GEOTECHNICAL APPLICATION OF GAMMA RAY LOGGING IN THE TRENTON LIMESTONES OF THE SAINT-LAWRENCE PLATFORM (CENTRE BLOCK REHABILITATION PROJECT CASE STUDY)

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Reflection on Resources

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ABSTRACT

For major construction projects involving excavations or tunneling in bedrock, a detailed stratigraphic and geo-structural model of the subsurface formations is required as input to geotechnical and structural design. A new approach has been developed to evaluate bedrock structure within Limestones of the Trenton group found in the St. Lawrence Platform, taking advantage of volcanic ash layers (K-bentonites) present within the geologic records. K-bentonite layers can be detected using gamma logging techniques in boreholes and provide specific stratigraphic marker horizons to identify geological discontinuities. The method is being applied in geotechnical assessments and design of Centre Block Rehabilitation (CBR) Project in Ottawa, Canada. This paper provides geological background on the origin and characteristics of K-bentonites, a summary of analytical methods for bedrock stratigraphic correlation and rock-mass structure evaluation, and commentaries on our latest findings.

RÉSUMÉ

Pour tous les grands projets de tunnel et d'excavation profonde dans le roc, la première étape consiste à établir un modèle stratigraphique et structural détaillé des formations souterraines qui sera ensuite utilisé pour la conception géotechnique et structurale. Une nouvelle approche qui tire parti de la présence de couches de cendres volcaniques - appelées K-bentonites - a été développée pour évaluer la structure du roc dans les calcaires du groupe de Trenton de la plate-forme du Saint-Laurent. Les lits de K-bentonite constituent des marqueurs stratigraphiques spécifiques qui peuvent être détectés en forage à l'aide de la diagraphie gamma et qu'on peut corréler pour identifier les discontinuités géologiques. La méthode proposée est actuellement utilisée dans le cadre des évaluations géotechniques pour le projet de réhabilitation du Centre Block (CBR) à Ottawa, Canada. Cet article rappelle le contexte géologique à l'origine des cendres volcaniques et les principales caractéristiques des lits de K-bentonite, présente les méthodes mises en œuvre pour recueillir et interpréter les données de diagraphie gamma et résume les principales informations obtenues dans le cadre du projet CBR.

1 INTRODUCTION

Gamma logging has long been recognized as a powerful tool for subsurface correlation and interpretation of sedimentary rock environments, particularly in petroleum exploration and hydrogeological studies (Bertozzi et al., 1981; Serra and Serra, 2004). It is often under-utilized or ignored in geotechnical assessments for major infrastructure projects, such as tunneling and mass excavations in bedrock, despite its capacity to provide geo-structural information not only at a singular point (as in conventional boreholes logged by coring, packer tests, televiewer, etc.), but across multiple boreholes.

The method takes advantage of radioactive ash layers present within limestone deposits of the mid-Ordovician Trenton Group, which extend across the St. Lawrence Platform between Montreal and Kingston in Canada, and in the eastern United States. Because K-bentonite ash layers were deposited as continuous layers, each of them within a narrow window of geological time across broad geographic areas, they provide specific stratigraphic marker horizons that can be used to detect geological discontinuities, and potential construction hazards and risks between variably investigated locations.

This paper is organized as follows: geological context that contributed to the deposition of a series of volcanic ash layers in Trenton Limestones is briefly introduced in Section 2. Section 3 presents primary physical and mineralogical features that establish K-bentonite volcanic ashes as unique marker horizons within the Ordovician rock sequence. The basic principle of stratigraphic correlation is briefly reviewed in Section 4, and specific geotechnical issues related to the presence of K-bentonites beds are introduced in Section 5. The current application of gamma logging and K-bentonite stratigraphic analysis at the Centre Block Rehabilitation Project is discussed in Section 6 as a case study, including descriptions of the data acquisition, processing steps, and acquired geo-structural interpretations used in the geotechnical analysis of the site.

2 GEOLOGICAL SETTING

Sediments forming the Trenton Group were deposited along the passive margin of the Laurentia continent during the Middle Ordovician period approximately 450 million years ago. During this time the Laurentia continent was periodically exposed to volcanic ash deposits originating from a succession of explosive eruptions along the Iapetus Ocean subduction zone (Huff et al, 1996). The tectonism created an ensemble of volcanically active island arcs and microplates against the southeastern margin of Laurentia, and ultimately gave rise to the Taconic orogeny (Scotese and McKerrow, 1991).

Some of the volcanic eruptions in the period provided huge amounts of ash that covered large swaths of North America. Figure 1 illustrates the depositional extent of a single volcanic event, as inferred from outcrops located both in Europe and North America (Bergström et al., 2004). Black dots indicate the location of the assessed outcrops and green lines depict the inferred thickness of the ash layer.

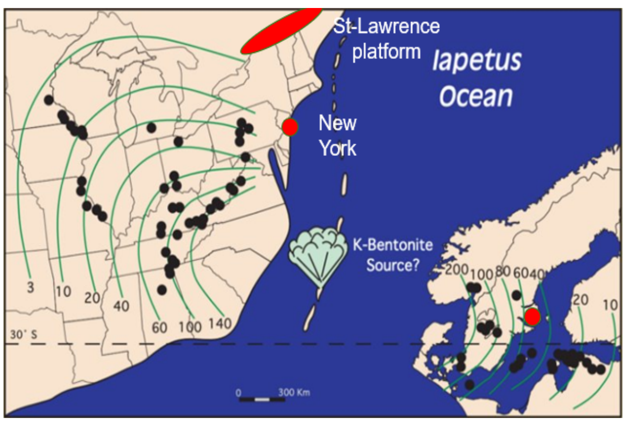

Figure 1. Dispersion of volcanic ash from the single so-called Milbrig volcanic event (Bergström et al., 2004). Reproduced with permission.

A series of similar volcanic events are recorded as individual K-bentonite ash layers embedded within the Ordovician bedrock sequence.

While the thickness of volcanic ash beds decreases with distance from the source, as illustrated in Figure 1, some of the erupted material reached what is now Eastern Canada. Volcanic ash deposits have been described in Ontario, and more specifically in the Ottawa area, by Sharma et al (2005), Gbadeyan and Dix (2013) and Oruche et al., (2018). In Montreal and Quebec, the presence of similar ash layers is described by Brun and Chagnon (1979).

3 K-BENTONITE CHARACTERISTICS

K-bentonite ash layers in Ontario and Quebec generally appear as 1 to 10 cm thick beds, comprised mostly of clayey, plastic, unconsolidated material within the limestone (Figure 2).

Figure 2. Typical K-bentonite ash layer embedded in a rock core drilled in the Trenton limestones, CBR Project.

Sometimes, K-Bentonite layers may appear in indurated form, which are often more difficult to detect in rock core with the naked eye.

The interface with the walls of the surrounding limestone is generally well delimited, and K-bentonite ash layers show discrete laminations which confirm their provenance and emplacement mechanism. K-bentonite horizons are often misidentified in core logs of Trenton Limestones as filled joints, fault gouges, or in the worst case simply as boring mud.

Volcanic ash layers that initially comprised amorphous "glass" of rhyodacitic composition, with some accessory minerals such as zircon, apatite, biotite, etc., are typically weathered to interstratified kaolinite-smectite and/or illite-smectite clay minerals (Huff., 2008). Because of their volcanic origin, K-bentonites strongly differ from the surrounding host rock both in mineralogy and geochemical composition, and more specifically (and fortunately) by their U, Th and K radioisotope content In the laboratory, material may be confirmed as K-bentonite using specific chemical and mineralogic signatures from specimens taken from either rock cores or outcrops.

In boreholes, K-bentonite ash layers may be identified using gamma logging. Natural gamma radioactivity of rocks is induced by natural isotopes: Potassium (^{40}K), Uranium (^{238}U), and Thorium (^{232}Th), and their associated decay products. Because of their relatively high content in U, Th and K radioisotopes, K-bentonites systematically coincide with peak anomalies in gamma logs. Figure 3 illustrates how such a layer embedded in the Trenton Limestones typically appears on a gamma log.

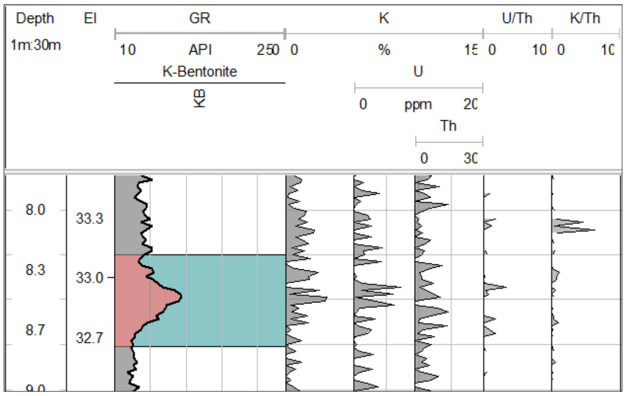

Figure 3. Typical gamma signature of K-bentonite ash layer embedded within Trenton limestone cores, CBR Project.

Natural gamma signatures in sedimentary rocks mainly reflect clay content. More information may be gained to differentiate shaley rock from ash layer using spectral gamma logging techniques. The spectral gamma method measures and analyzes all wavelengths of natural gamma radiation to extract K, U and Th concentrations, since each isotope has its own specific energy spectrum. The U/Th and K/Th ratios inferred from spectral gamma readings can be used to discriminate between volcanic ashes and detrital material.

4 STRATIGRAPHIC CORRELATION

The main advantage in using K-bentonite ash beds for stratigraphic and spatial correlations, as stated earlier, lies in the continuity of the K-bentonite layers deposited within narrow windows of geological time (a few weeks or months as compared to million years for the surrounding sedimentary rocks), and across broad geographic areas.

Using K-bentonite layers as geologic markers for stratigraphic correlation appears to be a powerful tool for the reconstruction and interpretation of multiple geological processes, including deformation and faulting giving rise to the current expression of the sedimentary rock profile. This has been done for large scale geodynamic reconstitutions (e.g., Oruche et al. 2018) of the Laurentia platform. As far as the authors know, this approach has not yet been used in Trenton Limestones at the scale of underground infrastructure projects, such as tunnels or deep excavation projects.

Figure 4 presents some basic geological principles that are used for the structural interpretation of a rock mass. The photograph was taken in a quarry excavated in the Trenton Limestone, on Montreal Island in Canada. It shows an initially continuous K-bentonite layer which is now at two different elevations along the same rock face. From a straightforward correlation of the layer, it becomes possible to accurately locate the fault that is responsible for the relative displacement of the ash bed along the face, and to measure its offset.

Figure 4. Offset of a K-bentonite layer by a normal fault - Lafarge Quarry, Montreal QC.

Most of the time, only boreholes are available for assessing underground infrastructure projects. K-bentonite beds can nevertheless be identified through gamma logging as previously noted. Any evidence of a perturbation in the initial geometry of an ash layer may be an indication that the rock mass has been deformed. As illustrated in Figure 5, the vertical displacement on each side of the fault appears as a local dip change of the ash layer between two boreholes.

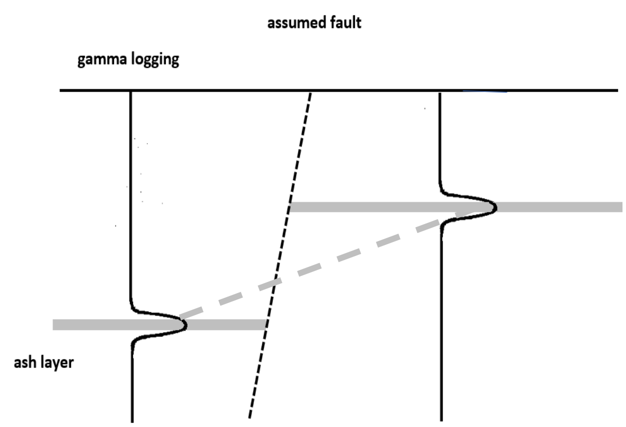

Figure 5. Schematic sketch of gamma log correlation of a K-bentonite layer in two neighboring boreholes, detecting a potential fault and its offset.

Both an approximate location and the offset of a fault, could be inferred in the same way as in the quarry outcrop example of Figure 4 by correlating gamma ray anomalies from two boreholes drilled on either side of the fault line. The degree of confidence in the interpretation may of course vary as a function of several parameters, such as distance between neighboring boreholes, offset amplitude, dip of bedding and folding for instance. A specific investigation strategy is therefore required depending on the expected spatial resolution of geologic features.

5 GEOTECHNICAL IMPLICATIONS

Besides the opportunity for using K-bentonite layers as stratigraphic markers for spatial correlation and structural reconstruction, their presence in the rock mass may give rise to important geotechnical issues that should be assessed during the initial design stages of any underground project.

While most of the clay content is the by-product of volcanic glass weathering, typical K-bentonite layers are rather described by routine laboratory tests (e.g., grain size analysis, Atterberg Limits) as clayey silts with a trace to some sand. Hydraulic conductivity for these layers is typically several orders of magnitude greater than the surrounding rock mass. Therefore, K-bentonite layers may provide a preferential pathway for groundwater seepage (and any entrained contaminants) through the rock mass. Figure 6 shows ice lenses and curtains formed by rock face seepage, from a K-bentonite horizon in Trenton Limestone.

Figure 6. Ice formation at interface of K-bentonite layer, Orignal Quarry, Ontario.

K-bentonite ash layers tend to impart planes of weakness within the rock mass. Shear strength of the material is generally low and sliding potential may be enhanced by hydrostatic pressure, depending on infiltration rates and seasonal variations in the groundwater table. During the last glaciation event, the presence of such preferential sliding planes led to the displacement and fracturing of rock layers close to the surface, as a result of stresses induced by glacier movements. Durand (1991) and Ballivy and Durand (1974) reported glacio-tectonic faulting at several locations – especially at the Olympic site - in the Montreal area.

Glacio-tectonism in conjunction with the presence of K-bentonite layers was mentioned as a probable factor in the collapse of at least three tunnels drilled in Trenton Limestones, using Tunnel Boring Machines on Montreal Island during the last 30 years (see Brierley et al, 1987; Ladanyi, 1993). In each case, fieldwork was interrupted for at least several months.

The presence of potential weak sliding planes in the bedrock as well as broken and faulted zones are serious issues in deep excavations and tunneling. Early identification of K-bentonite layers in underground infrastructure projects is therefore useful, not only for detecting existing faults through stratigraphic correlations but also for correct assessments and mitigation of potential geotechnical issues during construction.

6 CASE STUDY: CENTRE BLOCK REHABILITATION PROJECT

The described K-bentonite analysis is currently being applied in geotechnical designs for Centre Block Rehabilitation (CBR) Project in Ottawa Ontario, which is the hub of Canadian federal government and a national heritage site.

The CBR Project is currently the largest heritage building rehabilitation project in Canada, and one of the largest in the world. The project started in 2017 and is scheduled for completion in approximately 2030. It includes construction of a new 3-story subterranean Parliament Welcome Centre (PWC), with corridor and service linkages extending below Centre Block and in close proximity to the 100m tall Peace Tower. Excavations for the project are up to 24m deep into the bedrock, and foundation underpinning is required for both the Centre Block and Peace Tower superstructures. The foundations will also be equipped with a new seismic base isolation system to comply with Canada's National Building Code (NBCC).

A thorough geotechnical investigation program was undertaken for this complex project, including stratigraphic and geo-mechanical evaluations of rock core holes, optical borehole imaging, dilatometer testing, evaluations of in-situ field stress, hydraulic packer tests, etc. Detecting prominent structures within the rock mass, including faults, was an important challenge for accurate evaluation of seismic site response and stability concerns with respect to the deep excavations adjacent to sensitive structures with very low tolerance to ground movement.

6.1 LOCAL GEOLOGY

Bedrock of the Parliament Hill comprises Middle Ordovician limestone with some shaley interlayers (Bélanger et al., 1980). Gbadeyan and Dix (2013) subdivide the upper units into the Lindsay and underlying Verulam Formations. The former predominantly consists of fine to coarse-grained, fossiliferous, argillaceous limestone, with minor shaley partings. The latter comprises interbedded bioclastic to very-fine grained limestone and grey-green calcareous shale.

Both the Lindsay and Verulam Formations were identified during geotechnical investigations completed for the CBR Project. Based on the stratigraphic context (see section 2) the presence of K-bentonites beds was expected but remained to be confirmed by targeted testing.

6.2 COLLECTED INFORMATION

Over sixty boreholes were drilled for the CBR Project in a multi-phase investigation approach. Of these, eight boreholes drilled in the basement of Centre Block were identified for preliminary K-bentonite analysis and gamma scanning. The borehole locations are shown on Figure 7 Downhole gamma logging was conducted using a QL40 spectral gamma ray (SGR) probe manufactured by Mount Sopris. Total gamma radiation is provided in API units, a measurement developed by the American Petroleum Institute for the petroleum industry.

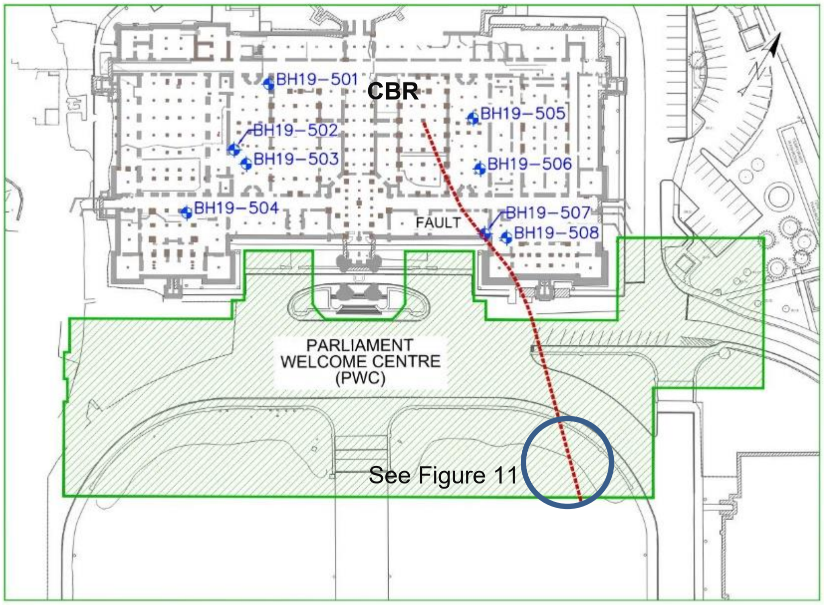

Figure 7. Center Block Rehabilitation Project – Location of Boreholes for K-bentonite scanning

Boreholes identified in Figure 7 were located in areas where no prior geotechnical information was available. Boreholes BH19-501 to BH19-504 were drilled beneath the western part of the building whilst boreholes BH19-505 to BH19-508 were located eastwards. The boreholes were approximately 30m deep and were advanced using NQ-size rods. Use of bentonitic drilling mud was of course prohibited to prevent contamination of the boreholes with respect to gamma scanning principles.

The on-site investigation combined spectral gamma ray (SGR) logging together with optical borehole imaging (OBI) and continuous rock core sampling.

As mentioned previously, natural gamma radiation mainly reflects clay content in sedimentary rocks and emissions are known to increase in clayey limestones and shales. The information from three sources, spectral gamma ray surveying, optical borehole imaging and core logging, were combined to discriminate K-bentonite ash layers from clay in limestone and shale, for our stratigraphic correlation purposes.

For gamma logging, both the sampling rate and gamma probe velocity were adjusted to obtain high resolution profiles and properly detect even small-scale individual gamma anomalies. In the spectral gamma logs, Uranium (U) and Thorium (Th) concentrations in rock samples are typically reported in parts per million (ppm), whereas Potassium (K) is given in weight percent (%).

Borehole imaging was carried out with the optical televiewer probe QL40-OBI-2G also by Mount Sopris. The equipment set-up included a 200m long winch, equipped with a telemetric system to obtain high-resolution elevation measurements, and the SCOUT-PRO data acquisition system. Logging was piloted through a rugged field computer with the appropriate logger suite software. Both gamma and OBI raw data were imported into WellCAD – a designed geophysical software package – for manipulating, formatting and interpreting the gamma log and OBI data.

Geological and structural descriptions of the rock cores were completed for stratigraphic and geo-mechanical assessments. The geologic contact between the Verulam and Lindsay Formations was tentatively identified based on the existing descriptions in the literature (Gbadeyan and Dix, 2013).

6.3 STRATIGRAPHIC CORRELATION

The succession of troughs and peaks of gamma logs observed in boreholes for the CBR Project reflects variations in mineral composition, that are directly dependent on geological processes controlling the stratigraphic sequence. Within this profile, volcanic eruptions forming ash deposition layers occur as major singular events. Figure 8 illustrates total gamma profiles measured in the eight previously referenced boreholes (BH19-501 to BH19-508). Correlating the gamma ray logs was simply done by pairing peaks and troughs from one profile to another.

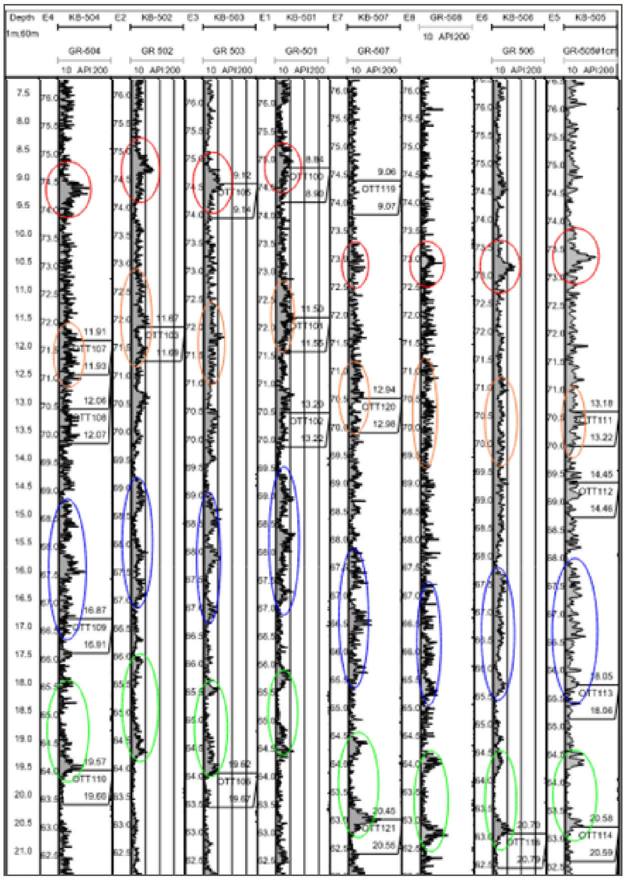

Figure 8. Total gamma records as found in boreholes BH19-501 to BH19-508 of the CBR Project. Colored ellipses correspond to four anomalous sequences. Gamma peaks labelled OTTx indicate ash sampling locations for laboratory tests.

Four distinct anomalies or peak sequences were specifically identified in the logs, as shown on Figure 8. It is worth noting that these anomalies systematically appear with the same sequence and at the same distance along the profiles, even if the correlation may not be exact from one gamma profile to another. Peak amplitudes may change for instance, and some secondary peaks may be absent in some profiles because of local variations in mineralogical composition, or small changes in the data acquisition process.

6.4 ROCK CORE LOGGING AND OBI VALIDATION

Major gamma anomalies observed in the project profile have been unambiguously related to K-bentonite ash horizons, from direct observations in rock core samples. The presence of four distinct K-bentonite horizons were confirmed within the investigated bedrock profile of the site, meaning there were at least four distinct volcanic events preserved within the investigated depth. Ash layers, such as the one illustrated in Figure 2, are easily detected by eye. It is worth mentioning however that the number of confirmed beds in rock cores could be different from one borehole to another, as illustrated in Figure 8. To account for such discrepancies, it is worth noting that the thickness of a given horizon may vary from a borehole to another, some layers may have been washed out during drilling, and others may be embedded in more shaley horizons or be too thin to be identified.

A total of twenty-two samples of suspected ash layers in the borehole core samples were selected for laboratory geochemical testing. The requested tests specifically targeted the elemental composition of the samples using multi-collector Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Assuming the ash beds could be discriminated based on their geochemical signature, then it would also become possible to assess rock cores where gamma data are not available. This work is currently in progress and will not be discussed further in this paper.

While Optical Borehole Imaging (OBI) is usually applied to detect joints, layering, fractures and fault gouges for structural assessments in boreholes, it may also be used for spatial correlation when combined with gamma logging records. Figure 9 below illustrates how a K-bentonite horizon typically corresponds to a filled open joint, that also coincides with a strong gamma anomaly.

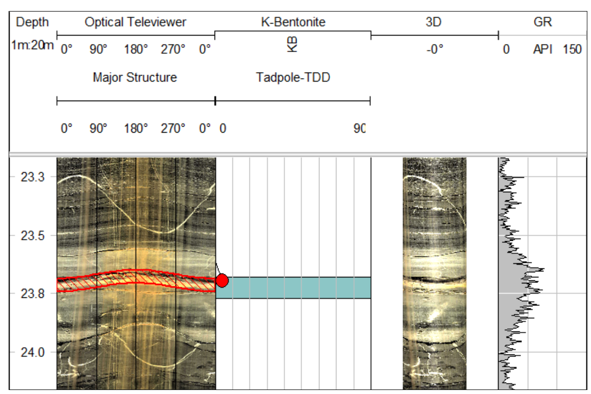

Figure 9. Typical OBI record of a K-bentonite layer, that is automatically interpreted as a filled open joint using specialized software.

As illustrated in Figure 9, the clay filled joint is embedded between two 10 cm thick massive, light-grey colored limestone beds. This forms a recognizable stratigraphic sequence that can be more easily detected on both rock cores and in OBI records.

6.5 STRUCTURAL INTERPRETATION

The eight previously referenced boreholes were stratigraphically correlated to produce a preliminary structural cross-section of the bedrock beneath Centre Block (Figure 10). Correlation of the boreholes is the result of an iterative process to tentatively eliminate any inconsistencies and converge toward a unique interpretation of the 3D bedrock geometry.

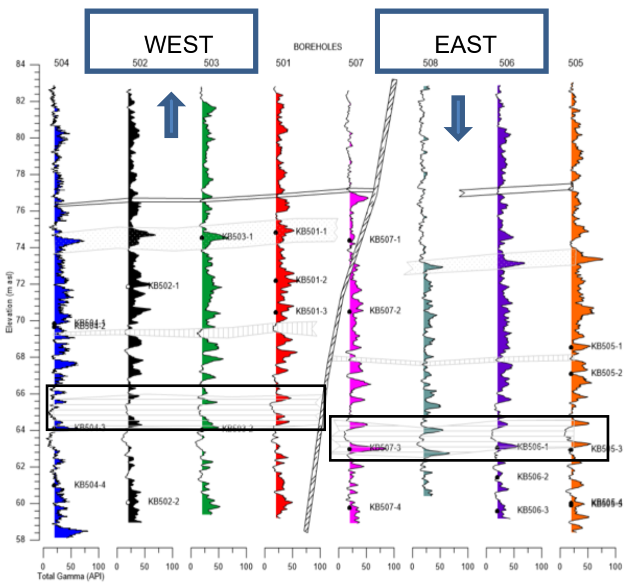

Figure 10. Gamma log and geo-structural cross-section beneath Centre Block.

The combined information indicates that the bedrock beneath the eastern side of Centre Block has been displaced approximately 2 m vertically with respect to the western side. Evidence of faulting, including calcite veining and breccia-like zones, was found in borehole BH19-507. The fault was interpreted to have a northwest-southeast trend. Owing to the spatial distribution of boreholes, the fault direction could not be more precisely defined. Within the two fault blocks, bedding is nearly horizontal.

Figure 11. Fault trace as observed in southern face of PWC excavation (approximate 2 m offset noted).

The fault was subsequently observed in both the north and south faces during the early PWC excavation works. Figure 11 provides a view of the fault trace on the floor and within the southern wall of the excavation, which confirms its orientation and offset. The position of the fault is reported on Figure 7 as a dotted red line for illustration. The fault will have significant design implications for the future PWC linkage excavations and structures extending beneath Centre Block.

7 DISCUSSION

Gamma logging was successfully used in the Centre Block Rehabilitation Project to extract preliminary 3D structural information for the bedrock profile using local 1D borehole data. High-resolution stratigraphic correlations were established between boreholes by taking advantage of the presence of volcanic ash layers, that provide gamma local sources that can be used as stratigraphic markers.

It is the first time to our knowledge that the existence of volcanic ash beds - also known as K-bentonite layers– has been demonstrated in the Parliamentary Precinct. Their existence could be suspected, however, based on the regional geological setting and previous findings in the greater Ottawa area. Four (4) distinct ash layers were formally identified from the information collected in eight boreholes advanced beneath the Centre Block building.

To the authors’ knowledge it is the first time that a high-resolution stratigraphic correlation has been undertaken in a geotechnical investigation for this type of project. A significant fault was detected, and its direction and offset were inferred from a stratigraphic correlations of K-bentonite marker layers between boreholes. The fault was later confirmed in the PWC excavation and in the Centre Block basement following demolition of the slab-on- grade. The fault is identified to be a design and construction risk.

Potential geotechnical issues associated with K-bentonite layers will be addressed with respect to rock wedge stability and groundwater seepage during the excavation works. The boreholes considered in this paper did not provide any substantiated evidence of glacio-tectonism beneath the CBR Project site.

The K-bentonite layers are being considered in Finite Element Models to analyze ground behavior (e.g., sliding, displacement) within and adjacent to the CBR Project excavations. Geo-structural information gained from high-resolution spatial correlations will be further integrated into the design process to improve modeling of seismic site response and to optimize the Centre Block basement level upgrades.

A sound structural model contributes to better understanding of geotechnical hazards and reduces project risks and potential construction change orders. The 3D model will be progressively extended across more of the site area using data compiled from existing boreholes or data systematically collected in forthcoming boreholes and / or excavation scanning. It is worth noting that gamma logging remains a quite inexpensive investigation method once the boreholes – with or without coring – have been drilled.

8 CONCLUSION

Gamma logging in combination with OBI and rock core logging has proven to be a powerful method for extracting 3D structural information from boreholes drilled for geotechnical investigations of large underground projects.

In the specific case of the Centre Block Rehabilitation Project, anomalous gamma signatures were identified as volcanic ash layers within limestone deposits of the Trenton Group (Lindsay and Verulam Formations). The layers were formed by volcanism during tectonic subduction at the margins of the Laurentia plate, about 450 million years ago. Because of the continental extent of the ash deposits, the proposed analytical approach in this paper is not only limited to the study area but could easily applied elsewhere in eastern Canada and USA. For example, in Montreal Quebec, the Trenton Formation comprises about 2/3 of the island area and several major projects such as the extension of the Metro blue line or the construction of the “Réseau Électrique Métropolitain (REM)” will involve tunneling in the Trenton Limestones.

9 ACKNOWLEDGMENTS

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