

2021 Report of the
NWMO Adaptive Phased Management
Geoscientific Review Group (GRG)

- Preliminary Geoscientific Assessments -

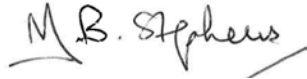
December 2021



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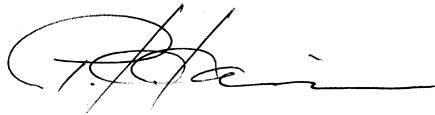
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2021 Report of the NWMO Adaptive Phased Management Geoscientific Review Group (GRG) December 2021

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1 Executive summary

This report summarizes the work completed in 2021 by the Adaptive Phased Management Geoscientific Review Group (APM-GRG; abbreviated to GRG). This year, due to the Covid-19 pandemic, all GRG meetings were held in a virtual format. The GRG and NWMO met 14 times by web-meeting including two meetings with Senior Management of NWMO and an extended set of three-day virtual meetings in September to provide time for detailed technical and scientific discussions. In Q4 2021, the GRG welcomed Dr. Sven Follin of Sweden as a new member to enhance the expertise of the GRG in hydrogeology and groundwater modelling/engineering.

The GRG reviews approaches, methods, criteria and findings related to broad geoscientific issues addressed by the NWMO. The focus during 2021 was on activities in crystalline rock at the Revell Site in the northern part of the Archean Revell batholith, Ignace area, and on test plans for drilling the first borehole (SB_BH01) and a 3D seismic investigation in Paleozoic sedimentary rock at the South Bruce Site. In addition to the GRG's regular and formal review of technical reports, the NWMO shared several other documents with the GRG for comments and feedback to the NWMO.

For the Revell Site and surroundings in the Ignace area, the GRG reviewed technical reports involving geoscientific data analyses, data integration and modelling, in preparation for the first version of the Descriptive Geosphere Site Model (DGSM) planned for 2022. These documents addressed: (1) Discrete Fracture Network (DFN) and integrated hydrogeological models at sub-regional scale for the northern part of the Revell batholith and its surroundings; (2) Geological and geophysical data integration for borehole IG_BH02; (3) 3D Geological Model (3DGM) Version 1.0 for the Revell Site; (4) Thermal, geomechanical, hydrogeochemical and hydrogeological data integration for boreholes IG_BH01–BH03; (5) Table of contents for the first version of the DGSM report; (6) 2020 Annual Report for Westbay fluid pressure monitoring and groundwater sampling along boreholes IG_BH01 and IG_BH03; and (7) 2021 summary of geological conditions at the Revell Site.

For the South Bruce Site, the GRG continued to review test plans in connection with the drilling of borehole SB_BH01. The test plans included activities labelled WP02 (Borehole drilling and logging), WP04B (Laboratory geomechanical and thermal testing of core), WP05 (Geophysical well logging and interpretation), WP07 (Opportunistic groundwater sampling) and WP08 (Temporary well sealing). These test plans complement others reviewed by the GRG during 2020 and reported on in their 2020 Annual Report. During 2021, the GRG also reviewed a plan for 3D seismic data acquisition in the South Bruce area and a Geoscientific Site Characterization Plan (GSCP) for the South Bruce Site.

As in previous years, the GRG made various contributions to geoscientific aspects, and these are briefly described in this report. The NWMO documented the GRG's suggestions, questions and comments in disposition tables, subsequently addressed them and provided final revised reports to the GRG. The NWMO continues to provide timely high-quality responses to points raised by the GRG in a transparent and professional manner. The GRG emphasizes again that feedback through the detailed disposition tables is most helpful for the GRG to monitor the impact of its review effort.

The GRG expressed its concern to the Senior Management of NWMO that there could be some difficulties to maintain the high-quality of work being carried out by the Geoscience team due to the forthcoming ramping up of new data from the South Bruce Site in a very short timeframe. Furthermore, the GRG expressed a desire to see an active integration of geoscience findings with activities concerning repository design and safety analysis.

Technical and scientific aspects are described in the main body of this report. A few high-level aspects from the Ignace area are highlighted below:

- The GRG welcomed the completion of sub-regional DFN and hydrogeological models in the Ignace area, providing the necessary broader framework for the Revell site-scale models.
- The GRG welcomed completion of the first version of the 3DGM at the Revell Site, with largely deterministic models for rock units, structural units capturing the general variation in fracture frequency and inferred fracture zones. This model forms the basic framework to be used in site modelling by other geoscientific disciplines.
- The GRG stressed the need to acquire more thermal data on the subordinate rock type amphibolite, bearing in mind its low thermal conductivity. The GRG welcomed that the NWMO is currently evaluating the origin of this rock type to predict its spatial distribution with more confidence.
- The GRG advised the NWMO to relate the geomechanics data to variations in rock type and structure along the boreholes, in particular to the occurrence of subordinate rock types, rather than providing undifferentiated trends in properties with depth.
- Whereas the GRG accepted the site characterization plan without *in situ* rock stress measurements along boreholes during Phase 2 site activities, the GRG identified the need to consider stress domains at different depths in the rock mass at the Revell Site for data interpretation. These stress domains can be identified from an extensive public stress data base for the Canadian Shield, refined with breakout and other data collected at the Revell Site. The significance of such domains for variations in geomechanical, hydrogeochemical and hydrogeological properties needs to be identified and addressed.
- The GRG is concerned that the current hydrogeochemical database for transmissive fractures is still very limited, thereby restricting evaluation of the relationship between groundwater in fractures and in the rock matrix. Nevertheless, very few transmissive fractures have been identified at the site and the GRG is pleased to see that NWMO has modified the data acquisition procedures to help improve the database. The GRG has also emphasized that water-rock interaction processes and potential drilling fluid contamination need to be evaluated in detail while interpreting ^{14}C age dating of groundwater.
- The GRG expressed concern about the handling of hydraulic test data, with insufficient emphasis on transmissivities of fractures and fracture zones, and the internal heterogeneity of hydraulic properties along such structures. In particular, there is a need to identify the character and orientation of the transmissive fractures. The GRG is satisfied that NWMO will provide more information on such fractures in the DGSM Version 0.0 document planned for 2022.
- The GRG supported the conclusion made by the NWMO that nothing has been identified to date in the geoscientific information to suggest that the Revell Site has unfavourable conditions for a repository.

Notwithstanding some technical issues described in this report and highlighted above and bearing in mind the different phases of site evaluation at the Revell and South Bruce sites, the GRG considers that the adopted approach and the quality of the studies by NWMO continue to follow, in large part, international practice. The GRG is also of the opinion that NWMO will have a satisfactory geoscience case for site selection by the end of 2023. The GRG looks forward to seeing the first version of the DGSM at the Revell Site and awaits with interest to review data from the first borehole at South Bruce.

1 Introduction

The Adaptive Phased Management Geoscientific Review Group (APM-GRG; abbreviated to GRG) was established by NWMO in 2012. It aims to provide independent review comments and advice on the geoscientific assessments being conducted as part of NWMO's evaluations to identify a single suitable deep geological repository site for Canada's used nuclear fuel in an informed and willing host community. More specifically, the GRG provides comments on the approach, methods and criteria used, the data interpretation, and the adequacy of proposed preliminary field investigation and drilling programs to advance the understanding of the geology and increase confidence in the potential suitability of the various siting areas being considered by NWMO. Increasingly, the GRG is providing feedback on draft data interpretation reports resulting from this site characterization program and related modelling of the potential repository sites.

This report covers the activities of the GRG during the year 2021. Previous GRG reports were issued and are publicly available on NWMO's website (APM-GRG 2013, 2014, 2016, 2017, 2018, 2019, 2020 www.nwmo.ca). Late this year NWMO has acted on the recommendation by the GRG to add expertise in the areas of hydrogeology and groundwater modelling/engineering and has expanded the GRG by contracting Dr. Sven Follin (SF GeoLogic AB, Stockholm, Sweden). Brief biographies of current GRG members are attached to this report.

2 Objectives of NWMO's geoscientific preliminary assessments

The suitability of communities is assessed using a staged approach including 'Initial Screenings', 'Preliminary Assessments' and 'Detailed Site Characterization', and considers both technical and community well-being factors (NWMO 2010).

The overall preliminary assessment is conducted through a series of technical, socio-economic and cultural studies conducted in two phases over several years. Technical studies involve geoscience, engineering, transportation, environment and safety. The objective of the geoscientific suitability preliminary assessment is to determine whether candidate areas have the potential to meet NWMO's site evaluation factors (geoscientific suitability). The two phases are:

- Phase 1 - Desktop Study: Undertaken for all communities electing to be the focus of a preliminary assessment. This phase involved desktop studies using available geoscientific information, and a set of key geoscientific characteristics and factors that can be realistically assessed at the desktop phase of the preliminary assessment. Desktop studies for all communities are completed.
- Phase 2 - Preliminary Field Investigations: Undertaken to further assess the potential suitability of a subset of communities selected by the NWMO. Depending on the geological setting, Phase 2 field investigations can include high-resolution surface and airborne surveys, geological mapping, and initial borehole drilling.

The subset of communities advanced to Phase 2 preliminary assessment were selected based on the findings from the desktop study during Phase 1, considering technical, socio-economic and cultural considerations. It is important to note that the mandate of the GRG is exclusively focussed on the approach, methods, criteria and findings associated with the geoscientific suitability assessments. The GRG is not involved in matters pertaining to transportation and environment, and is not consulted when narrowing down the number of communities.

The status of involvement by different communities in NWMO's site selection process as of December 2021 is illustrated in Figure 1. There are currently two communities remaining in the site selection process. They are both in Phase 2 of the preliminary assessment, and

include Ignace on crystalline rock and South Bruce on Paleozoic sedimentary rock. During 2021, the GRG reviewed geoscience data analysis and interpretation reports related to the Ignace community, with focus on a specific site inside this area referred to as the Revell Site. Review activities for the sedimentary site (South Bruce) involved test plans for borehole drilling and other fieldwork in that area as well as an initial plan for geoscientific site characterization.

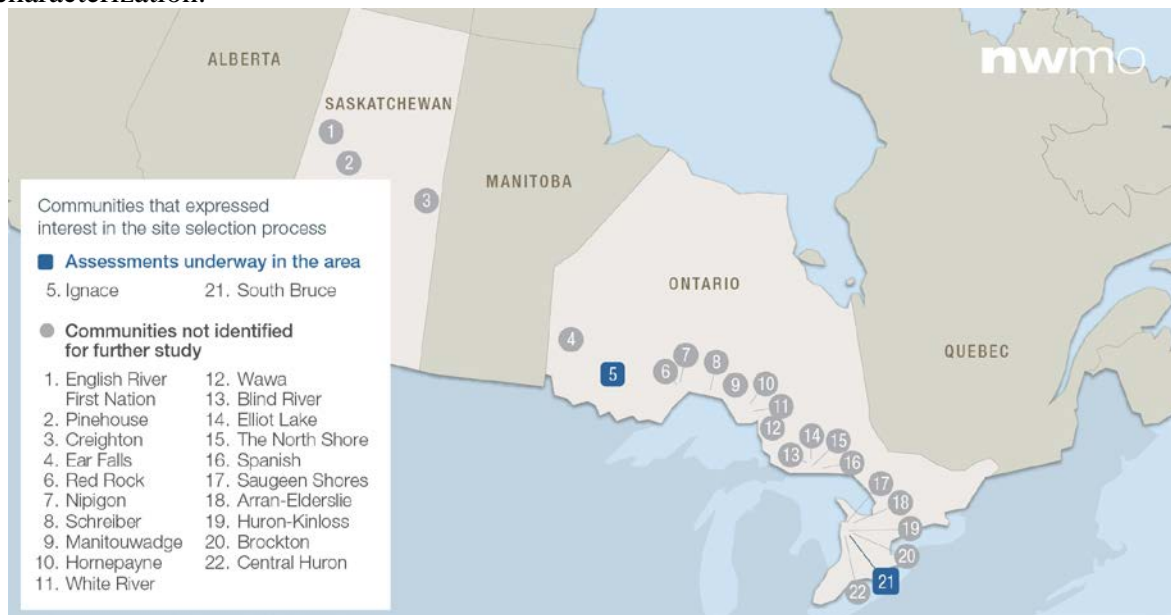


Figure 1. Communities that expressed interest in the site selection process (as of December 2021). Communities 1 to 16 are located on crystalline rock, and communities 17 to 22 on sedimentary rock. The two remaining communities are highlighted (5 and 21).

3 GRG review activities in 2021

As the following list of activities illustrates, 2021 was another rather demanding period for the GRG. Due to the Covid-19 pandemic, twelve virtual web-meetings were held to discuss specific technical/scientific issues, and to discuss questions and recommendations emerging from the reviews of eighteen documents. Two web-meetings in February and September were scheduled with NWMO’s Senior Management to inform the GRG of the overall program goals and approaches, and to discuss areas that deserve further attention in the opinion of the GRG. The GRG continued to fulfill its advisory function on all forthcoming work tasks.

3.1 Meetings between GRG and NWMO

In 2021, the GRG (Figure 2) was primarily involved in reviewing NWMO’s geoscientific activities in the Ignace area. The GRG also reviewed NWMO’s geoscientific work plans related to the geoscientific site characterization, including planning of drilling and other fieldwork for the South Bruce Site, Ontario. The meetings included:

- Web-meeting on January 19, 2021.
Focus: Overview of the integration workflow for 2021–2024 for Descriptive Geosphere Site Model (DGSM) development in Ignace and South Bruce.
- Web-meeting on February 23, 2021.
Focus: Ignace 3D Geological Model (3DGM) Version 1.0 with report overview.
- Web-meeting on February 23, 2021.
Meeting with Senior Management.
- Web-meeting on March 23, 2021.

- Focus: Overview of detailed fracture and lineament field mapping, and microseismic station installation planned for Ignace in 2021.
- Web-meeting on May 18, 2021.
Focus: 2D seismic interpretation in Ignace and 3D seismic acquisition plan in South Bruce.
- Web-meeting June 23, 2021.
Focus: DGSM sub-disciplines preliminary modelling plans.
- Web-meeting on August 17, 2021.
Focus: IG_BH01–03 fracture orientation set identification for DFN development.
- Web-meeting September 14, 2021.
Focus: DGSM workflow diagram and table of contents review, and IG_BH04–05 geological summary.
- Web-meeting September 15, 2021.
Focus: Hydrogeochemistry results, ongoing work and plans.
- Web-meeting September 17, 2021.
Focus: Geomechanics results, ongoing work and plans, and SB_BH01 geological summary.
- Web-meeting September 23, 2021. Meeting with Senior Management.
- Web-meeting October 21, 2021.
Focus: How the department of Safety Assessment uses geoscience data (presentation by Safety Assessment).
- Web-meeting November 16, 2021.
Focus: Update on hydrogeological modelling at the Revell Site (Ignace area) and geophysical log results from SB_BH01 at the South Bruce Site
- Web-meeting December 14, 2021.
Focus: Noble Gas Data from IG_BH04 and Posiva flow log data from IG_BH04–06.

Feedback from the GRG for consideration by the NWMO was shared during and after each virtual meeting but, more importantly, individual GRG members communicated directly by e-mail or during additional focused virtual meetings. Overall, the GRG is satisfied with the adopted mode of communication that allows the GRG to operate effectively. In particular, the GRG appreciates and applauds the diligent use of disposition tables in response to GRG document reviews. In this manner, the GRG can track and respond, if necessary, to actions planned by NWMO.

The GRG is pleased to note that the Geoscience team has been expanded with quality staff but is still concerned that the team will not be able to complete the required work at two potential sites, and at a standard that meets or exceeds international standards of geoscience characterization for site selection. Whereas the quality and consistency of reporting is at a high standard, the GRG is concerned that integration across sub-disciplines will be lagging, because the team members are expected to work on two fundamentally different potential repository sites.

The GRG provided feedback concerning key issues around the development of the first Descriptive Geosphere Site Model (DGSM) for the Revell Site at Ignace. After the detailed September meetings, outstanding issues were raised both in a Memo to the Geoscience team and during a separate virtual meeting to NWMO Senior Management. For example, the GRG provided recommendations bearing on the conceptual thinking around the origin of the subordinate rock amphibolite at the Revell Site. This issue is technically important due to the significance of this rock for the evaluation of thermal properties at the site and, therefore, for

the repository design. The GRG also urged the Geoscience team to focus attention on the relationship between all gently dipping subordinate rock occurrences and hydraulically conductive features. Limited hydrogeochemical data from transmissive fractures, insufficient focus on groundwater transmissivities along fractures and fracture zones, the heterogeneity of hydraulic properties along these structures, and aspects related to the integration of *in situ* rock stress and hydrogeological features were all raised as concerns by the GRG. The GRG recommended that stress domains at depth need to be identified, and their impact on the groundwater regime and for construction should be evaluated. The GRG encouraged the Geoscience team to carry out a focused reassessment of Canadian Shield stress data. The GRG welcomes that these issues are now being addressed in the continued preparation work for the DGSM Version 0.0 planned for 2022.

At South Bruce, the GRG recommended that the identification and characterization of fractures (faults, joints, and veins) along the two boreholes should be included, to evaluate the extent of diffusive or advective transport processes in the host rock (Ordovician Cobourg Formation) and its surrounding formations. The GRG remains concerned about the lack of velocity (P- and S-wave) testing on confined borehole samples but understand that this activity will be carried out at the site selected for more detailed characterization. From the point of view of model iteration, the GRG would have welcomed a geoscientific 3D predictive site model for South Bruce, based on a revised regional-scale 3D stratigraphic model for the area around this site and rock properties from investigations at the Bruce Nuclear Site, prior to acquisition of new data at South Bruce. However, the GRG understands that the time window does not permit completion of this activity.

At special meetings of the GRG with Senior Management, the GRG was seeking an understanding and, subsequently, confirmation of its understanding with respect to NMWO's site selection strategy, i.e., the goals, approach and timing of selection of a single safe site. The GRG was particularly interested in the interaction between the Geoscience and Safety Assessment teams, and expressed a desire to see an active integration of geoscience findings in the repository design. Issues touched on included *in situ* rock stress state, groundwater residence times, fracture transmissivities and several others. The GRG is satisfied that the October web-meeting was designed to specifically address this interaction. The GRG also raised the issue of competent resources to simultaneously handle two potential repository sites in distinctly different geological settings in a very short timeframe.



Figure 2. APM-GRG members Peter Kaiser (Chairman), Alexander Cruden, Sven Follin, Andreas Gautschi, Michael Stephens and Anders Ström

3.2 *Specific studies reviewed by the GRG*

The GRG systematically reviewed approaches, methods and findings reported in the following geoscientific studies, and summarizes some comments on them in later sections of this report. Most of these activities address geoscientific data analyses, data integration and modelling in and around the Revell crystalline rock site, Ignace area (Section 5.1). Reports related to the sedimentary site at South Bruce (Section 5.2) focused on test plans and scopes of work for the first two boreholes, a test plan for a 3D seismic investigation, and the initial

version of the Geoscientific Site Characterization Plan. Only documents that were received and reviewed prior to December 1st, 2021 are addressed in this report.

- Sub-regional scale Discrete Fracture Network (DFN) modelling for the Revell batholith (Section 5.1).
- Sub-regional scale integrated hydrogeological model for the Revell batholith and surrounding area (Section 5.1).
- Phase 2 initial borehole drilling and testing, Ignace area: WP10 – geological integration report for borehole IG_BH02 (Section 5.1).
- 3D site-scale geological model in the Revell batholith: Model Version 1.0 (Section 5.1).
- Phase 2 initial borehole drilling and testing, Ignace area: Data integration reports (Thermal, Geomechanics, Hydrogeochemistry, Hydrogeology) for boreholes IG_BH01, IG_BH02 and IG_BH03 (four separate components in Section 5.1).
- Descriptive Geosphere Site Model of the Revell Site: Table of Contents (Section 5.1).
- 2020 Annual Report for Westbay fluid pressure monitoring and groundwater sampling along boreholes IG_BH01 and IG_BH03 (Section 5.1).
- 2021 summary of geological conditions at the Revell Site (Section 5.1).
- Phase 2 initial borehole drilling and testing, South Bruce: WP02 test plan – Borehole drilling and coring for SB_BH01 (Section 5.2).
- Phase 2 initial borehole drilling and testing, South Bruce: WP04B test plan – Laboratory geomechanical and thermal testing of core from SB_BH01 (Section 5.2).
- Phase 2 initial borehole drilling and testing, South Bruce: WP05 test plan – Geophysical well logging and interpretation for SB_BH01 (Section 5.2).
- Phase 2 initial borehole drilling and testing, South Bruce: WP07 test plan – Opportunistic groundwater sampling for SB_BH01 (Section 5.2).
- Phase 2 initial borehole drilling and testing, South Bruce: WP08 test plan – Temporary well sealing for SB_BH01 (Section 5.2).
- Phase 2 – 3D seismic Investigation, South Bruce: Project test plan (Section 5.2).
- South Bruce site – Geoscientific Site Characterization Plan (Section 5.2).

In addition to the GRG's regular review tasks, the following documents were shared with the GRG in 2021 for review or comments:

- A review of a draft of a data compilation led by the NWMO Research and Development (R&D) team: 'Equivalent porous media rock mass and fracture zone permeability versus depth in a Canadian Precambrian rock setting' written by University of Waterloo geoscientists, to be published in the open literature.
- Comments on a draft scope of work entitled 'State of Science Review of Groundwater and Porewater in Cratonic Crystalline Rocks' written by the NWMO R&D and Geoscience teams.
- A review of a test plan (WP04E) on sorption core testing for IG_BH04 to be carried out by the Safety Assessment Group in the context of NWMO's R&D program.
- Comments on an updated version of the geoscience definitions in the glossary of terms used in the Adapted Phase Management Deep Geological Repository programme.
- Comments on a technical memorandum providing pre-drilling geological interpretations in boreholes IG_BH05 and IG_BH06, based on previous work at the Revell Site in the Ignace area.

- Comments on a technical memorandum providing pre-drilling stratigraphic interpretations in boreholes SB_BH01 and SB_BH02 at the South Bruce site.
- Comments on plans to establish shallow groundwater monitoring networks at both Ignace and South Bruce.
- Comments and advice on ongoing interpretations of amphibolite-bearing rock units at the Revell Site.

The NWMO R&D and Geoscience teams expressed their appreciation for the GRG feedback to the additional documents and indicated that they plan to address these issues in updated report versions.

4 Overall assessment of progress during 2021

The GRG's review process followed the same approach as in previous years, although all meetings were held in virtual format in 2021 due to the Covid-19 pandemic:

- Prior to meetings, NWMO shared draft work plans and initial findings in technical reports, as they became available, to solicit review comments.
- The web-meetings and e-mail exchanges with NWMO were held to discuss the GRG's review comments.
- GRG comments to all technical reports were documented and tracked in disposition tables, which, together with NWMO responses and in most cases final dispositions, were returned to the GRG to ensure that the approach to address the review comments was appropriate.

The GRG's overall contributions in 2021 focussed on the tasks listed in Section 3.2, the results of which were presented to the GRG in the form of technical documents or oral presentations at the meetings.

The GRG is still most satisfied with the systematic, iterative approach and the methods adopted by the NWMO, and is impressed by the progress made despite the continued disruptions by the Covid-19 pandemic. In particular, the GRG is pleased that efforts have now been taken to complete sub-regional Discrete Fracture Network (DFN) and integrated hydrogeological models for the northern part of the Revell batholith, where the Revell Site is located, and its surroundings. These models provide a broad framework for the models at site scale.

The development of the first version of the 3D Geological Model (3DGM) for the Revell Site, based on integrated geological and geophysical data from the ground surface and three boreholes, marks an important milestone in the site selection process for the Ignace area. This model provides a firm basis for data analyses and modelling in the fields of geomechanics, thermal properties and the hydrogeological system (hydrogeochemistry, hydrogeology and transport properties), which all have more direct links to the design and safety assessment of a repository. Drilling of subsequent boreholes IG_BH04 and IG_BH05 at the Revell Site has provided confidence for the conceptual thinking in the first version of the 3DGM. Following earlier recommendations by the GRG, we are also satisfied that a focused field effort to evaluate at least some of the lineaments and drone imagery of fractures in quarry walls close to the Revell Site have been initiated. The fracture study aims to provide support to the DFN simulations that will be required at repository scale.

The GRG considers that there is considerable work to be completed with detailed data analyses and modelling before the desired quality level intended for all areas in the Descriptive Geosphere Site Model (DGSM) Version 0.0 at Ignace can be reached during 2022. The table of contents for this forthcoming DGSM is on the right track but the GRG

feels that some aspects concerned with the hydrothermal system and geomechanics components still need to mature somewhat. As indicated earlier, the GRG is concerned that there is currently insufficient focus in the fractured crystalline rock at Ignace on discrete water-conducting features and aspects of heterogeneity in hydraulic properties along fractures and fracture zones. Furthermore, the hydrogeological system needs to be interpreted in the context of the potential influence of different stress domains at different depths in the rock mass.

The GRG is satisfied with the test plans in connection with drilling of the two boreholes at the sedimentary South Bruce Site. The GRG also looks forward to reviewing the data analyses from the first borehole, drilling of which has now been completed, and the results of the 3D seismic survey at this site. The GRG has emphasized that fractures (faults, joints and veins) and fracture zones, not only stratigraphy, need to be evaluated from both the borehole and 3D seismic information. It is apparent to the GRG that work at South Bruce is progressing according to plan.

The NWMO team and its consultants have again undertaken high-quality work. The approach adopted by NWMO allowed the GRG to review findings and progress in detail, and the GRG was able to provide timely input for consideration by NWMO. Suggestions by the GRG for process improvements were considered and implemented by NWMO in a rapid, transparent and professional manner. The GRG wishes to emphasize again that NWMO has provided timely and excellent feedback through the disposition tables that are most helpful for the GRG to monitor the impact of the review effort. NWMO is to be congratulated for their outstanding efforts with these tables. Consequently, NWMO continues to maintain a high standard of quality work and is making steady progress in the site evaluation process at Ignace, and in the drilling and planning for other field activities at South Bruce. In the GRG members' opinion, the adopted approach continues to follow in large parts and, in the case of how NWMO responds to the GRG in the disposition tables, even exceeds international practices.

5 GRG review comments

5.1 *Data analysis, integration and modelling at the Ignace crystalline rock site*

- Review of sub-regional scale Discrete Fracture Network (DFN) modelling for the Revell batholith

This technical report documents the workflow and summarizes the results of sub-regional scale fracture network modelling using Version 3.6 MoFrac software in an area centered on the northern part of the Revell batholith. The GRG requested more emphasis, even in the Executive Summary, that the DFN models are based on the interpretation of lineaments with a surficial trace length greater than 500 m, inferred using high-resolution LiDAR, ortho-imagery and airborne magnetic data sets, in combination with the fundamental assumption that the lineaments represent fracture zones. In this respect, the DFN models are 'semi-deterministic' in character. The GRG also requested clarification around evaluation of the consistency between each realization in the modelling procedure and the degree of fit to the input data. Inspection of the disposition table shows that the revised version of the report addresses these review comments. Furthermore, considerable text has been modified or added, to meet virtually all the other points raised in the review process.

- Review of sub-regional scale integrated hydrogeological model for the Revell batholith and surrounding area.

This sub-regional scale hydrogeological model presents a rather general equivalent porous medium approach to the Canadian Shield hydrogeology, which is fine at the early stage of the

project. According to the test plan, there was no intent to use the first provisional results from Ignace borehole drilling as an input for the models (geological, hydrogeological and hydrogeochemical data). The GRG identified several issues that need to be addressed in the future with respect to hydrogeological modelling studies (e.g., presence of sub-horizontal water-conducting fractures (as at Whiteshell URL), validation of modelling results using hydrogeochemical data (such as total dissolved solids), comparison of water ‘ages’ based on isotopic signatures with mean groundwater residence times (from recharge to the sampling point). Concerning the role of mafic dykes, it was suggested to add additional sensitivity runs with dykes acting as conduits, not only as barriers to groundwater flow.

The GRG was informed by NWMO that hydrogeochemistry, hydrogeology and transport properties will be merged into one chapter in the Descriptive Geosphere Site Model (DGSM) Version 0.0 report and all general GRG review comments will be incorporated during this amalgamation.

- Review of Phase 2 initial borehole drilling and testing: WP10 – geological integration report for borehole IG_BH02

The GRG was impressed by the quality of the WP10 report for borehole IG_BH02, which had accommodated many of the changes recommended in reviews of equivalent WP10 reports for boreholes IG_BH01 and IG_BH03. The GRG advised NWMO to follow the format of the WP10 IG_BH02 document in future WP10 reports.

The GRG questioned some aspects around the interpretation of the neutron logs and the significance of the alteration types referred to as ‘potassic alteration’ and ‘carbonatization’. The GRG have been informed that the NWMO is investigating in more detail the mineral assemblages of rock alteration at Ignace. Virtually all other GRG review comments have been handled in the revised document.

The GRG also provided comments on several issues arising from the evaluation of the geology along IG_BH02 that should be considered in forthcoming work. These include the location of high fracture frequency intervals linked to the occurrence of secondary rock types along each borehole and a more detailed treatment of logged aperture along fractures. The GRG noted the need for a detailed comparison of geophysical televiewer and geological core logs/photographs, bearing in mind the link between aperture and hydraulic properties.

- Review of 3D site-scale geological model in the Revell batholith: Model Version 1.0

The 3D Geological Model (3DGM) Version 1.0 report for the Revell Site is well-structured, easy to follow and marks an important milestone in the site selection process for the Ignace area.

The GRG emphasized the importance of the integrated rock unit containing a higher frequency of amphibolite for thermal characterization and modelling at the site. For this reason, the GRG also summarized the need to evaluate the origin of the amphibolite in this integrated rock unit at the first September web-meeting. NWMO demonstrated in their reply an understanding of the need for tight integration with the thermal modelling team.

In response to the GRG review, the NWMO acknowledged the need to describe the link between lithological breaks along boreholes and fracture frequency. The NWMO indicated that this issue will be addressed in the forthcoming 3D Discrete Fracture Network (DFN) model report (2022), and in the next iteration of the site-scale geological modelling exercise. The GRG also emphasized that the DFN work should integrate tightly with the framework and findings of the 3DGM Version 1.0. The NWMO assured the GRG that the DFN will honour the location of fractures in the boreholes and their orientations. Furthermore, the intensity of the fractures through the DFN model in 3D will honour the division of the site

into integrated structural units in the 3DGM Version 1.0, which capture the general variation in fracture frequency along each borehole.

Specific comments provided in the GRG review sheet and track changes in an accompanying word document have been accepted or are planned to be completed in the next model version. Modifications have been made accordingly.

- Review of Phase 2 initial borehole drilling and testing: Thermal data integration for boreholes IG_BH01, IG_BH02 and IG_BH03

This report is well-structured. Comparisons with Swedish and Finnish data sets have also been completed and show a good overall agreement with the Revell data set. The GRG raised questions concerning the methodology for thermal modelling including upscaling and the effects of anisotropy in samples selected for thermal conductivity measurements. The NWMO indicated that these issues will be tackled once there are enough data to study them. They also indicated that more information on the occurrence of foliation in rock samples, including photographic information, will be added in the forthcoming DGSM Version 0.0 report (2022). The GRG emphasized and NWMO acknowledged that there is an urgent need for more thermal data on especially the secondary rock type amphibolite on account of its low thermal conductivity and the experience at the Forsmark site, Sweden. Specific points raised in the GRG review sheet have been completed or are in progress and will be incorporated in the DGSM Version 0.0 report.

- Review of Phase 2 initial borehole drilling and testing: Geomechanical data integration for boreholes IG_BH01, IG_BH02 and IG_BH03.

It was pointed out that this report is not a data integration report and, thus, is not ready for integration into the DGSM Version 0.0 report. Some fundamental principles were ignored (e.g., relating properties to stress state in the Canadian Shield), and no attempt was made to relate the geomechanics data to lithologies and structures. These reports are also not consistent with formats of companion reports (e.g., thermal property reports). The abstract was too vague and did not reflect the technical findings. Furthermore, the report must reflect the encountered variability in data, and outline the current limitations in data together with a statement of future remedies to fill the gaps.

A disposition table was distributed by NWMO with responses indicating that revisions will be implemented, and updated drafts distributed for a second review. At the time of writing, a revised report had not yet been received.

- Review of Phase 2 initial borehole drilling and testing: Geochemical data integration for boreholes IG_BH01, IG_BH02 and IG_BH03.

The GRG suggested that the title should be changed to 'Hydrogeochemical data integration' to show the difference to geochemical signatures of rocks (lithochemical data). Furthermore, some comparisons with Canadian Shield experience and discussions of climatic influences should be added. The content of the report requires significant revision before the material can be included in the DGSM Version 0.0 report. The GRG has noticed that the interpretation of ^{14}C age dating does not consider the complex water-rock interaction processes that also need information from rock carbonates. This could lead to unreliable (too high) age data. The GRG recommended to contract an experienced isotope geochemist to help resolve this problem and NWMO has agreed.

The GRG is concerned that the current hydrogeochemical database for transmissive fractures is too limited, thereby restricting evaluation of the relationship between groundwater along fractures and in the rock matrix. The GRG is aware that very few transmissive fractures have been identified at the Revell Site and welcomes that NWMO has modified the data acquisition procedures to help improve the database.

When comparing the data set with the Geoscientific Site Characterization Plan (GSCP), the GRG identified a series of missing parameters. The NWMO confirmed that there will be attempts to measure these parameters during the drilling of BH04 to BH06 or in Westbay Multipacker Systems.

- Review of Phase 2 initial borehole drilling and testing: Hydrogeological data integration for boreholes IG_BH01, IG_BH02 and IG_BH03.

This report is well structured and written. GRG is concerned about comparing hydraulic properties of different rock types from different depths (i.e., under different rock stress conditions). The GRG understands that internal heterogeneity of water-conducting fractures, and correlations between hydrogeological properties and hydrochemistry will be addressed later in the DGSM Version 0.0 document. Another concern raised by the GRG relating to the need for a more detailed evaluation of hydraulic test data was addressed during a follow-up meeting. This matter involved use of average hydraulic conductivity of a test interval versus allocation of transmissivities to individual fractures along or outside inferred fracture zones. The GRG is satisfied that NWMO will provide more information on such fractures in the DGSM Version 0.0 document.

- Review of Descriptive Geosphere Site Model of the Revell Site: Table of Contents

The GRG has so far reviewed two versions of the table of contents for the DGSM Version 0.0 report of the Revell Site and has discussed this document at the first September web-meeting. Most of the relatively minor recommendations for changes in Sections 1 to 7 and 9 in the first version were completed in the second version. However, some terminological adjustments in the contents table and critical issues in Section 8, which addresses the descriptive hydrogeological system model, remain. Apart from modification to the title of Section 8 in the first version, the GRG pointed out that a hydraulic conductivity value for a test interval is not enough information for modelling radionuclide transport. In addition to hydraulic conductivities, transmissivities of discrete water-conducting features should also be addressed. The GRG considers that the table of contents for the forthcoming DGSM Version 0.0 of the Revell Site is progressing well but anticipate that a review of a newly updated version of the document is necessary.

- Review of 2020 Annual Report for Westbay fluid pressure monitoring and groundwater sampling along boreholes IG_BH01, IG_BH03

The GRG recommended a more detailed evaluation of potential contamination of the groundwater sample by drilling fluid and of the ^{14}C data for determining groundwater age. NWMO has indicated that corrections have been made to the ^{14}C data due to the influence by drill fluid. Argon isotope data mentioned in the Geoscientific Site Characterization Plan were currently missing in the report.

- Review of 2021 summary of geological conditions at the Revell Site

This report provides a good summary of the current understanding of the geoscientific character of the Revell Site and the GRG provided recommendations for modification of the order of presentation of different sections. The GRG pointed out that there is not enough focus on hydraulic transmissivity along groundwater-conducting fractures (along or outside inferred fracture zones). The GRG was disappointed that there was no discussion of a possible link between variation of *in situ* rock stress and hydraulic-hydrogeochemical properties with depth. The GRG is confident that these issues will be resolved in the forthcoming DGSM Version 0.0 document.

The GRG also reminded NWMO that comparisons of predictions and outcomes are an important part of developing a sound understanding of the site and in building confidence.

The GRG supported the conclusion that nothing has been identified to date in the geoscientific information suggesting that the Revell Site has unfavourable conditions for a repository.

5.2 Plans for Phase 2 initial borehole drilling and testing, and other fieldwork activities, at the South Bruce sedimentary rock site

- Review of Phase 2 initial borehole drilling and testing, South Bruce: WP02 test plan – Borehole drilling and coring for SB_BH01

The GRG considered that the test plan is mature and well-written and is pleased that an external review will also be made. Only a few editorial comments were provided in the review process, and these have been addressed satisfactorily in the revised document.

- Review of Phase 2 initial borehole drilling and testing, South Bruce: WP04B test plan – Laboratory geomechanical and thermal testing of core from SB_BH01

The GRG expressed concern about the plan to obtain P- and S-wave velocities from unconfined test samples and in unloaded state. This data is of importance for the calibration and interpretation of geophysical logs measuring the confined properties of the rock near the borehole. For this reason, the GRG strongly recommends testing of samples from the South Bruce site in confined or at least axially loaded states. The GRG understands that this activity will be carried out later during detailed site characterization if the South Bruce Site is selected.

- Review of Phase 2 initial borehole drilling and testing, South Bruce: WP05 test plan – Geophysical well logging and interpretation for SB_BH01

The GRG suggested that new multi-mineralogical geophysical log interpretation tools (e.g., by Schlumberger), calibrated by quantitative mineralogical and petrophysical core analyses, should find application in the site characterization program. This procedure is commonly applied by oil companies and is also used by Nagra in Switzerland. The NWMO replied that they are familiar with Schlumberger's tool and their ability to do multi-mineralogical interpretations and may utilize this tool if South Bruce is selected for detailed site characterisation. For the first two boreholes, however, NWMO will internally integrate geophysical logging (WP05) and geological core analysis data (WP03).

- Review of Phase 2 Initial Borehole Drilling and Testing, South Bruce: WP07 Test Plan- Opportunistic Groundwater Sampling for SB_BH01.

This test plan is very detailed and well written, and more detailed than other test plans, mainly due to detailed appendices that have a character of an internal handbook. Issues raised by the GRG concerning the MOSDAX downhole sampler and back up / archive water samples were answered satisfactorily.

- Review of Phase 2 initial borehole drilling and testing, South Bruce: WP08 test plan – Temporary well sealing for SB_BH01

The GRG considered that the test plan is well-structured and well-written and is satisfied with the technical aspects. Only a few editorial comments were provided in the review process, and these have been addressed satisfactorily in the revised document.

- Review of Phase 2 – 3D seismic investigation, South Bruce: Project test plan

The GRG is satisfied that the 3D seismic investigation at the South Bruce site aims not only to target and image the spatial extent of significant horizons in the sedimentary succession, not least the Ordovician Cobourg Formation, but will also address faults in the succession and characterize rock physical properties by linking the seismic data to geophysical data from deep boreholes. The GRG expressed some concern around the influence on the quality of the seismic data related to the exclusion of areas where there is restricted land access. NWMO

informed the GRG that an attempt to minimize this problem by adding additional shot points where there may be less coverage for the source and receiver points. The GRG is satisfied with this response and other technical aspects in the report. NWMO also satisfactorily completed the recommended editorial comments in the review process.

- Review of South Bruce site – Geoscientific Site Characterization Plan

The GRG had a mixed impression on the maturity of the plan for the geoscientific site characterization of the South Bruce Site. There are several examples where significant revision of the strategic thinking is necessary. For example, natural radionuclide barriers are more than simply the planned repository host rock at the site (Ordovician Cobourg Formation). The relevant properties of the surrounding formations also need to be documented in the site description. The GRG also recommended that drilling, if possible, should continue into the upper part of the Precambrian basement to provide a more complete understanding of the hydrogeology of the site. Furthermore, groundwater residence times, not only mean times to discharge, should be addressed in the hydrogeological modelling exercise. Probably the most important problem in the plan concerns the inbuilt assumption that radionuclide transport in the host rock and surrounding barrier rocks is entirely diffusive in character. The aim of the investigations at South Bruce must be to demonstrate in which parts of the geosphere radionuclide transport is dominated by diffusion, by advection or even by a mixture of both processes. For this reason, fractures in the sedimentary formations (i.e., joints, faults, and veins) must be documented and evaluated during site characterization. The GRG also noted serious problems with the content of the chapter dealing with site characterization of the geology of the site and some differences in approach compared to the Revell Site (Ignace area) where it concerns single borehole data integration work. There are also some differences to the Revell Site with regards to the terminology used for different scales of modelling.

NWMO have responded in considerable detail to all the review comments by the GRG and the GRG is satisfied that the issues raised have already been or will be completed in a subsequent revised document. NWMO have also indicated that a second review procedure of the revised plan will be carried out.

6 Concluding remarks

As indicated in previous reports, the GRG is in large parts satisfied with the progress made and continues to be impressed by the systematic and consistent approach adopted by the NWMO to conduct geoscientific site evaluation. The NWMO has developed sound workflows for the various field studies and interpretation exercises to ensure consistency, which has allowed the GRG to be able to carefully assess approaches, interpretations and conclusions. The GRG continues to actively interact with the NWMO Geoscience team to provide proactive assistance to ensure clarity and consistency in approaches, and in communication of results. On this basis, the GRG supports the overall outcomes from these studies at this stage of investigation.

The GRG has made many suggestions for improvements in data interpretation processes at the crystalline rock Revell Site in the Ignace area and is pleased to report that the NWMO has mostly responded to the issues identified in a timely, highly transparent, technically sound and professional manner. Nevertheless, the GRG has identified several important issues that should be prioritised for attention at the Revell Site. These include the integration of rock stress and hydrogeological features at different depths, completion of the hydrogeochemical database for transmissive fractures, more focus on groundwater transmissivities along fractures and fracture zones, and investigations of the heterogeneity of hydraulic properties

along these structures. The GRG welcomes that these issues are now being addressed in the continued preparation work for the DGSM Version 0.0 planned for 2022.

The GRG also reviewed test plans for drilling and a plan for the acquisition of 3D seismic data at the sedimentary South Bruce Site. The GRG looks forward to the first results from these investigations and will continue to provide feedback to the NWMO Geoscience team to ensure consistency in future work at this site.

Notwithstanding some technical issues described in this report, the GRG concurs that the adopted approach and the quality of the studies by NWMO continue to follow in large parts international practice at this phase of site evaluation. The GRG is also of the opinion that NWMO will have a satisfactory geoscience case for site selection by the end of 2023.

7 References – Documents available from www.nwmo.ca

APM-GRG, 2013. 2012-2013 Report of the NWMO Adaptive Phased Management Geoscientific Review Group (GRG).

APM-GRG, 2014. 2014 Report of the NWMO Adaptive Phased Management Geoscientific Review Group (GRG).

APM-GRG, 2016. 2015-2016 Report of the NWMO Adaptive Phased Management Geoscientific Review Group (GRG).

APM-GRG, 2017. 2017 Report of the NWMO Adaptive Phased Management Geoscientific Review Group (GRG).

APM-GRG, 2018. 2018 Report of the NWMO Adaptive Phased Management Geoscientific Review Group (GRG).

APM-GRG, 2019. 2019 Report of the NWMO Adaptive Phased Management Geoscientific Review Group (GRG).

APM-GRG, 2020. 2020 Report of the NWMO Adaptive Phased Management Geoscientific Review Group (GRG).

NWMO, 2010. Moving Forward Together: Process for Selecting a Site for Canada's Deep Geological Repository for Used Nuclear Fuel, Nuclear Waste Management Organization.

8 Attachment - Brief biographies of the APM-GRG members

The APM-GRG is composed of five internationally recognized experts from Canada, Australia, Sweden, and Switzerland. They combine extensive multidisciplinary international experience in areas relevant to the siting of deep geological repositories in both crystalline rock and sedimentary rock formations.

Dr. Peter Kaiser

Dr. Peter Kaiser, Chairman of the APM-GRG, is Professor Emeritus of Mining Engineering at Laurentian University, former Chair for Rock Engineering and Ground Control, former Director of the Rio Tinto Centre for Underground Mine Construction, and former Founding Director of the Centre for Excellence in Mining Innovation. His interests lie in geomechanics, underground excavation stability, mine design, mechanized excavation, and the applications of emerging technologies that increase mining safety and productivity. Dr. Kaiser is a Fellow of the Canadian Academy of Engineers and a Fellow of the Engineering Institute of Canada.

Dr. Sandy (Alexander) Cruden

Dr. Sandy (Alexander) Cruden is Professor of Tectonics and Geodynamics in the School of Earth, Atmosphere and Environment at Monash University (Australia). Dr. Cruden has more than 25 years of geoscience experience related to structural geology, analysis and characterization in both crystalline and sedimentary rock settings. Dr. Cruden completed a fault reactivation analysis and structural characterization of southwestern Ontario as part of site characterization activities for Ontario Power Generation's proposed Low- and Intermediate-Level Waste Deep Geologic Repository at the Bruce site.

Dr. Sven Follin

Dr. Sven Follin is a geoscience consultant who has been actively involved in the Swedish site evaluation process for hosting a deep geological repository, including geoscientific feasibility studies and the detailed site characterization of the Forsmark site, which was selected by SKB (the Swedish Nuclear Fuel and Waste Management Company) as the site for the deep geological repository for spent nuclear fuel in Sweden. Focus has been on hydrogeological aspects. He was also involved in SKB's subsequent safety assessment.

Dr. Andreas Gautschi

Dr. Andreas Gautschi was Chief Geoscientific Advisor at the Swiss National Cooperative for the Disposal of Radioactive Waste. Since his retirement he works as an international geoscientific consultant. Dr. Gautschi has more than 30 years of geoscience experience related to the planning, co-ordination, and implementation of site evaluation programs for deep geological repositories in both crystalline and sedimentary rocks. He coordinated successful geoscience activities that contributed to the selection of the Opalinus Clay formation as the preferred geological setting for the long-term management of high-level waste in Switzerland. He still has a lectureship at ETH Zurich on Deep Geological Disposal of Radioactive Waste.

Dr. Michael Stephens

Dr. Michael Stephens is a retired Senior State Geologist with the Geological Survey of Sweden in Uppsala. Dr. Stephens has been actively involved in the Swedish site evaluation process, including country-wide reconnaissance studies conducted in Sweden to identify potentially suitable regions for hosting a deep geological repository, geoscientific feasibility studies, and the detailed site characterization of the Forsmark site, which was selected by SKB as the site for the deep geological repository in Sweden. Focus has been on base geological aspects.

Mr. Anders Ström

Mr. Anders Ström is Senior Program Manager of final disposal solutions for spent fuel at SKB (the Swedish Nuclear Fuel and Waste Management Company). Mr. Ström has been actively involved in SKB's siting program since the early 1990s, among other things, in charge of the development of requirements on the crystalline rock for the spent fuel repository and criteria for site evaluation. During the site characterization project, he was Chief Project Manager for the multidisciplinary site descriptive modelling conducted for the two candidate sites at Forsmark and Laxemar-Simpevarp (Oskarshamn). He is now also in charge of the close co-operation between SKB and Posiva, in Finland, for implementing final disposal solutions according to the KBS-3 concept.