which is determined by the geometry of the ore and the geotechnical risk. For example, in some blasthole zones a pillarless sequence is used to avoid concentrating stress. For primary/secondary sequences the secondary pillars are normally dimensioned to 'fail', so that large induced stresses and related seismicity are not encountered. In some cases, it is required to mine ore blocks in close proximity to each other and sometimes the longest stringers are prioritized to minimize lengthy retreats.

The long-term mine planning and related extraction sequencing is assisted by numerical modeling. In addition to input of the different rock strength properties, field investigations are often conducted prior to creating any two and three-dimensional models. Investigations normally involve examination of diamond drill cores for RQDs and disking, geotechnical mapping, and confirmation of the different rock types. For in-house numerical modeling, Craig Mine uses 3D boundary element models and 2D finite element models. Occasionally, the mine uses external consultants for 3D non linear modeling. In all cases, determination of *In-situ* stress magnitude and orientation with depth becomes a key input parameter to determine to determine the appropriate mining method, mine sequencing and ground support systems at the Craig Mine.

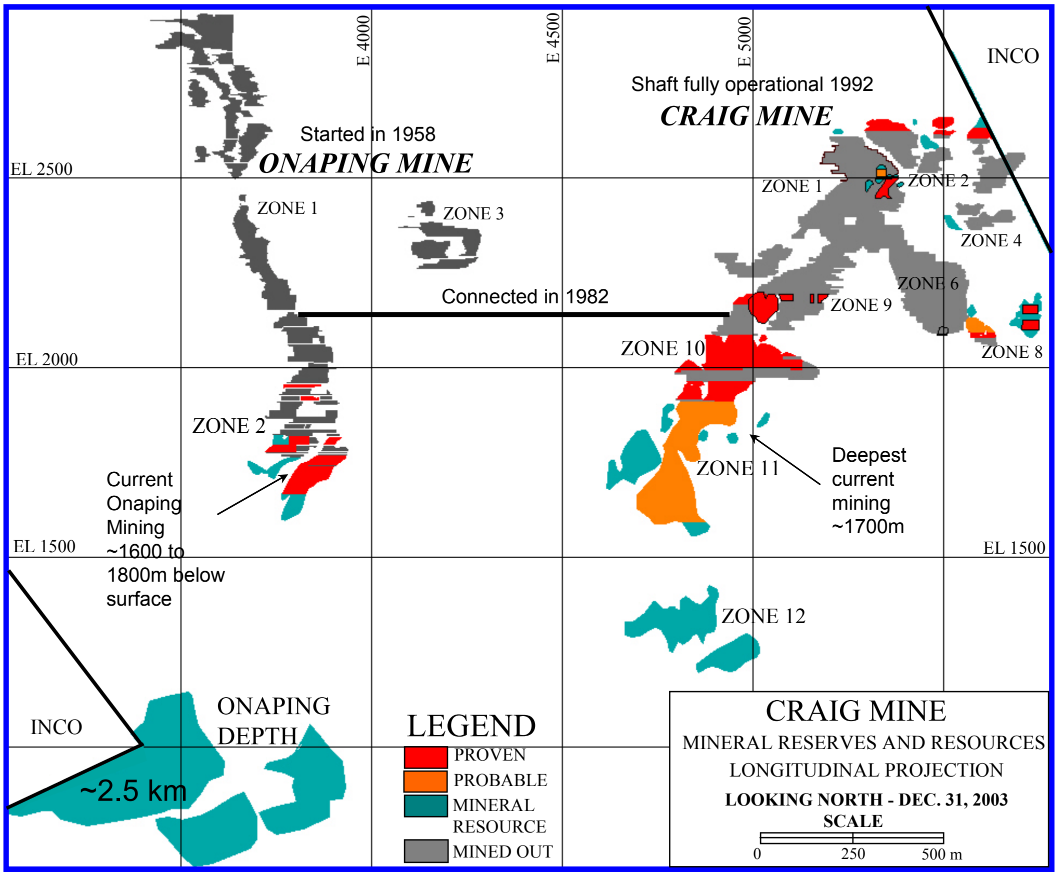

Figure 2. Craig-Onaping mine zones (Simser, 2008).

4 ACOUSTIC EMISSION TECHNIQUE

Acoustic emissions (AE) are bursts of high frequency elastic waves caused by localized failure of a material when it is placed under load. When a rock core sample is loaded and the acoustic emission monitored, it is observed that at a certain stress level the amount of acoustic emission increases markedly (see Figure 3). The arrow in Figure 3 indicates the stress at which the acoustic emission increases markedly. The basis of the proposed AE stress measuring technique is the identification of the stress at which the AE increases markedly with the maximum previous stress along the loading axis to which the core had been subject by its in situ environment.

The effect was first observed by Kaiser (1953) in the experimental study of metal that were able to "recollect" the previous applied stress level. The Kaiser effect was also observed in rock (Kurita and Fujii, 1979) and it is believed that the Kaiser effect in rock is closely related to the extension of microcracks that had been formed in a previous stress state (Seto et al., 1995). The extension of the microcracks induces the active AE and inelastic strain behavior after the previous stress level is exceeded. In addition, the AE is generated by the irreversible movement of a discontinuity or a crack inside a rock core specimen, such as shearing and closure, as well as microcracking.

Since a rock specimen inevitably includes microcracks, the first loading cycle often produces noise associated with crack closure or compaction that can sometimes obscure the take-off point of increased activity. This noise in the first cycle of loading, however, can be suppressed by subsequent unloading-reloading cycles at stress levels below the Kaiser effect, thereby making the take-off in AE associated with the Kaiser effect more pronounced. Most noise is reduced by the second cycle and the previous stress can be estimated by a clear AE take-off in the second cycle of loading (Seto et al, 1999).

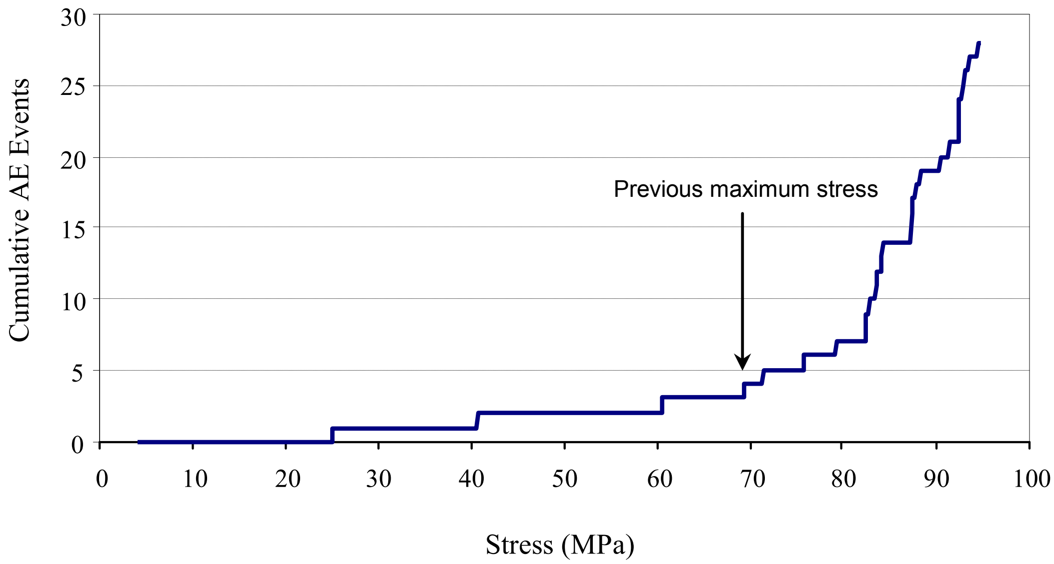

Figure 3. Typical AE cumulative count of core sample versus stress - Craig Onaping Mine specimen.

5 STRESS TENSOR CALCULATION

The stress tensor is six dimensional (three normal stresses and three shear stresses) and therefore six independent normal stress measurements are required to determine the stress tensor:

$$[\sigma] = \begin{pmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{pmatrix} \quad (1)$$

with respect to a mine north (X), east (Y), vertical (Z) right-handed co-ordinate system. Six independent instances of the equation (2.14) of Brady and Brown (1985):

$$\sigma_n = l_x^2\sigma_{xx} + l_y^2\sigma_{yy} + l_z^2\sigma_{zz} + 2l_xl_y\tau_{xy} + 2l_yl_z\tau_{yz} + 2l_zl_x\tau_{zx} \quad (2)$$

where σ_n is the stress obtained from the Acoustic Emission of a core sample, whose orientation is given by the unit vector $l_x\bar{i} + l_y\bar{j} + l_z\bar{k}$ and used to form a system of equations which can be solved for the stress tensor $[\sigma]$. The principal stresses are then determined by a standard eigenvalue analysis of the tensor $[\sigma]$.

The underlying philosophy of WASM technique stress measuring technique requires six small cylindrical samples of rock that are undercored from conventional oriented drill core recovered from the site for which stress data is sought (Villaescusa et al, 2003). Undercoring means re-drilling in the laboratory the oriented core obtained from the field in order to obtain the specimens for testing. Each undercored sample is instrumented with pair of acoustic emission (AE) transducers. The samples are then loaded uniaxially with the AE transducers providing a record of the number of AE 'events' with increasing load and hence stress. Finally, the AE information from the six axes (see Figure 4) is analysed to give six independent normal stresses from which the full stress tensors can be obtained. Figure 5 shows the typical uniaxial compressive strength for each of the undercoring axis for the 18-20mm rock specimens tested at the Craig Onaping Mine. The WASM AE methodology and sample selection it is well documented (Villaescusa et al, 2002; 2003; 2008) and currently being implemented worldwide on a number of deep mining projects.

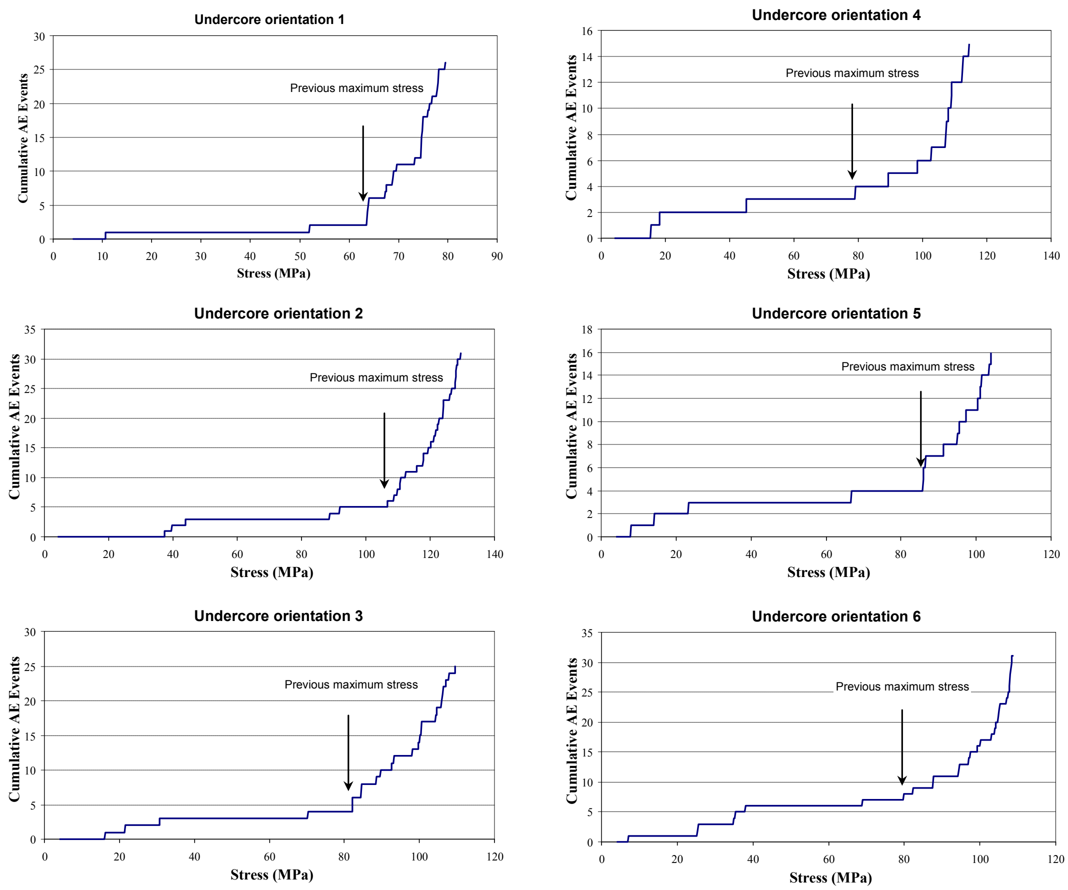

Figure 4. Typical cumulative AE events versus stress curves for each undercoring orientation for Craig-Onaping Mine, 2311m deep.

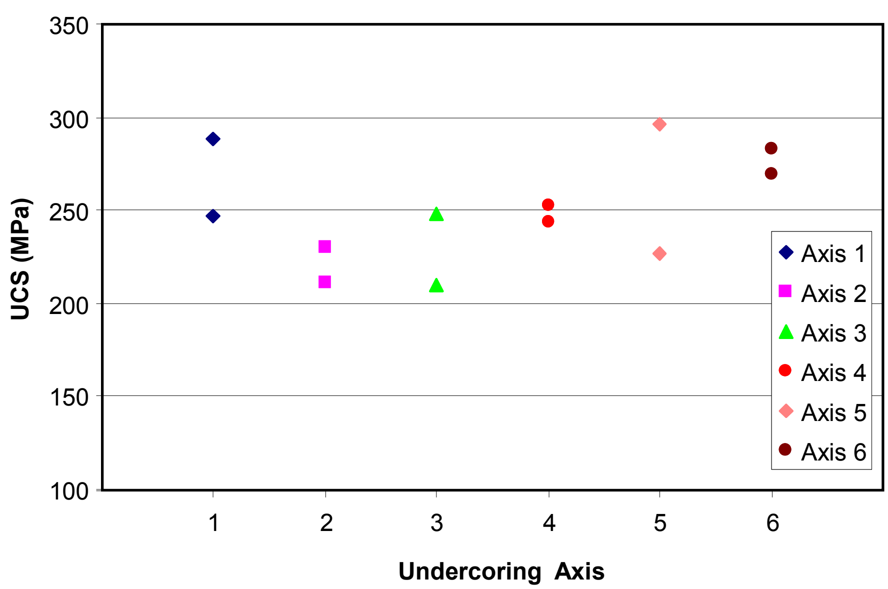

Figure 5. Typical unconfined compressive strength for each undercoring orientation for Craig-Onaping Mine.

6 IN-SITU STRESS ORIENTATION AND MAGNITUDES FOR CRAIG-ONAPING MINE

The methodology described above was used to estimate the *in-situ* stresses at (8) locations drilled at depth from three oriented cores at Craig-Onaping (see Figure 6 & Figure 7). Two measurements were taken on a flat hole (CR49123) and six measurements on two steeply dipping holes (OD4984 & OD4985). The quality of the oriented core at great depth is shown in Figure 8.

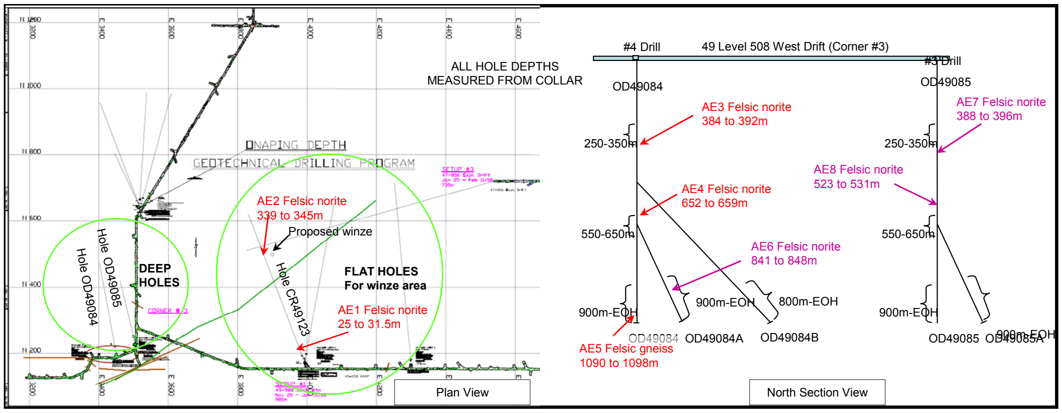

Figure 6. Schematic plan and section view of holes OD4984, OD4985 and CR49123.

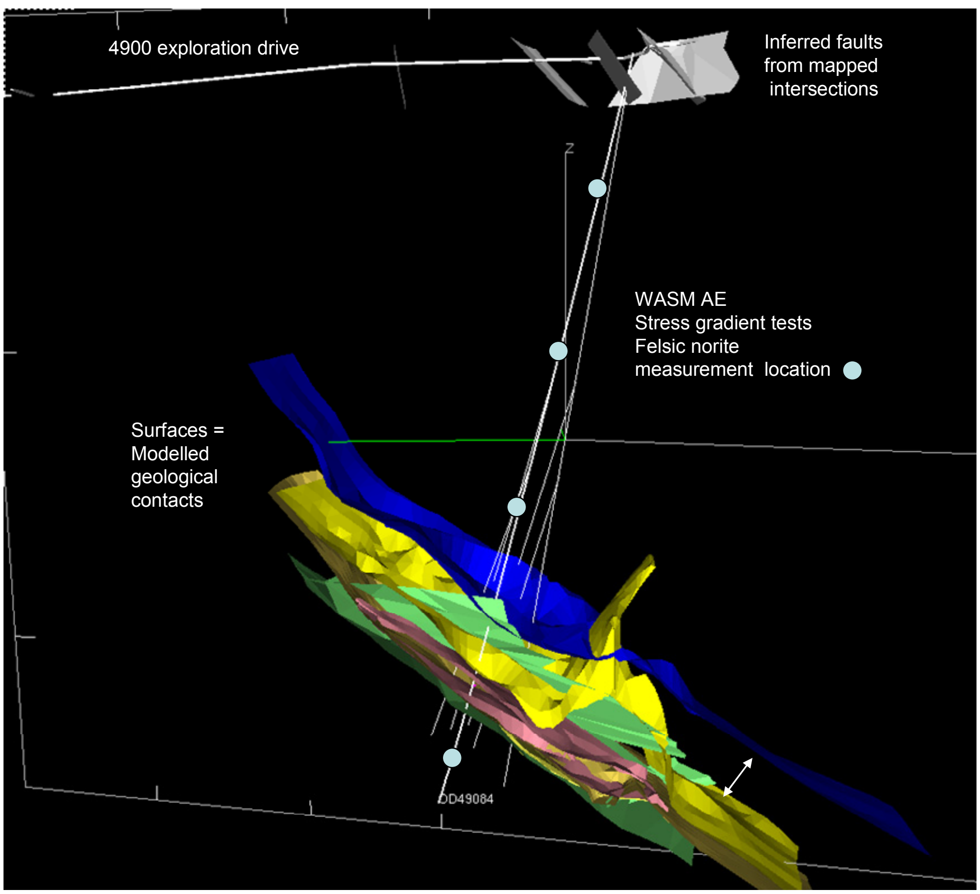

Figure 7. Section view (3D) of steeply dipping holes OD4984 and OD4985.

Figure 8. Condition and drill recovery for the OD4984 oriented core at approximately 2600m below surface .

Figure 9 shows the estimated principal stress orientations with respect to the borehole orientations (mine grid north) provided. The orientation of the main principal results appear parallel to a common sub trend in NE/SW direction (See Figure 1). Field evidence of horizontal stress consists of back overbreak, hole squeezing and fracturing in excavation back of previous cut within the cut-and-fill operations (See Figure 10).

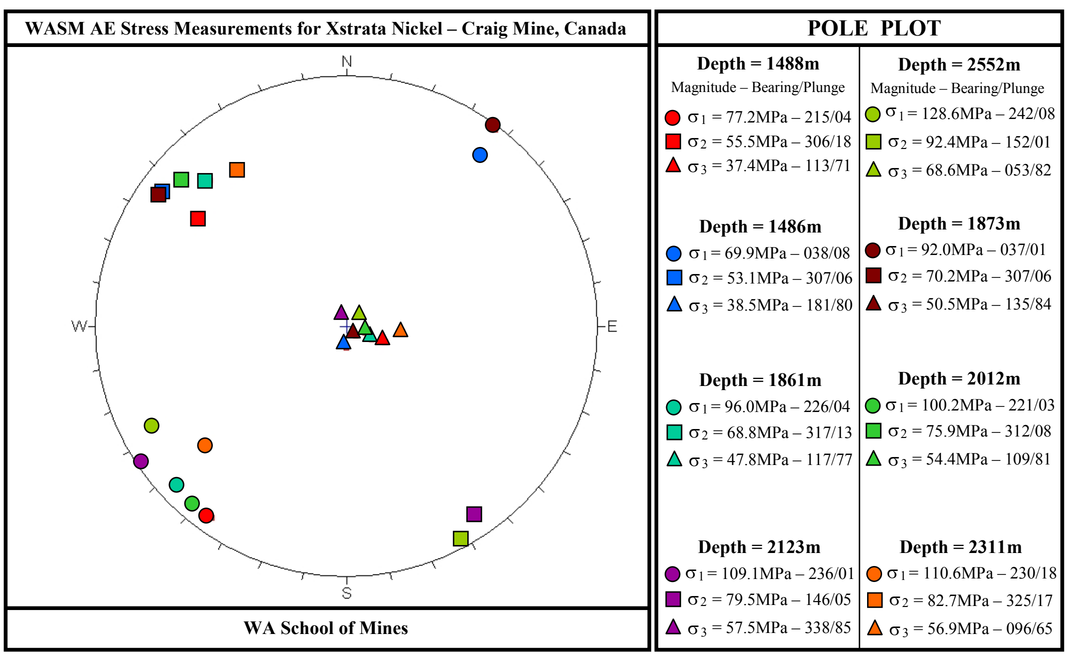

Figure 9. Principal stress orientations WASM AE– Craig Onaping Mine.

Figure 10. Evidence of stress-driven fracturing above excavation backs.

Figure 11 shows the stress magnitude profile with depth for the measurement sites. Figure 12 shows the ratios of horizontal to vertical stress for those depths at Craig-Onaping.

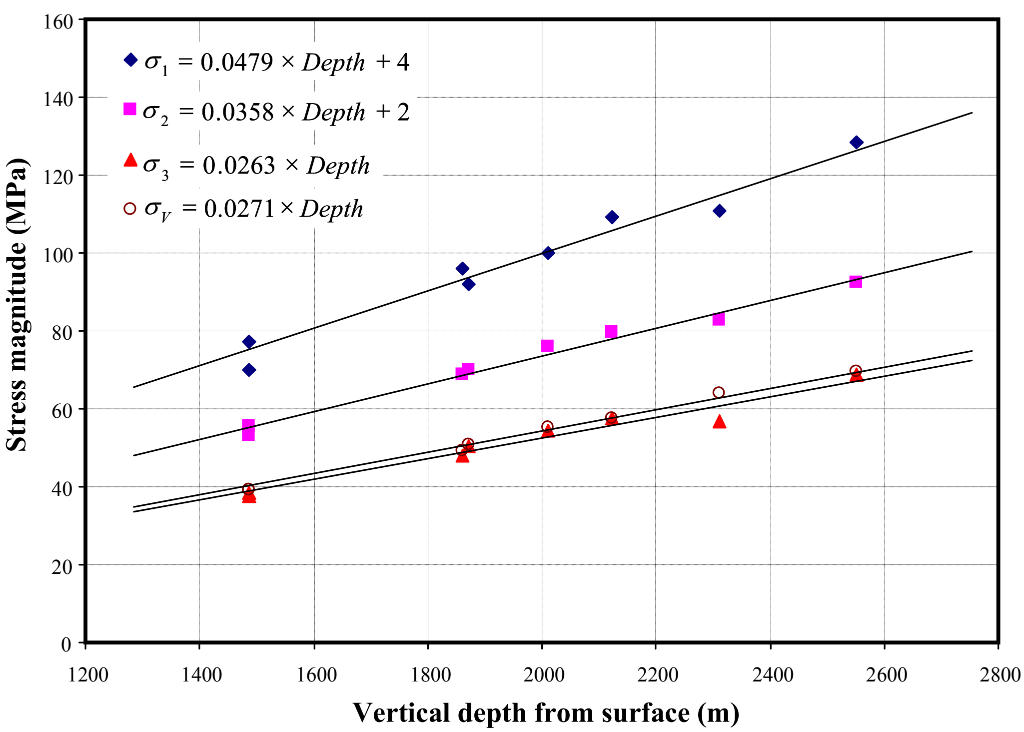

Figure 11. Principal stress magnitudes WASM AE– Craig Onaping Mine.

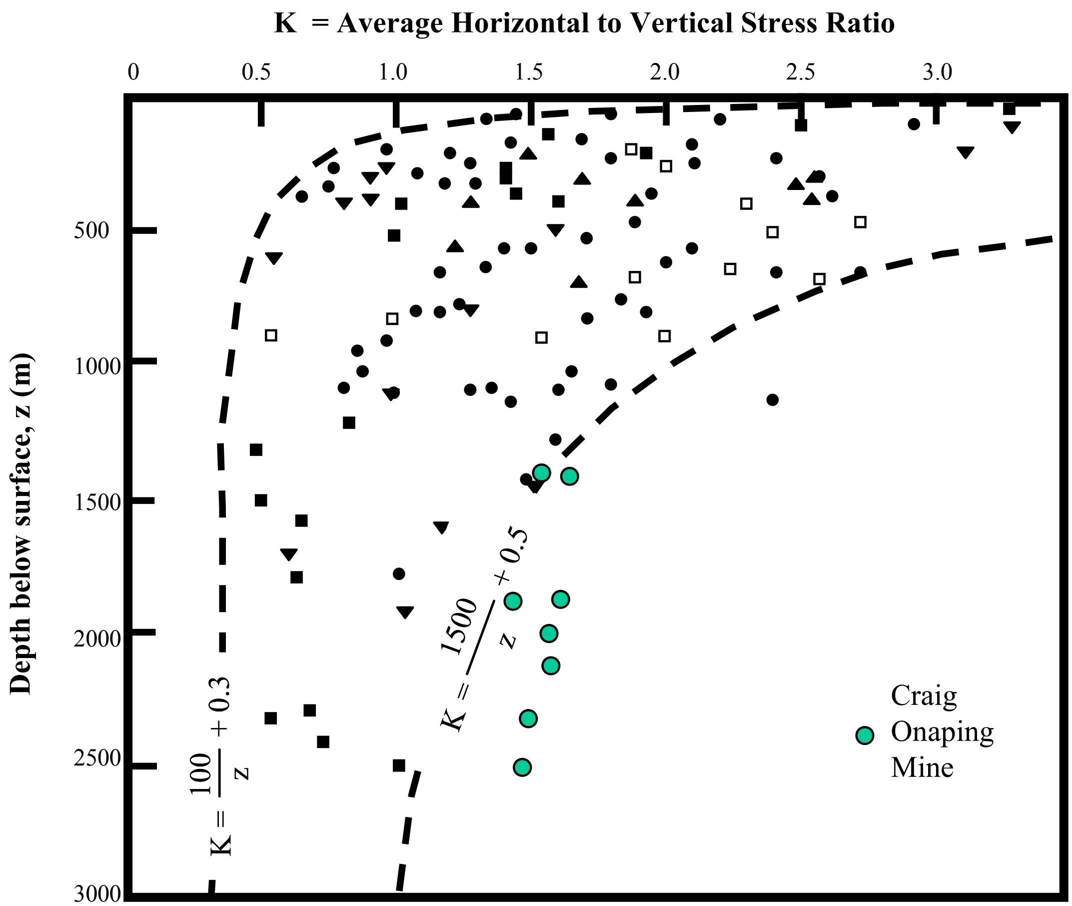

Figure 12. Ratio of horizontal to vertical stress WASM AE– Craig Onaping Mine.

7 CONCLUDING REMARKS

The WASM AE methodology has been successfully applied to the determination of in-situ stress using oriented core drilled at great depths at the Craig Onaping mine. The results constitute the deepest measurements undertaken to date at the WA School of Mines. The results indicate that the main principal stress is horizontal and oriented parallel to a common regional sub trend in a NE/SW direction. Field observations from cut-and-fill back exposures support the sub-horizontal nature of the main principal stress at Craig Onaping.

ACKNOWLEDGEMENTS

The financial support and permission to publish the results by Xstrata Nickel are gratefully acknowledged.

REFERENCES

Brady, B.H.G. and E.T. Brown, (1985). Rock Mechanics for Underground Mining. Allen & Unwin, London.

Kaiser, J (1953). Erkenntnisse unde Folgerungen aus der Messung von Gerauschen bei Zungbeanspruchung von metallischen Werkstoffen, Archiv. Fur das Eisenhuttenwasen, pp.43 – 45.

Kurita, K. and N. Fujii (1979). Stress memory of crystalline rocks in acoustic emission, Geophys. Res. Lett., Vol.6, No.1, pp.9 – 12.

MAP249 – District of Sudbury (1984). The geology and Ore Deposits of the Sudbury Structure. Ontario Geological Survey, Special Volume 1. Edited by E.G. Pye, A.J. Naldrett, and P.E. Giblin. Ontario Ministry of Natural Resources.

Seto, M., Utagawa, M. and K. Katsuyama (1995). The relation between the variation of AE hypocenters and the Kaiser effect of Shirahama sandstone, Proc. 8th Int. Cong. on Rock Mechanics, Vol.1, Tokyo, Japan, pp.201 – 205.

Seto, M., D.K. Nag, and V.S. Vutukuri (1999). In-situ rock stress measurement from rock cores using the acoustic emission and deformation rate analysis, Geotechnical & Geological Engineering, Vol. 17, No.3-4, pp.1 – 26.

Simser, B. (2008). Mining in a seismically active fault zone: a case study from Xstrata's Craig Mine, Sudbury, Ontario. Proc. Strategic vs Tactical Approaches in Mining, J. Hadjigeorgiou (Ed), Laval University.

Villaescusa, E., M. Seto and G.R. Baird, (2002). Stress measurements from oriented core. Proc. Int. Journal of Rock Mechanics and Mining Sciences,Vol 39, 603-615.

Villaescusa, E., C.R. Windsor, G. Baird and M. Seto, (2003). Stress measurements from cored rock. Minerals and Energy Research Institute of Western Australia, Research Report No. 233, 124p.

Villaescusa, E., L. Machuca & C. Windsor, 2008. Sample selection for an AE stress measurement program at the Western Australian School of Mines. Proc. Mass Min Conference, Lulea Sweden, H. Schunesson & E. Nordlund (Eds), 825-834.

Windsor, CR, E. Villaescusa, T. Funatsu and R. Lachenicht, (2007). Measurement of the regional and local stress field along a 10km strike of the Zuleika Shear Zone in the Kundana gold mining province of Western Australia. 1st Canadian US Rock Mechanics Symposium, Vancouver.