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Variation of Horizontal In Situ Stress with Depth for Long-Term Performance Evaluation of the Deep Geological Repository Project Access Shaft

Authors:

AG Corkum[a]

B Damjanac[b]

T Lam[c]

Affiliations:

[a] Dalhousie University, Halifax, Nova Scotia, Canada (andrew.corkum@dal.ca)

[b] Itasca Consulting Group, Inc., Minneapolis, Minnesota, USA (branko@itascacg.com)

[c] Nuclear Waste Management Organization (TLam@nwmo.ca)

Corresponding Author:

AG Corkum

Mailing Address:

Civil and Resource Engineering

Dalhousie University

1360 Barrington St.

Rm D215, PO Box 15000

Halifax, Nova Scotia B3H 4R2

Canada

Phone: +1 (902) 494-3960

Fax: +1 (902) 494-3108

Email: andrew.corkum@dal.ca

Research Highlights

37 • A literature review of compiled in situ stress data for Ontario, Canada is presented
38 • Variation in geological formation stiffness impacts horizontal stresses
39 • A simplified *FLAC3D* model was developed to account for the stratigraphic profile
40 • Model calibrated by borehole breakouts, stress measurements and observations
41 • An improved estimate of the horizontal stress profile was developed

42

Abstract

   A site characterization program was carried out for a proposed Deep Geological Repository (DGR) project for Ontario Power Generation's (OPG) low- and intermediate-level nuclear waste repository near Kincardine, ON. The repository is proposed to be constructed at approximately 680 m below ground surface within the competent argillaceous limestone of the Cobourg Formation. The in situ stress state at the project site will have significant impact on both the short- and long-term performance of repository openings, such as emplacement caverns and access shafts. As part of the site characterization program, an evaluation of the in situ stress state of the project site was conducted which consisted, primarily, of a review and synthesis of existing stress measurements conducted at various locations throughout Ontario and the midwestern U.S. A summary of the results of past in situ stress studies available in the literature that were utilized for project "scoping study" level analysis is presented. These past studies, however, do not account for the impact of the known variation of stress due to contrasts in stiffness of discrete rock units. This simplification may result in significant miscalculation of the estimated in situ stress condition. Based on geomechanics data from deep boreholes and stress measurement data, a simplified FLAC3D model of the full stratigraphic profile was developed and used to simulate the influence of regional tectonic strain in the project area. In particular, this method takes into account the rock properties, such as stiffness, for discrete units at the DGR site. The model was calibrated on the basis of in situ stresses measured at Norton Mine, in a similar geological environment as the DGR site, and with site-specific borehole televiewer observations (i.e., breakouts). The model-predicted horizontal in situ stress profile showed general agreement with the observations and also showed the significant influence of discrete rock unit stiffness.

   Keywords: in situ stress; shaft; *FLAC3D;* long-term performance; nuclear waste isolation

1.0 Introduction

Ontario Power Generation (OPG) is evaluating development of a Deep Geological Repository (DGR) for long-term storage of Low- and Intermediate-Level Nuclear Waste (L&ILW) at the Bruce nuclear site near Kincardine, ON. The repository is proposed to be constructed at approximately 680 m below ground surface (mBGS) within the competent argillaceous limestone of the Cobourg Formation. A conceptual illustration of the proposed DGR is shown in Fig. 1. In support of this project, numerous geoscience and engineering studies have been carried out as part of a site characterization program. A detailed description of these studies is summarized in Intera [1] and NWMO [2].

From a rock mechanics engineering perspective, one of the key challenges is the determination of contemporary ground stresses at the DGR project site. In situ stresses are influenced by several factors, the most dominant being: tectonic strain, glaciotectonics and isostatic rebound, regional and local structural geology, deposition and erosion, and topography. Moreover, the geological history associated with these events is also a major factor. As a result, the stress regime can be complex and variable.

The stratigraphic profile at the site consists of a near horizontally bedded sequence of carbonates and shales. The strength and stiffness characteristics of these various discrete rock units are anticipated to vary significantly. Amadei et al. [3] and Esterhuizen et al., [4] have shown that horizontal in situ stresses could be dependent on the stiffness of discrete rock units. Further to that, these horizontal stresses vary with direction in the horizontal plane with a *maximum principal horizontal stress (σ_H)* and *minimum principal horizontal stress (σ_h)*.

Currently, there are no in situ stress measurements at the project site. There are great challenges in obtaining, within suitable confidence levels, the in situ stress magnitude and orientations at the depth of interest from a surface-based exploratory borehole. This is particularly the case for the horizontally bedded formations at the Bruce nuclear site as hydrofracture techniques cannot be used with confidence because the vertical stress is less than the horizontal stresses [5]. Traditional strain-relief methods, such as overcoring, are suitable only for relatively shallow measurements and testing within exploration boreholes at the repository depth has not been successfully demonstrated. Consequently, during the course of the DGR site characterization program, the state of in situ stress was estimated

101   based on several lines of reasoning including: regional stress data [6-9]; observations made
102   during drilling and monitoring of the DGR series of vertical boreholes [1]; and the in situ
103   stress modelling of the sedimentary succession below the site described in this paper.

104   As part of a project to evaluate the long-term performance of shafts and repository
105   excavation openings [10], the authors have examined in situ stress conditions, in particular
106   the variation of horizontal stresses due to rock unit stiffness within the sedimentary
107   sequence. This was done by carrying out a three-dimensional finite difference analysis
108   model using *FLAC3D* [11] to simulate the tectonic strain within the sedimentary sequence.
109   The model was calibrated with the site-specific borehole televiewer observations and other
110   in situ stress observations pertinent to the project site.

111   This paper first presents a review of the in situ stresses from literature followed by the
112   interpretation of acoustic televiewer data from deep exploration boreholes at the site.
113   Finally, the in situ stress model analysis (*FLAC3D*) that accounts for the contrasting
114   stiffness of the various layers is described. The findings from these three approaches are
115   compared.

2.0 Background: In situ Stresses in Southern Ontario

117   This section presents a brief overview of the geological setting in the project area and
118   a review of in situ stress measurement compilations carried out for the Southern Ontario
119   region. The in situ stress measurement carried out at 670 m depth in Norton Mine, Ohio, is
120   also discussed.

2.1 Geological Setting

122   A summary of the regional site geology of the proposed site is presented by Intera [1].
123   The NE-SW trending Algonquin Arch separates the Michigan and Appalachian Basins in
124   Southern Ontario (see Fig. 2). The proposed DGR site is in the eastern portion of the
125   Michigan Basin within a sequence of sedimentary units of Upper Cambrian to Upper
126   Devonian age. The sedimentary rocks rest on the southern margin of the Canadian Shield
127   crystalline basement rocks of the Proterozoic Grenville Province. A stratigraphy profile of
128   the bedrock at the DGR site based on four deep boreholes is shown in Fig. 3 [1].

2.2 Vertical Stresses

It is generally believed that the vertical in situ stress (σ_v) in the region is comprised of a simple gravitational gradient based on the density of the rocks within the stratigraphic section. Given that the sedimentary rocks in the upper approximately 800 m have similar density, a uniform vertical stress gradient is a suitable approximation for the depths under consideration for the DGR project. Valley and Maloney [12] proposed: $\sigma_v = 0.0259z$ (in MPa): where z is depth in meters.

2.3 Horizontal Stresses

Based on the geological (i.e., tectonic) history of the region, high horizontal stresses exist and this has been supported by numerous measurements and observations [13]. The horizontal to vertical principle stress ratios for the maximum horizontal stress ($K_H = \sigma_H/\sigma_v$) and minimum horizontal stress ($K_h = \sigma_h/\sigma_v$) both exceed one. Different horizontal stress gradients have been reported by several authors, some prepared specifically for the DGR project, and these are summarized in the following sections.

2.3.1 Adams and Bell, 1991

Using overcoring stress measurements in shallow boreholes and workings, and deep hydraulic fracturing borehole data from Darlington, Ontario, Adams and Bell [6] demonstrated the high horizontal compressive stress characteristic of the Mid-Plate Stress Province of Eastern North America. Most of the stress data are measured in the Paleozoic rock sequence of Southern Ontario which consists of near flat-lying carbonate, shale and sandstone formations of Ordovician, Silurian and Devonian periods. The state of high horizontal stress in the rock of this region is primarily the product of major depression of the area during the Wisconsin Glaciation and subsequent isostatic rebound. Adams and Bell [6] presented data mostly from Silurian and Ordovician formations while deep hydraulic fracturing stress values, to depths of just over 300 m in the Precambrian Shield basement, were measured at Darlington, Ontario by Haimson and Lee [14]. A compilation of stress measurements in the Precambrian Shield for Northern Ontario was developed by Kaiser and Maloney [8] and updated by Yong and Maloney [15]. The results from the former are discussed in the following section.

158   The reported strain relief in situ stress measurements conducted at shallow depths were

159   all obtained using USBM (United States Bureau of Mine) borehole deformation gauges.

160   The measurements show significant scattering, but provide a general trend for the in situ

161   stress gradient with depth. Hydraulic fracturing tests indicated a lower vertical stress

162   gradient with depth. Based on these findings, the following expressions of vertical

163   horizontal in situ stress with depth were established:

164
$$s_H = 0.027z \ \text{(in MPa)} \tag{1}$$

165
$$s_h = 0.017z \ \text{(in MPa)} \tag{2}$$

166 ### *2.3.2 Kaiser and Maloney, 2005*

167   Kaiser and Maloney [8] published a review of an in situ stress database for the

168 Ontario portion of the Canadian Shield. Much of the shield database was a recompilation

169 of an in situ stress database compiled by CANMET Mining and Mineral Sciences

170 Laboratories [16]. This study utilized linear regression techniques on overcoring

171 measurement data from mines in northern Ontario, subdividing the Shield region into

172 various sub-regions and three depth zones or "stress domains" similar to those of

173 Canadian and Swedish regions reported by Martin et al. [17].

174   Domain 1 (Stress Relaxed Zone) is a zone influenced by near surface topography,

175 weathering, etc. and extends from the ground surface to a depth of approximately

176 300 mBGS. Domain 2 (Transition Zone) is a transition zone between Domains 1 and 3. It

177 exists between approximately 300 and 600 mBGS. Domain 3 (Maximum Stress Zone or

178 Undisturbed Zone) exists below approximately 600 mBGS below ground surface and is a

179 region of limited fracturing and minimal impact from surficial conditions.

180   The following in situ stress gradients were recommended for each domain based on

181 linear regression of existing measurements. Note that the values in square brackets

182 represent the 95% confidence interval limits on the respective component.

183 **Domain 1:**

184
$$s_H = 5.768 \ [\pm 3.358] + 0.071 \ [\pm 0.019] \times z \ \text{(in MPa)} \tag{3}$$

185
$$s_h = 3.287 \ [\pm 2.600] + 0.043 \ [\pm 0.015] \times z \ \text{(in MPa)} \tag{4}$$

186
$$s_v = 0.034 \ [\pm 0.005] \times z \ \text{(in MPa)} \tag{5}$$

187   **Domain 3:**

$$s_H = 23.636\ [\pm 11.556] + 0.026\ [\pm 0.012] \times z\ \text{(in MPa)} \qquad (6)$$

188

$$s_h = 17.104\ [\pm 10.538] + 0.016\ [\pm 0.010] \times z\ \text{(in MPa)} \qquad (7)$$

189

$$s_v = 1.066\ [\pm 8.247] + 0.020\ [\pm 0.008] \times z\ \text{(in MPa)} \qquad (8)$$

190

191   **Domain 2:** The transition zone can be described by a linear construction between
192   Domain 1 and Domain 3. Variability and uncertainty is high in this transitional stress
193   domain.

194   Yong and Maloney [15] provided an update to the 2005 database and the domains
195   using 75 new measurements since 2005. This new dataset covers measurements ranging
196   from depths between 12 and 2,552 m. A data screening process was also performed to
197   assess quality and reduce uncertainty when establishing representative ground stress state
198   equations. The state of ground stress was found to be consistent with the 2005 study,
199   subdividing into the same three domains.

200   *2.3.3 Lam et al., 2007*
201   Lam et al. [7] carried out a review of the available stress data in the Paleozoic rocks
202   measured from over 20 sites in the lower Great Lakes Region. These measurements were
203   primarily made using overcoring methods (mostly at shallow depths with several at about
204   700 m in the Norton Mine, Ohio) and by hydraulic fracturing to depths of 5,100 m in central
205   Michigan State. They were made in various rock types such as shale, carbonate and
206   sandstone. The analysis of the regional ground stress data allows for an estimate of the
207   approximate range of stress ratios at the repository depth under consideration. On the basis
208   of this review, the following recommended stress ratios were proposed for the DGR
209   project: $\sigma_H/\sigma_v = 2.0$ to 2.5 and $\sigma_h/\sigma_v = 1.5$. Assuming a uniform density of 2600 kg/m^3 for
210   the stratigraphic units over the depth of interest, these stress ratio values can be converted
211   to the following stress gradients:

212

$$s_H = 0.051z\ \text{to}\ 0.064z\ \text{(in MPa)} \qquad (9)$$

213

$$s_h = 0.038z\ \text{(in MPa)} \qquad (10)$$

8

214　　*2.3.4 Horizontal Stress Orientation*

215　　　　An excerpt from the World Stress Map project [18] shows the locations of stress

216　　measurements and stress indicators (e.g., borehole breakouts) in Southern Ontario and the

217　　Mid-Western U.S. in Fig. 4. There are no measurements or direct observations mapped

218　　within approximately 200 km of the DGR site prior to drilling the DGR deep boreholes at

219　　Bruce nuclear site in 2007. Based on the mapped stress orientations, there is some

220　　variability in orientations in the Ottawa-Quebec City region (St. Lawrence Lowlands). In

221　　the remainder of the map area, the stress orientation indicators are consistent and indicate

222　　an *ENE-WSW* major principle stress orientation. This regional orientation was also

223　　presented by most other researchers [6-9]. This general trend was confirmed by ellipticity

224　　detection analyses using acoustic televiewer logs from four DGR deep boreholes [2]. Given

225　　the consistency of the stress indicator orientations and the similarity of the geological

226　　setting within the map area, the stress orientation in the DGR area is likely similar to the

227　　general regional trend with an ENE-WSW maximum principle horizontal stress (σ_H)

228　　orientation. The minimum principal horizontal stress (σ_h) is orthogonally oriented with an

229　　NNW-SSE trend.

230　　**2.4 Norton Mine Stress Measurements**

231　　　　The Cobourg Unit is the target formation for the DGR host rock (i.e., storage caverns).

232　　The depth and litho-mechanical variations around the repository horizon are very similar

233　　to those of the Columbus limestone at the Norton Mine near Akron in Ohio. Bauer et al.

234　　[19] described a program of in situ stress measurements that was carried out in the

235　　limestone for evaluation of a proposed compressed air energy storage project. Although

236　　this room-and-pillar limestone mine is located approximately 350 km away, horizontal in

237　　situ stress magnitudes would be controlled by similar stiffness contrasts between

238　　stratigraphic units. The Columbus limestone unit ($E = 49$ GPa) has mechanical properties

239　　similar to those of the Cobourg limestone ($E = 37.1$ GPa). Moreover, the two units occur

240　　at similar depths: approximately 670 m for the Columbus Unit and 655 m for the Cobourg

241　　Unit (see Fig. 3).

242　　　　The in situ stress measurement program was carried out in 1999 and 2000 using the

243　　USBM overcoring method. The measurements were made in Drift 9B in an area of the

244　　room-and-pillar mine relatively isolated from other near-by excavations. The authors also

245 pointed out that results agreed with other in situ stress testing in the vicinity using

246 overcoring and hydrofracturing methods. The recommended in situ stress values from the

247 program at Norton Mine were: σ_H = 36.7 MPa (oriented N75°W); σ_h = 28.3 MPa; σ_v =

248 22.5 MPa (~1.26 × overburden).

249   The recommended stress values at Norton Mine are substantially higher than

250 proposed by Adams and Bell, but similar to those proposed by both Lam et al. and Kaiser

251 and Maloney.

252 **2.5 Summary**

253   The vertical and horizontal stress orientations presented in past studies are in close

254 agreement. However, there is some discrepancy in the proposed horizontal stress

255 gradients. Fig. 5 shows the maximum (σ_H) and minimum (σ_h) horizontal stress gradients

256 from all authors, along with the measured values from Norton Mine. On this plot the

257 values from Norton Mine are plotted within the Cobourg Unit, a mechanically

258 comparable limestone unit at similar depth as the Columbus Limestone where the actual

259 measurements were made.

260   From the plot in Fig. 5, it can be seen that the Adams and Bell gradient results in the

261 lowest stress magnitudes while the Kaiser and Maloney tri-linear gradient has the highest

262 magnitudes above 600 mBGS. The Lam et al. gradients are essentially bounded by the

263 Adams and Bell (at shallow depth), and the Kaiser and Maloney (at greater depth)

264 gradients. Below about 600 – 700 mBGS the Lam et al. gradients are the highest stress

265 magnitudes. Both the Kaiser and Maloney, and the Lam et al. agree well with the

266 measured values at Norton Mine (within repository horizon). Given the overall

267 agreement, either of the above predicted gradients seem suitable to be used to develop a

268 representative ground stress profile.

269   A number of authors [20-22] have recognized the impact of the elastic parameters on

270 the distribution of horizontal in situ stresses and have verified the observation by

271 comparison to measured values. Based on an analysis of hydrofracturing results, Swolfs

272 [23] determined that horizontal stiffness has a significant impact on horizontal stresses.

273 Horizontal stresses in horizontally bedded sedimentary basins are affected by the

274 distribution of relative stiffness of the rock units (i.e., stiff sandstone versus soft

275   mudstone). Because of the high contrasting stiffness of stratigraphic units along the

276   proposed DGR Access Shafts, and the high contrast in situ horizontal stresses, this may

277   be an important factor in long-term shaft performance.

278   **3.0 Borehole Televiewer In Situ Stress Constraints**

279   As part of the site characterization program at Bruce nuclear site, an acoustic televiewer

280   was used to log the six DGR deep boreholes drilled between 2007 and 2010. This

281   allowed for estimation of in situ stress magnitudes using observations from borehole wall

282   conditions (e.g., breakouts), assuming that one principal stress is vertical. The absence of

283   breakout observed in the boreholes set an upper bound on the allowable maximum

284   horizontal stress magnitude of the formation. The logs were reviewed to evaluate

285   borehole wall damage and shape, such as breakouts, tensile fractures and "ovaling."

286   Breakouts are zones of failure that occur in the borehole wall where the strength of the

287   rock is exceeded by the stresses in the borehole perimeter. Often breakouts occur as

288   diametrically opposed "notches" in the borehole wall. Tensile fractures are sometimes

289   difficult to distinguish from other structural features in the borehole walls, but are

290   typically expressed as a steeply dipping parallel family of fractures. Borehole ovaling is

291   distortion of the circular borehole due to the stress field. Because of their relationship

292   with borehole stresses, these features are often an indicator of the in situ stress field in the

293   plane of the borehole. The location of the breakouts and tensile fractures provides an

294   indication of the orientation of the stress field and, by comparison to the rock strength,

295   the features provide an indication of the stress magnitude.

296   Valley and Maloney [12] reviewed the televiewer logs and carried out a series of

297   calculations in order to constrain the likely stress field for the DGR project. The televiewer

298   logs indicated that no borehole breakouts exist along DGR-1 and DGR-2. The lack of

299   observed borehole breakouts is a positive sign for shaft performance; however, it limits the

300   opportunity to evaluate the in situ stress field. While calculation of the stresses exceeding

301   the rock strength is not suitable in these cases, an analysis can be carried out to determine

302   the maximum stress conditions that could be present without inducing borehole breakout.

303   Two zones of tensile fracturing were observed and intervals of borehole ovaling were also

304   observed.

305   According to Zoback [24], observations and measurements indicate that in situ stresses
306   at depth are limited by stress acting on critically oriented discontinuities in the earth's crust
307   with strength parameters of zero cohesion and Coefficient of Friction (μ) of 0.6 to 1. For
308   borehole excavation-induced stresses σ'_1 and σ'_3 are the maximum and minimum stresses
309   around the borehole calculated elastically, respectively. On the basis of this observation,
310   the maximum stress ratio that can exist is limited by:

311
$$s'_1 \big/ s'_3 = \frac{(s_1 - u)}{(s_3 - u)} = [(m^2 + 1)^{1/2} + m]^2 \tag{11}$$

312   Eq. (11) provides one constraint on the in situ stress field in a large-scale context.
313   Borehole breakouts provide an additional constraint. In order to compare rock strength with
314   borehole televiewer observations, applicable strength parameters were required.
315   Laboratory testing data using core samples from DGR-1 and DGR-2 was used to determine
316   the applicable formation elastic and strength properties for the formations of interest [12].
317   The rock compressive strength can be compared to the maximum tangential stress ($\sigma_{\theta,max}$)
318   around a borehole wall calculated from:

319
$$s_{q,\max} = 3s_H - s_h - u_{bh} - \alpha u \tag{12}$$

320   Where: u_{bh} borehole fluid pressure;
321   α effective stress coefficient for the rock in compression;
322   u formation pore pressure.

323   A simplified and conservative model for pore pressure (u) was assumed with a
324   hydrostatic pore pressure gradient from ground surface: $u = 9.81z$ in kPa. According to
325   Brace and Martin [25], α is typically close to 1 for low porosity rocks.

326   There is some question as to what is the appropriate measure of rock strength for
327   breakout prediction. Typically, the Unconfined Compressive Strength (σ_c) has been used;
328   however, Martin [26] has suggested the Damage Initiation threshold (σ_{cd}) is a better
329   indicator of failure at the borehole scale. More recently, the Crack Initiation threshold (σ_{ci})
330   has been identified as the likely best indicator of the onset of spalling for rock excavations
331   [27].

332   Tensile fracturing was also used to constrain the stress field. Tensile failure was

333   predicted when the tensile strength (σ_t) was exceeded by the minimum tangential stress

334   ($\sigma_{\theta,min}$) around the borehole according to:

335
$$s_{q,\min} = 2s_h - s_H - u_{bh} - bu \tag{13}$$

336   Where: β effective stress coefficient for the rock in tension.

337   Valley and Maloney [12] stated that as a conservative estimate, it was assumed that σ_t

338    $= 0$ and $\beta = 0$. Although it could be argued that the laboratory-scale tensile strength would

339   be a more suitable constraint, the condition assumed by the authors is likely a conservative

340   assumption with respect to the predicted in situ stress bounding conditions.

341   Although a single stress field tensor could not be determined from the calculations,

342   Eqs. (11), (12) and (13) were used by Valley and Maloney to provide a range of possible

343   stress conditions. By further adding the rock strength for each unit, the maximum

344   permissible magnitude of σ_H and minimum permissible magnitude of σ_h could be

345   determined for the full stratigraphic profile where strength data were determined. Table 1

346   presents the constrained stress values on the basis of the strength parameter $\sigma_{ci} = 0.5\sigma_c$.

347   These stress values are also shown in Fig. 6.

348   In addition to observations of borehole wall damage, the televiewer data was used to

349   measure borehole shape, in particular to observe ovaling of the hole. Histograms of

350   borehole ovaling orientations from televiewer observations are provided in Fig. 7. Valley

351   and Maloney concluded that systematic SE oriented elongation implied a NE-SW

352   maximum principal stress orientation (σ_H). This is in agreement with the estimated

353   principal horizontal stress orientations proposed by other researchers, as discussed in

354   Section 2.3.4.

355   The absence of borehole breakouts and minimal observed tensile fractures limit the

356   applicability of constraining the stress tensor with this exercise. However, as part of a

357   preliminary evaluation of the in situ stress conditions for the DGR project, these

358   observations related to in situ stress conditions are a significant benefit to the site

359   characterization program.

4.0 Modelling Methodology for In Situ Stress Evaluation

In order to develop a three-dimensional *FLAC3D* model that captures the important aspects of the site stratigraphy without unnecessary complexity, the stratigraphy was simplified into units of similar mechanical behavior. This simplified model is referred to as a *Geotechnical Model*. The simplifying assumptions were based on a relative comparison of the elastic properties of the geological units, the geological/geotechnical descriptions of the units, and groupings previously proposed by others [12,28].

As part of this study the authors synthesized laboratory testing data carried out on core samples from four boreholes at the DGR site (DGR-1 through DGR-4). The testing consisted of uniaxial compressive strength, triaxial compressive strength, long-term compressive strength, and Brazilian testing. In total, data from 176 different laboratory tests was correlated. Test data were not available for all units in the stratigraphic sequence. Units where testing was unavailable were grouped with adjacent units of similar geological description and characteristics. The proposed stratigraphic units and elastic properties are provided in Table 2. Note that the units are numbered in the table from 1 – 12 for identification. Further details regarding the site characterization and laboratory testing program can be found in [1,2,10].

The strength and stiffness characteristics of the various discrete rock units anticipated to be encountered throughout the sedimentary sequence are expected to vary significantly. The variation of Young's modulus ranges from about 5 to 75 GPa (a factor of 15) from the softest to stiffest unit with a similar variation in strength parameters. If a uniform stress gradient were used to evaluate rock mechanics stability that omits the impact of horizontal stiffness on stresses, this could result in significantly overestimating damage in soft/weak rocks and underestimating damage in stiff/strong rocks.

The objective of the modelling study was to evaluate the horizontal in situ stresses while accounting for the stiffness of discrete rock units along the proposed DGR access shaft's stratigraphy. Three-dimensional variability, such as topography and variation in geological conditions away from the borehole locations, was not considered in this modelling exercise. Given these limitations, the issue could be addressed for the site by developing a simple linear elastic three-dimensional multi-layered solution. An analytical method to calculate the stress distribution, including the variation of horizontal stress due

391   to the elastic parameters of discrete rock units, was developed by Amadei et al. [3].

392   However, because a three-dimensional stress analysis model using *FLAC3D* was already

393   in development to evaluate the DGR access shaft design it was efficient to use a simplified

394   version of this model to carry out an in situ stress evaluation.

395   Using the finite difference code *FLAC3D*, a very slender single-zone wide (1 m cubic

396   elements) model was developed that extended vertically from the ground surface to a depth

397   below ground surface of 1200 m. The model included the 12 geological units listed in Table

398   2. An elastic constitutive model was used for all zones and the elastic parameters for each

399   unit is provided in Table 2. In the model, a uniform density of 2600 kg/m^3 was used

400   throughout the stratigraphic sequence. The model was set up so that the *x*-axis and the *y*-

401   axis represented the NE-SW and the NW-SE orientations, respectively.

402   The model was executed in two stages: Stage 1 to capture gravitational loading and

403   Stage 2 to apply tectonic strain. Initially, the model boundary conditions consisted of *roller*

404   boundaries (i.e., constrained only in the direction normal to the face) on all sides and the

405   bottom with a *free* boundary at the ground surface. These boundary conditions simulated

406   lateral symmetry consistent with a large lateral spatial extent. The model was cycled until

407   *pseudo-static equilibrium* was achieved (i.e., a low ratio of unbalanced forces within the

408   model relative to the maximum nodal force in the model). At this initial state, the model

409   was in equilibrium under the zone's body forces (gravitational loading) and the horizontal

410   stresses in the model were due to Poisson's ratio only. In this state the horizontal stresses

411   can be approximated by:

412
$$s_H = s_h = gz \frac{n}{1-n} \tag{14}$$

413   Following the state of initial equilibrium, the next stage was to "squeeze" the model

414   laterally to simulate the effect of tectonic compression experienced by the sedimentary

415   basin over geological time scales. The roller boundary conditions were removed from the

416   positive *x* and positive *y* faces of the model. Constant velocity boundary conditions were

417   then added to the positive *x* and *y* faces moving them in a compressional direction. The

418   magnitude of the velocity boundary conditions was set so they moved slow enough so that

419   the model remained in a state of pseudo-static equilibrium at all times during model

420   cycling. In order to achieve a suitable ratio of in situ horizontal stresses, the constant

421 velocity boundary conditions were applied in a *velocity ratio* (v_H/v_h) equal to the desired

422 ratio of σ_H/σ_h. A schematic illustration of the *FLAC3D* model is shown in Fig. 8.

423   In order to arrive at a *calibrated* model, or a model deemed to reasonably match actual

424 in situ stress conditions, numerous model simulations were carried out. Models were cycled

425 with the constant displacement boundary conditions using several velocity ratios and each

426 simulation was cycled until a close match to the constraining data was achieved. The

427 resulting stress profile from each simulation was compared to the constraints from the

428 borehole observations ($0.5\sigma_c$) and the deep stress measurement from Norton Mine. As

429 mentioned previously, the Cobourg Limestone unit is the target formation for the

430 repository, as such it was considered particularly important to match the measured stresses

431 in the Columbus Limestone from Norton Mine.

432 **5.0 Model-Predicted Horizontal Stress Gradient**

433   From the various simulations carried out, a good match to the constraining data was

434 achieved from the *FLAC3D* model with horizontal strains of $\varepsilon_x = 5.16 \times 10^{-4}$ and

435 $\varepsilon_y = 2.84 \times 10^{-4}$. This corresponds to a velocity ratio of 1.82. The horizontal stress profiles

436 for the calibrated model are shown in Fig. 9 compared with the constraining conditions and

437 literature-reported gradients. The model results are highly variable, compared to the

438 literature-reported gradients and illustrates the implications of rock bed stiffness on the

439 horizontal in situ stresses.

440   Compared to a uniform stress gradient, the model-predicted profile clearly shows

441 elevated horizontal stresses in Unit 5 (Salina E: 379 – 415 m) and Unit 9 (Cobourg-

442 Collingwood: 665 – 693 m) units, and the deep Unit 12 (Cambrian and Precambrian: below

443 848 m). The horizontal stresses were particularly low in Unit 2 (Lucas: 131 – 176 m) and

444 Unit 7 (Cabot Head: 612 – 656 m). Even more significant than the variation in stresses

445 across units is the abruptness of the model stress changes along the profile. The horizontal

446 stresses transitioning between adjacent units can vary up to 100% or more.

447   By comparing the model-predicted horizontal stresses and the literature-reported

448 gradients shown in Fig. 9, it can be seen that the model-predicted stresses are bound by the

449 Adams and Bell gradient on the low side, and the Kaiser and Maloney gradient on the high

450 side. In particular, the Adams and Bell gradient shows a better match in the upper 650 m,

451 while the tri-linear Kaiser and Maloney gradient shows a better match at greater depth. As

452 mentioned previously, the Lam et al. gradient (shown with the range of values in yellow)

453 provides a transition between the Adams and Bell, and the Kaiser and Maloney gradients.

454 The Adams and Bell gradient is based primarily on softer sedimentary rocks in southern

455 Ontario while the Kaiser and Bell is based on a wider geographical region of the Canadian

456 Shield including rock units of metamorphic and igneous origin. As a result, model-

457 predicted stresses in the softer upper sedimentary units tend towards the Adams and Bell

458 gradient, while the stiffer lower units tend towards the Kaiser and Maloney gradient. The

459 model results are in good agreement with the literature-reported gradients in addition to

460 providing a good match to the constraints (Norton Mine measurements and borehole stress

461 constraints at the Bruce nuclear site).

462 A profile of the in situ stress ratios (K_H and K_h) is plotted in Fig. 10. The corresponding

463 plot of in situ stress ratios is similar to those presented by other researchers [22] with high

464 ratios in the upper 100 m and reducing significantly with depth to some stabilized value.

465 Moreover, the variation of stress ratio relative to discrete bed stiffness is similar to that

466 proposed by Amadei et al. [3].

467 Long-term performance of the DGR is being evaluated for a period of 1 M years;

468 therefore, both short- and long-term performance issues were considered. The Access Shaft

469 numerical modelling-based rock mechanics evaluation accounted for many issues, such as:

470 excavation, glacial loading, seismic loading, time-dependent degradation of rock and seals

471 materials and pore pressure evolution [10]. The horizontal in situ stresses likely have the

472 greatest impact on the long-term time-dependent behaviour of the shaft and seals. For

473 relatively unjointed rock mass (e.g., $GSI > 60$), the short-term shaft boundary/wall damage

474 (e.g., spalling) is dependent on the ratio σ_{max}/σ_c [17] where σ_{max} is the maximum tangential

475 stress calculated elastically around a circular opening.

$$s_{max} = 3s_H - s_h \tag{15}$$

477 Based on the findings of Damjanac and Fairhurst [29] deviatoric stress in the rock unit

478 dominates long-term behaviour which can also be evaluated at the excavation boundary by

479 the ratio σ_{max}/σ_c. Therefore, the magnitude of σ_{max} is critical to shaft performance

480 prediction.

17

481   A plot showing the profile of σ_{max} from the model-predicted horizontal stress profiles

482 and two of the literature-reported gradients, for comparison are presented in Fig. 11.

483 Accounting for the in situ horizontal stresses due to stiffness of discrete units results in a

484 significantly different σ_{max} profile and consequently resulting predictions of shaft short-

485 and long-term performance. Table 3 provides a summary of conditions at Access Shaft seal

486 locations analyzed for preliminary engineering studies carried out by the authors [10]

487 showing the geological unit, horizontal stresses, maximum tangential stress, and predicted

488 ratio of σ_{max}/σ_c for each seal analyzed. The units corresponding to specific seal locations

489 differs, to some extent, from the simplified Geotechnical Model used in modelling for

490 horizontal stress evaluation. There are some differences in the specific units corresponding

491 to seal locations, and their associated mechanical properties listed in Table 3, compared to

492 those of the overall Geotechnical Model presented in Table 2.

493   Although the calibrated model has captured the influence of discrete bed stiffness on

494 horizontal stresses, there are some notable limitations: most notably, the lack of site-

495 specific in situ stress measurements for a more direct calibration. In addition, the *FLAC3D*

496 model simulates all of the processes related to in situ stress through the application of

497 horizontal strain acting on linear elastic materials, although it is clear that many other

498 processes such as glaciotectonics and geological history are major factors. In addition, the

499 model does not account for the effects of large- or small-scale structural geology. Some of

500 the units are particularly weak and/or prone to long-term creep (i.e., time-dependent shear

501 strain under constant load), such as the evaporite rocks in the Salina Formation. For these

502 rocks, creep over geological time scales would likely reduce the in situ stress ratios from

503 those induced by tectonic strain to values near $K_H = K_h = 1$ [30].

504 **6.0 Conclusions**

505   To assess the performance and the design of an underground repository, an estimation

506 of in situ stress representative of the site is a necessity, in particular the horizontal

507 components. This is typically challenging using surface-based investigation programs.

508 Literature-reported stress gradients are generally adequate only for the task of preliminary

509 or scoping analysis. However, in a horizontally layered sedimentary sequence of shales

510 and carbonates where the stiffness contrasts of discrete rock units exist, a simple approach

18

of modelling horizontal ground stresses in the discrete rock units responding to tectonic strains has been proposed to capture the complexity of sedimentary profiles. This approach increases confidence in the estimation of horizontal in situ stresses by incorporating site specific information that has not been accounted for in past evaluations of regional stresses.

This paper described the use of simplified three-dimensional finite difference modelling (*FLAC3D*) to simulate the regional tectonic strain through the full stratigraphic section of interest for the DGR project site consisting of a sedimentary sequence of discrete rock unit with contrasting stiffness. The model was calibrated with tectonic strain deduced from in situ stress measurements from Norton Mine, where similar lithological conditions exist, and from DGR site-specific borehole information. The calibrated model agreed well with literature-reported values, field measurements and observations while capturing the impact of discrete rock unit stiffness. This is particularly important for long-term evaluation of shaft performance (e.g., shaft seals).

Although the model-predicted in situ stress profile represents an improvement over information provided in historical literature, it would require validation by a site-specific in situ stress measurement program. For the DGR project, ground stress tensors in the host and other selected formations will be verified by performing mine-by instrumented excavation type experiments during repository lateral development and by overcoring stress measurements during shaft sinking, respectively [2]. Future work may also account for the anisotropic stiffness of the horizontally layered sedimentary rocks and perhaps long-term creep, especially in the evaporite units, which could have significant effect on stress estimation. However, given the typical high range of uncertainty related to in situ stress determination programs, and the lack of any site-specific measurements, the model-predicted horizontal stresses offer a significantly improved estimate for the performance assessment of the proposed DGR shaft.

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617

TABLE CAPTIONS

619

620 **Table 1.** Constraints on stress magnitudes given by borehole televiewer log observations

621 using $\sigma_{ci} = 0.5 \ \sigma_c$ and $\sigma_t = 0$ as compressive and tensile strength criteria, respectively.

622

623 **Table 2.** Stratigraphic Units corresponding elastic properties comprising the

624 Geotechnical Model. These Unit numbers are shown on Fig. 3.

625

626 **Table 3.** Formations and stress conditions at the Access Shaft seal locations for preliminary

627 design purposes [10].

628

629

630

631 **Fig. 1.** Conceptual illustration of proposed DGR project at the Bruce Nuclear Site (after

632 [31]).

633

634 **Fig. 2.** Regional geological basins in the DGR project area (modified after [32]).

635

636 **Fig. 3.** Bedrock stratigraphy at the proposed DGR site based on boreholes DGR-1 and

637 DGR-2 (after [7]). The Stratigraphic Unit numbers (circled) corresponding to those in

638 Table 2 are shown.

639

640 **Fig. 4.** Stress measurements and indicators in Southern Ontario and Mid-Western U.S.

641 from the World Stress Map Project (modified after [32]).

642

643 **Fig. 5.** Literature-reported in situ stress gradients for Southern-Ontario for the full depth

644 of the proposed DGR Access Shaft.

645

646 **Fig. 6.** Horizontal in situ stress constraints from borehole televiewer observations. (a)

647 Markers indicate the maximum value of σ_H. (b) Markers indicate the minimum value of

648 σ_h.

649

650 **Fig. 7.** DGR borehole long axis orientation histograms for Middle Ordovician formations.

651 (a) DGR-1 and DGR-2; (b) DGR-3; and (c) DGR-4. Peak values are interpreted to

652 indicate the orientation of the minimum horizontal in situ stress for all orientations (upper

653 region with vertical lines) and for axis ratios greater than 1.0025 (lower solid region).

654

655 **Fig. 8.** Conceptual schematic showing the setup of the single-zone-wide *FLAC3D* model.

656 The model extends through the full vertical stratigraphy of the proposed DGR Access

657 Shaft. The model was deformed at a constant x- and y-velocity ratio to simulate tectonic

658 strain (indicated by arrows) resulting in stress variations relative to the stiffness of the

659 various units.

660

Fig. 9. Profile of horizontal stresses from the calibrated *FLAC3D* in situ stress model compared with constraints (borehole and Norton Mine measured values) and literature-reported gradients.

664

Fig. 10. Model-predicted horizontal stress ratios. The results are similar to those reported by Sheorey [22].

667

Fig. 11. Model-predicted σ_{max} compared with values calculated from literature-reported stress gradients. The parameter σ_{max} is an important indicator of short- and long-term shaft performance.

671

Figures
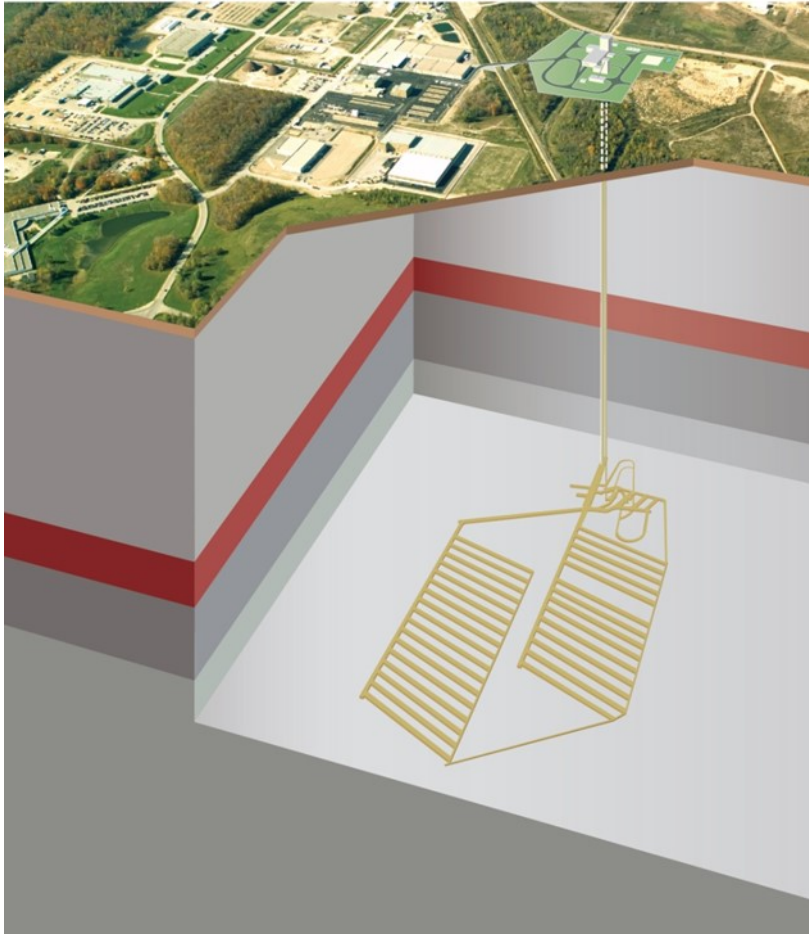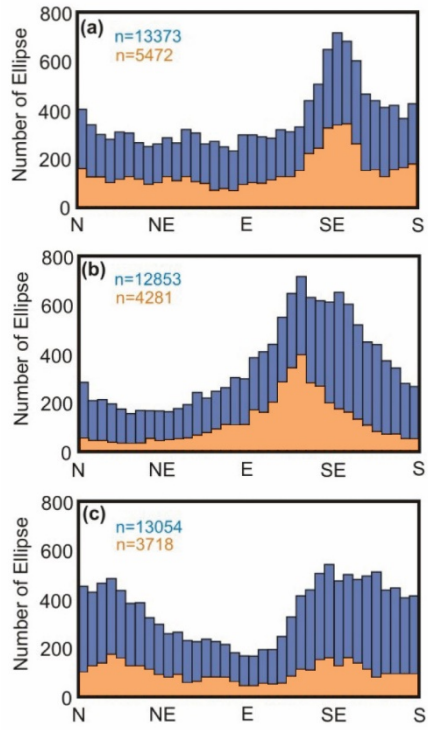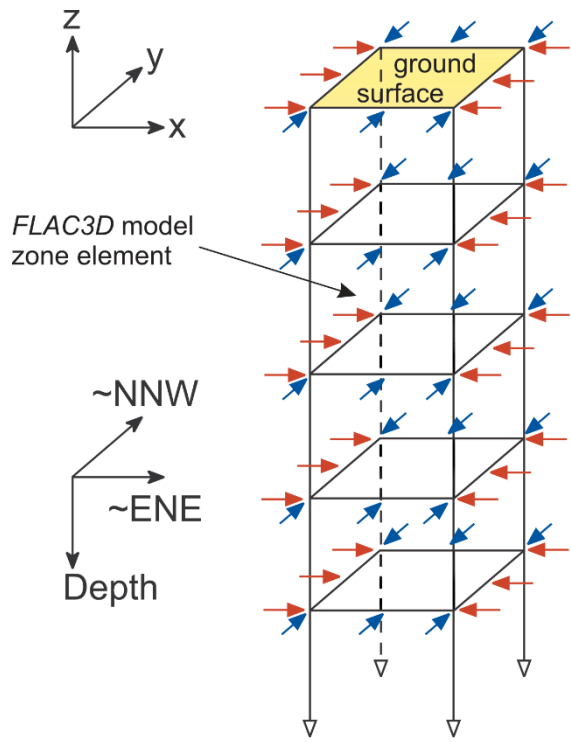
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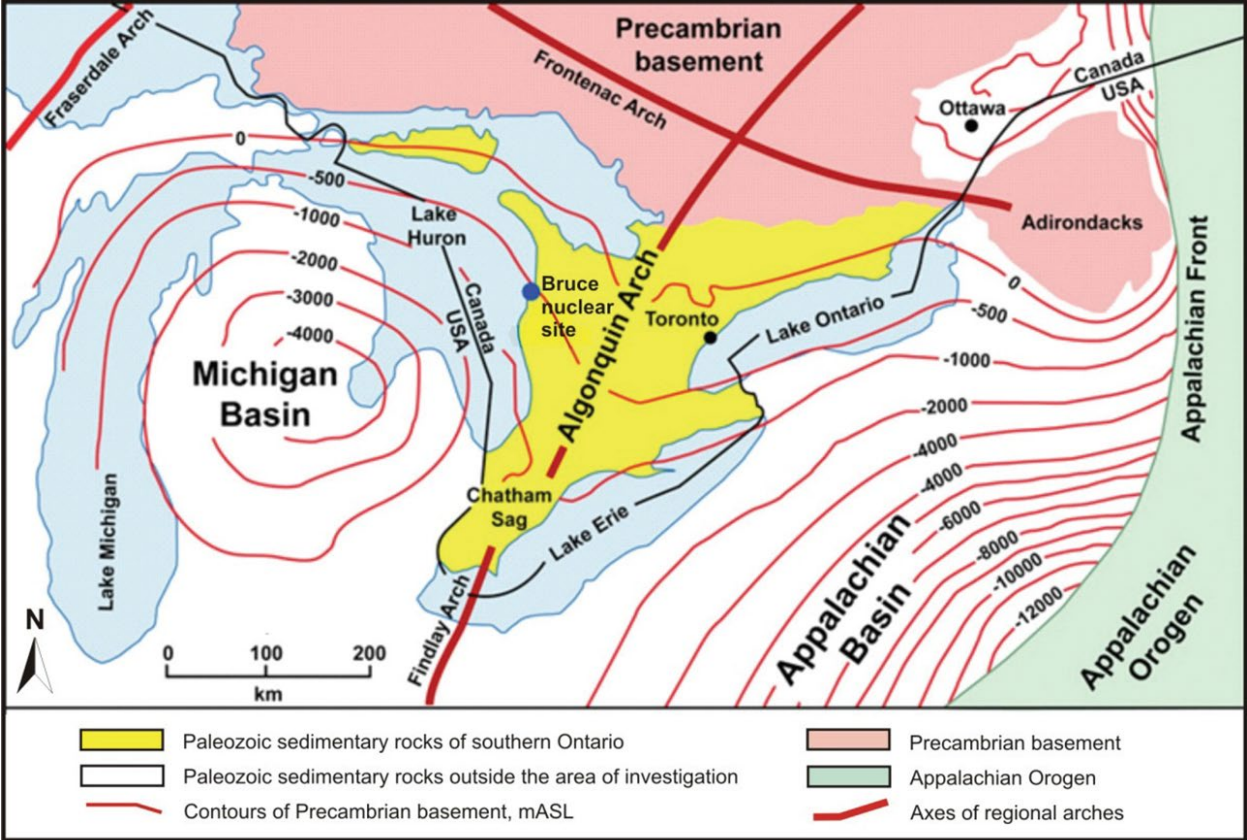
Figure 2

Figure 3

Figure 4

(a)

(b)

Figure 5

(a)

(b)
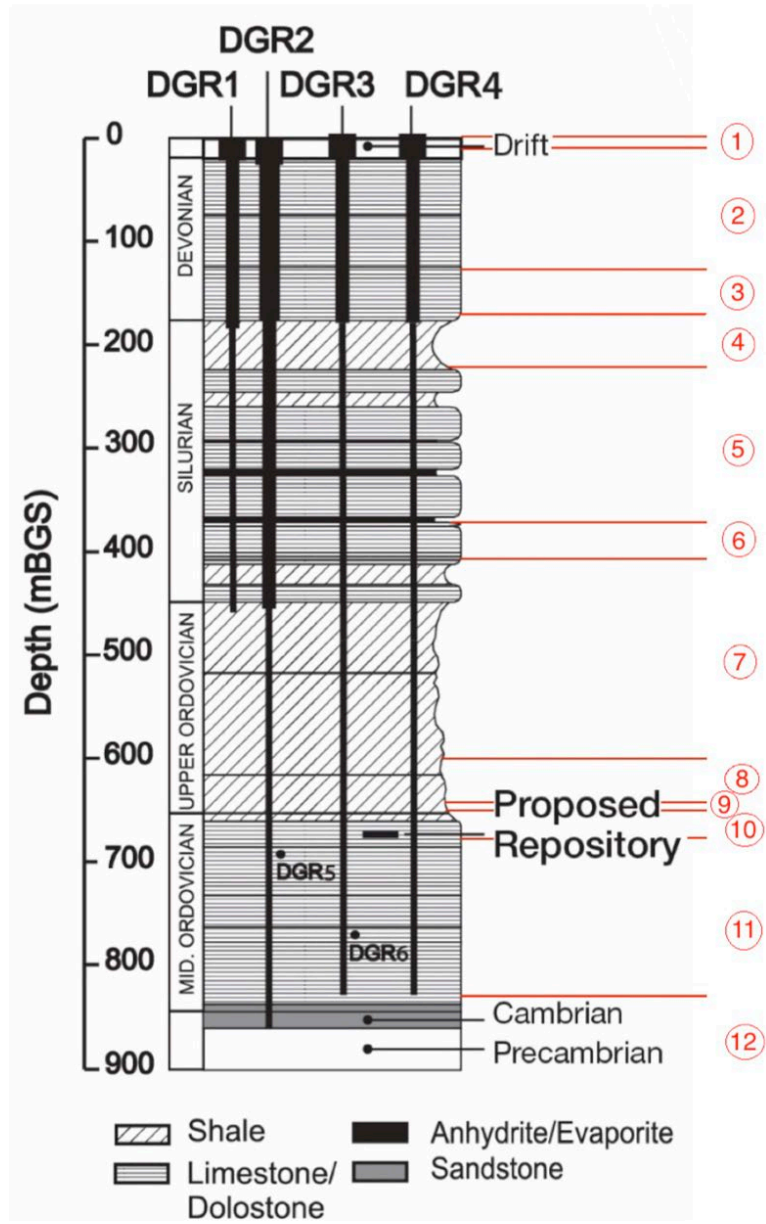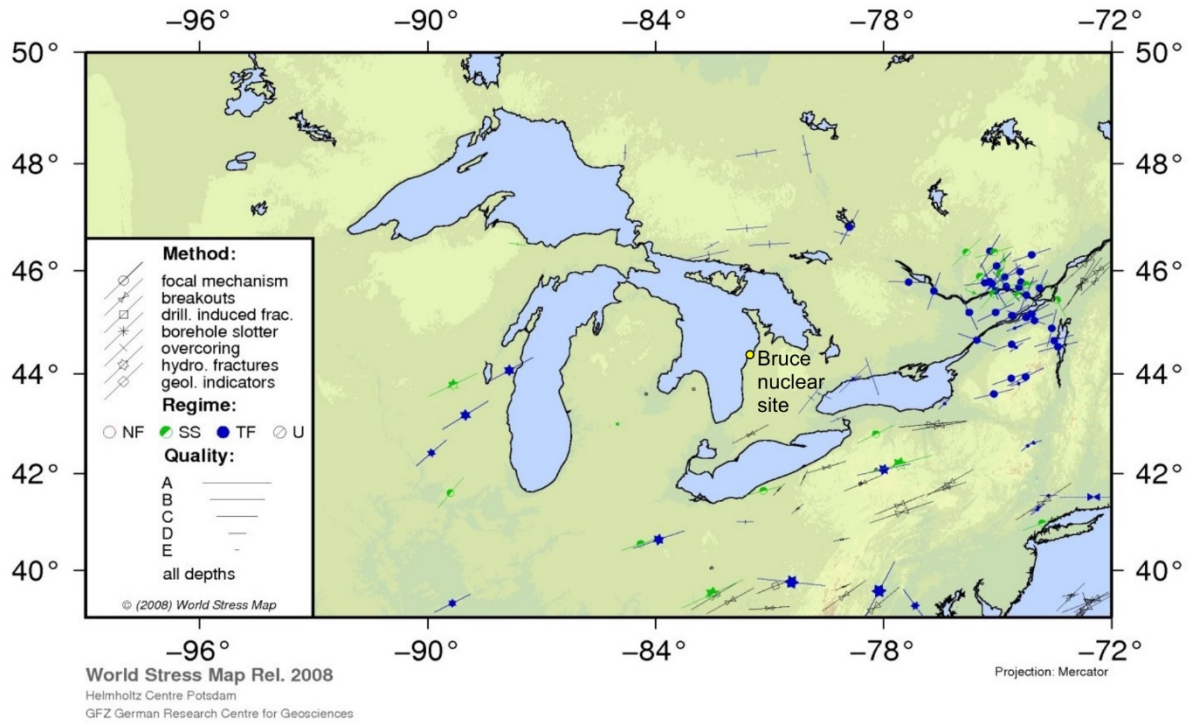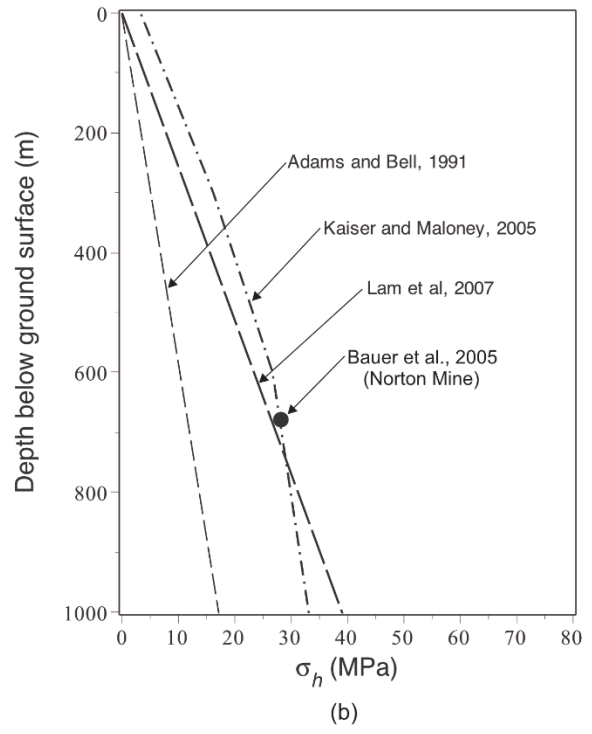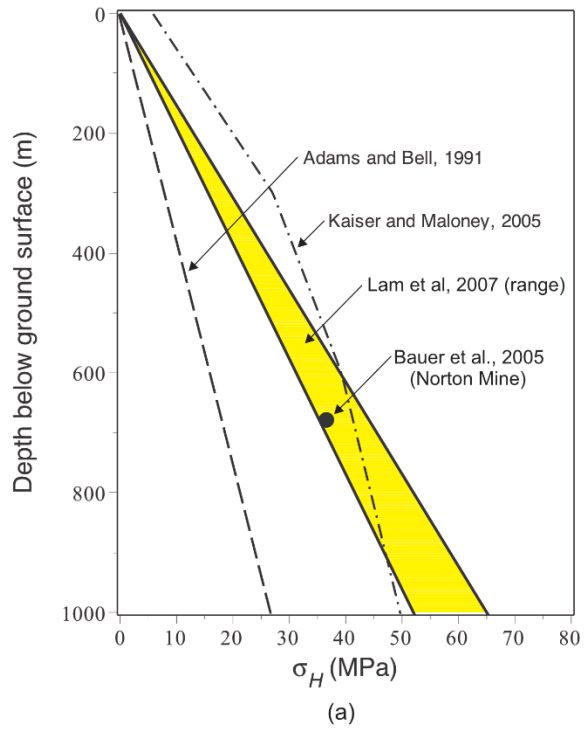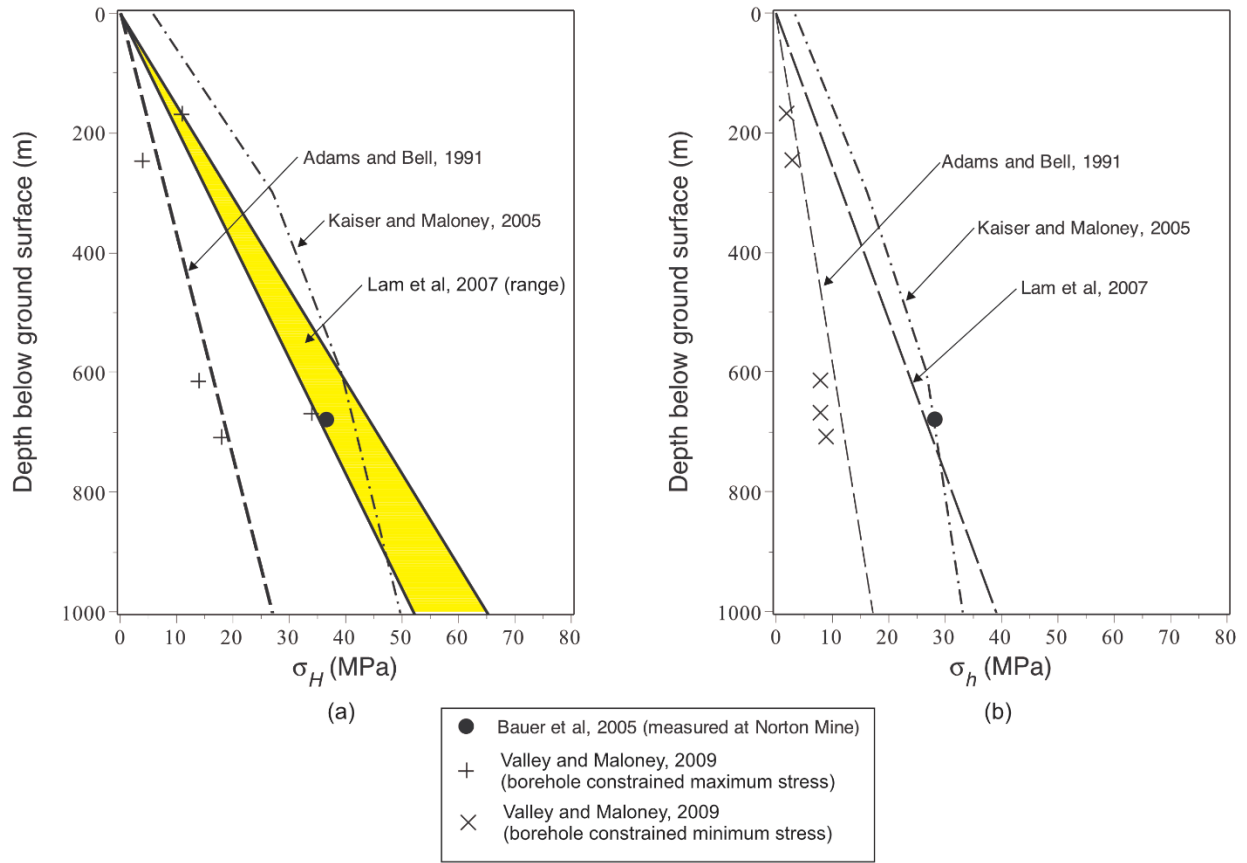
Figure 6

Figure 7

Figure 8

(a)

(b)

- ● Bauer et al, 2005 (measured at Norton Mine)
- + Valley and Maloney, 2009 (borehole constrained maximum stress)
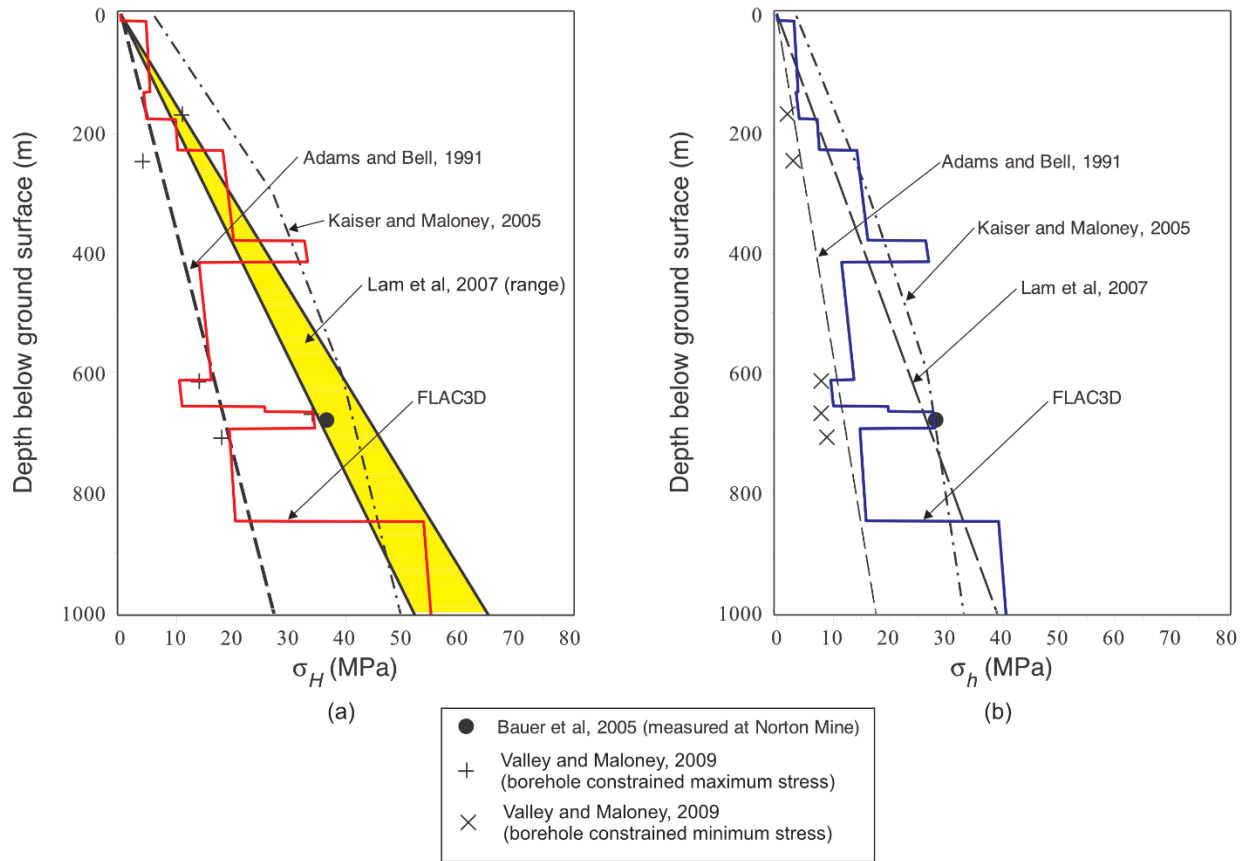- × Valley and Maloney, 2009 (borehole constrained minimum stress)

Figure 9

Figure 10

Figure 11