

Project Phoenix Pumped Hydro Energy Storage Project - successful implementation of the Engineering Geological Model approach in support of the energy transition

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1 ABSTRACT

ACEN Phoenix Pty Ltd (ACEN Phoenix) engaged GHD to complete prefeasibility and feasibility investigations on Phoenix Pumped Hydro, a proposed pumped hydropower project in regional NSW. The aim of these works was to develop a thorough understanding of site-related geological and geotechnical hazards early in the project, to guide design and enable more accurate cost estimation, whilst reducing, where possible, the need for intrusive on-site investigations. The Engineering Geological Model (EGM) approach can be used to effectively identify and assess geological relationships and geotechnical properties and provides an important framework to enable thorough understanding of geomechanical behaviour and potential hazards (Schofield and Roberts, 2024). On this project, the conceptual geological model was refined in near real-time as the detailed geological mapping identified and delineated an unmapped complexly folded and faulted dolerite sill intruded prior to regional deformation. The investigations were rescoped to provide confidence in the interpretation and hence allowing design optimisation to exploit more favourable geotechnical conditions.

This project demonstrates the benefits of the use of fundamental geological skills as part of the Engineering Geological Model approach in large civil engineering projects to optimise design and deliver both time and cost savings through appropriate and scientific targeting of intrusive investigations.

2 INTRODUCTION

The planned Phoenix Pumped Hydro scheme will be constructed on a greenfield site in Central-West NSW on the eastern side of Lake Burrendong between the population centres of Wellington and Mudgee. It will have an installed capacity of approximately 810 MW for a nominal duration of 12 hours.

The concept design of the scheme allows for construction of new upper and lower reservoirs with an interconnecting waterway and other ancillary infrastructure. There is an approximately 330 m head difference between the reservoirs which means approximately 12 GL of water storage is required in each reservoir to provide the 810 MW of generation.

The concept design conveyance arrangement comprises an excavated vertical shaft and tunnel from the upper reservoir to the surface powerhouse excavated to below the minimum operating level of the lower storage. The installed capacity of 810 MW adopts three standard reversible fixed-speed Francis pump-turbine units of 270 MW capacity. The connection to the network consists of a 330 kV transmission line to a new connection on the existing 330 kV Wellington to Mt Piper line.

Uniquely, GHD identified the site and undertook initial assessments and studies regarding feasibility and site suitability using internal funding mechanisms with ACEN Phoenix ultimately taking on development of the project. GHD was then engaged to complete prefeasibility and feasibility investigations and design. The aim of these works was to develop a thorough understanding of site-related geological and geotechnical hazards early in the project, to guide design and enable more accurate cost estimates. The Engineering Geological Model approach was utilised, as it enables effective identification and assessment of geological relationships and geotechnical properties and provides an important framework to enable thorough understanding of geomechanical behaviour and potential hazards (Schofield and Roberts, 2024) and a scientific approach to the scoping, completion and use of data from intrusive geotechnical investigations.

This paper discusses the engineering geological model development process and findings that were used to guide the geotechnical investigation and demonstrates how following a logical and staged approach with identification of hazards and gaps is an effective approach to understanding ground risk for major projects.

3 ENGINEERING GEOLOGICAL MODEL GUIDELINES

In order to maximise information gathered, the geotechnical and engineering geology assessments of the site were conducted in stages to allow for an iterative development of the geological model, as per the Engineering Geological Model (EGM) Guidelines (Baynes et al 2022). The Engineering Geological Model (EGM) approach facilitates effective identification and assessment of geological relationships and geotechnical properties to ensure a thorough understanding of geomechanical behaviour and potential hazards.

The guidelines provide a valuable framework for development and use of geological models in engineering geology. All available information was utilized to develop a conceptual geological model which will be continually revised as new data becomes available through the rest of the design process, construction and into operation.

4 DESKTOP STUDY

This part of the process studied the regional geological, geomorphological and geophysical characteristics of the site. The published geological mapping and associated mapping reports and memoirs were reviewed to both identify the geology of the site and to understand the processes that contributed to the geological conditions present.

The desktop review identified that the site is dominated by a thick sequence of folded low-grade metasedimentary and possibly volcanic rocks. These materials were deposited in a deep marine environment known as the Hill End Trough which is thought to be part of a large back arc basin system formed during the Lachlan Orogen in the Late Silurian to Early Devonian (approx. 390 to 425 million years ago (Ma)).

Figure 1 shows the 1:100,000 scale Geological Survey of NSW map (Morgan et al, 1999) of the project area which is dominated by the Cunningham Formation with a small area of Merriions Formation towards the north. Approximate locations of the upper and lower reservoir are also presented.

A summary of the geological mapping codes with Formation/Unit names and lithological descriptions is presented in Table 1.

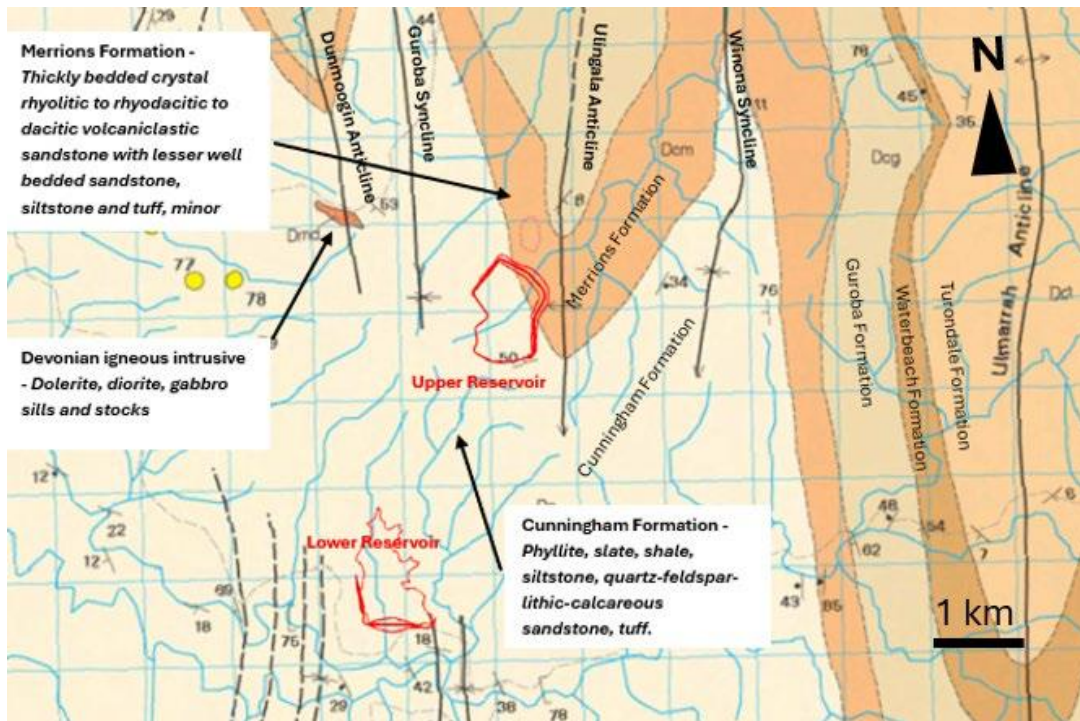


Figure 1: Site geology with project elements shown (after Morgan et al, 1999)

Table 1: Regional bedrock geological units (units in bold are within project boundaries)

Geological map code (youngest to oldest)	Unit Name	Description
Dmd	Not named	Dolerite, diorite, gabbro sills and stocks
Dn	Cunningham Formation	Phyllite, slate, shale, siltstone, quartz-feldspar-lithic-calcareous sandstone, tuff.
Dcm	Merrions Formation	Thickly bedded crystal rhyolitic to rhyodacitic to dacitic volcanoclastic sandstone with lesser well bedded sandstone, siltstone and tuff, minor lava and ignimbrite.
Dcg	Guroba Formation	Thinly to thickly bedded, muddy crystal lithic, rhyolitic to rhyodacitic volcanoclastic sandstone interbedded with lesser tuff, siltstone, phyllitic shale and paraconglomerate.
Dcw	Waterbeach Formation	Well bedded to laminated slate, siltstone and phyllitic shale with lesser lithic, feldspathic sandstone
Dct	Turondale Formation	Thickly bedded, crystal lithic, rhyolitic to rhyodacitic volcanoclastic sandstone interbedded with lesser thinly bedded, pelagic and volcanoclastic sandstone, siltstone and phyllitic shale; minor rhyolitic tuff and conglomerate.

The Cunningham Formation is thought to have been deposited via a combination of marine sedimentation punctuated by submarine debris flows and turbidity currents comprising clay, silt and volcanoclastic sand. Some limestone debris or blocks, resulting from failures along the edge of a carbonate shelf, may also be found in the Cunningham formation (Meakin and Morgan et al, 1999). This mode of deposition may lead to the presence of laterally variable rock types.

The Merrions Formation represents a deposit of volcanically derived material comprising sediments (probably volcanoclastic sandstones) and porphyritic igneous rocks thought to have been lava erupted and emplaced submarine. The clasts present in the sediments match the mineral assemblages present in the lava flows indicating they have been derived from erupted lava (Cas, 1976).

High quality, 1m resolution lidar data was available for the site. Using this data colluvium and alluvium was identified which is not shown on the published geological maps. The lidar data also revealed bedding or foliation structure of the metasedimentary rock across the landscape and an interpretation of the regional scale structural geology was completed. This interpretation indicated the presence of at least four major folds and smaller scale parasitic folding on these main fold limbs, and several short fault strands across the project area. Based on this structural interpretation it was identified that the bedding dip and lithology would be variable across the project area, and that the folded structures may have also lead to the presence of bedding parallel shears and ramp flat thrust, wedge and hinge faulting associated with stresses induced during the folding process.

As surface instability in the form of landslides is a key hazard to surface penstocks (with the exact configuration yet to be decided at the time), a geomorphological assessment was undertaken along the waterway route to identify possible landslides. Although areas of instability, in the form of translational earthflows and rockslides, were identified, these were away from the waterway route. An anomalous feature, of uncertain origin, was also identified in the topography. This feature coincided with a regional geophysical anomaly noted in the airborne radiometric survey data as shown in Figure 2. This radiometric anomaly was similar to one that coincided with a diorite outcrop on the published geological map. The Merrions Formation is also clearly visible in the radiometric data. The radiometric mapping overlaid on the geological mapping with key components of the project and geological features labelled is presented in Figure 3. The areas of landsliding and this geomorphological and geophysical anomaly were added to the itinerary for the geological reconnaissance mapping stage.

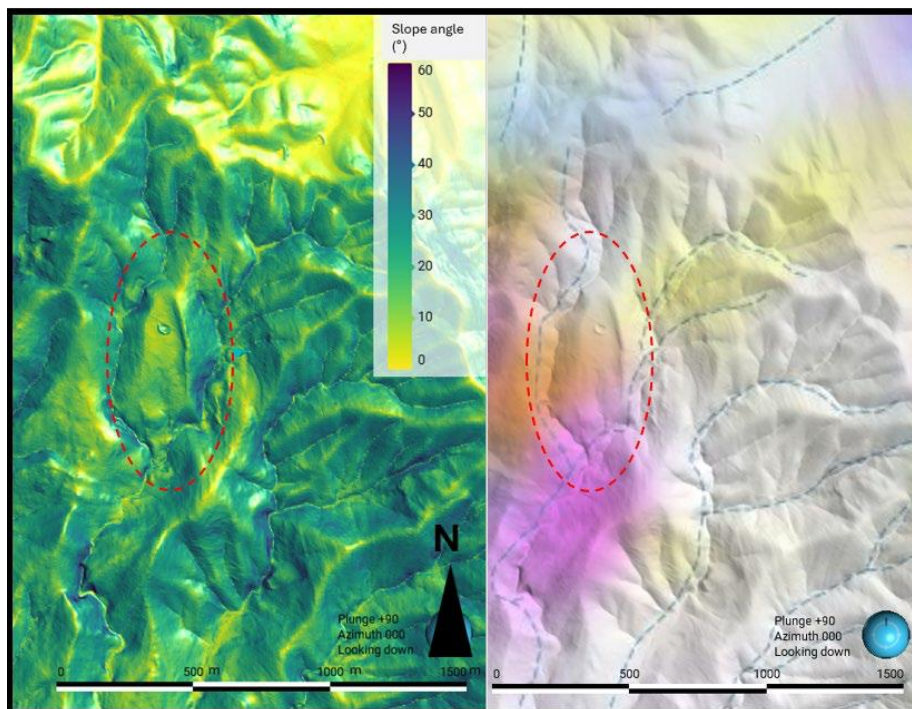


Figure 2: Geomorphological (left) and radiometric anomaly (right)

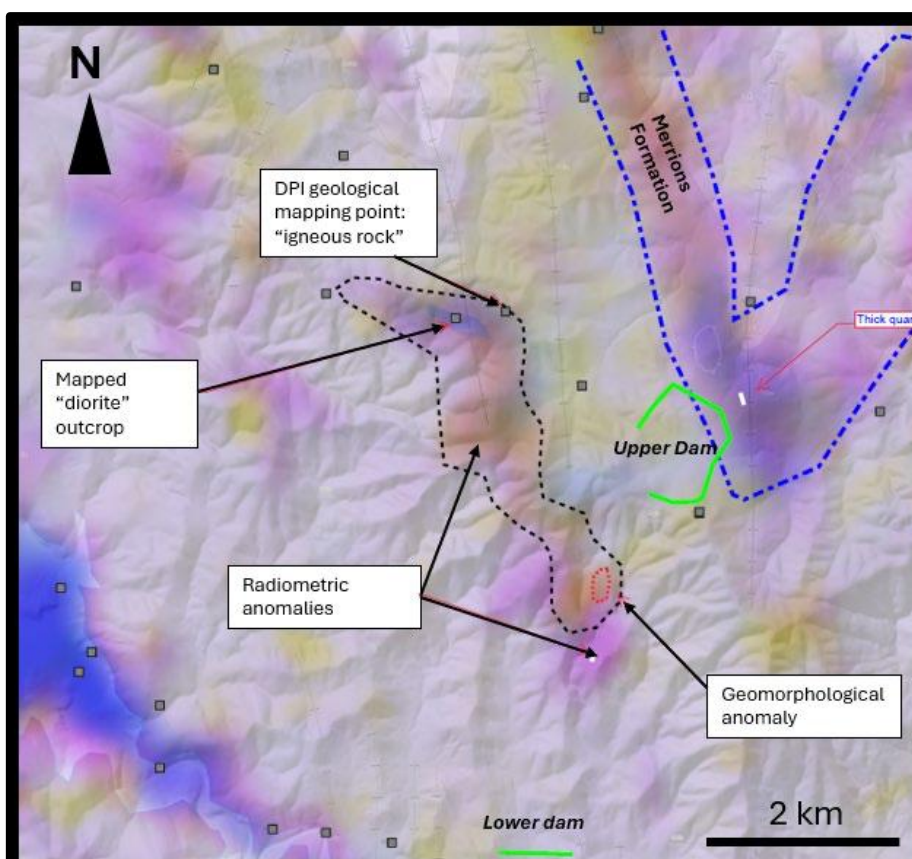


Figure 3: Igneous rock and radiometric anomalies possible indicating broader extent of igneous rock outcrop (DPI = NSW Department of Primary Industries) (after Minview, 2022)

5 GEOLOGICAL RECONNAISSANCE MAPPING

To inform the development of the conceptual geological model, which would be used to develop a scope of works for intrusive geotechnical investigations, geological reconnaissance mapping was completed. The primary aim of this mapping was to identify lithological and geotechnical characteristics and variability in areas of the upper and lower reservoir and along the waterway alignment. Anomalies as discussed in the previous section were also included in the itinerary and assessed. Collection of dip and dip direction structural data of significant features such as foliation, major joints and crushed seams was completed opportunistically.

The mapping identified a number of rock types across the broader project area including:

- A very high strength, slightly weathered volcanoclastic sandstone located in the north eastern part of the project area and which is believed to be part of the Merrions Formation
- A moderately weathered, medium strength fine grained meta-argillite (metasedimentary rock) with dominant foliation
- Fresh, extremely high strength vein quartz up to 1.8 m width

The mapping suggested that the foliation in the metasedimentary rock is broadly aligned in a north south direction. The collected measurement data is presented graphically as a stereo plot in Figure 4. The concentration of poles representing the subvertical north-south striking cleavage and the variable bedding dip (from 20° to the south east to 80-90° to the west and east) and a southerly plunging fold have been marked in the figure. This geological structure is consistent with the Geological Survey of NSW mapping data and the structural mapping completed using the lidar data.

Bedding was difficult to ascertain in many outcrops and is therefore underrepresented in the dataset. The difference between cleavage foliation and bedding in an outcrop on the right abutment of the lower dam is illustrated in a photograph taken during the inspection presented in Figure 4.

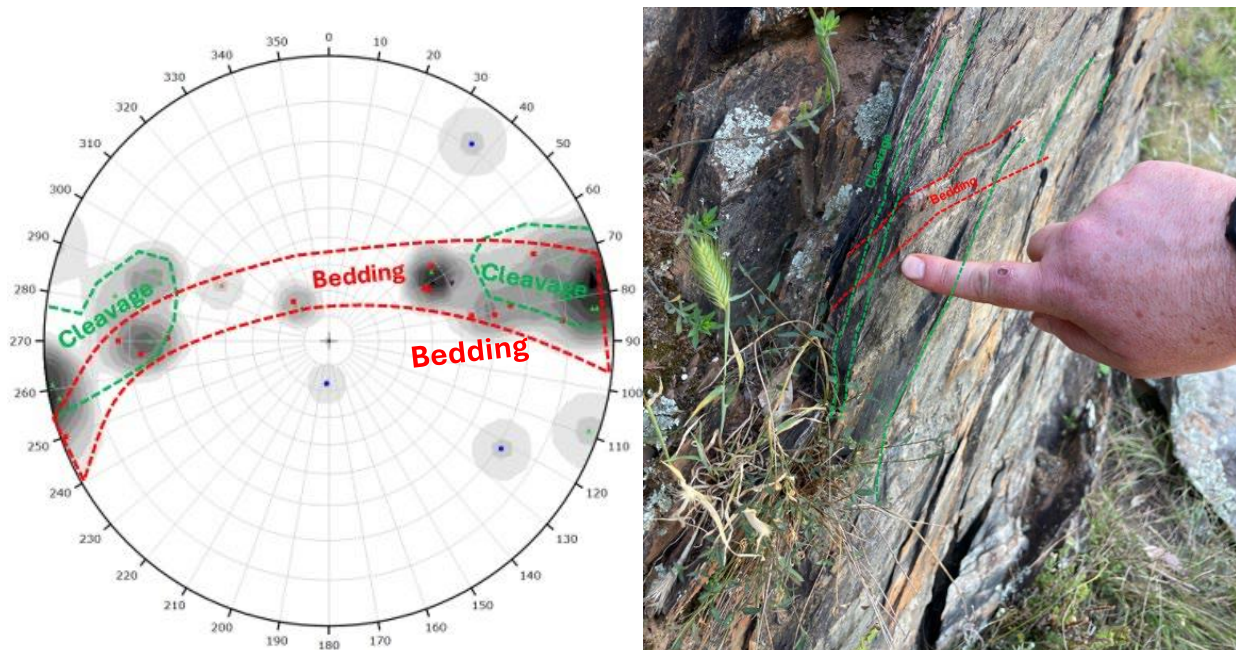


Figure 4: Stereo plot showing results of mapping across the project area (orientated towards true North) (left) and image of site rock showing relationship between cleavage and bedding (right)

Upon field examination of the anomalous area of geomorphology identified during the desktop stage, a reddish orange clay soil and differing vegetation was observed. A weathered rock outcrop was identified in a farm dam excavated in the centre of the feature. The rock identified was an extremely weathered to highly weathered mafic medium grained igneous rock that had developed characteristic “onion skin” concentric weathering. Quartz veins were observed within the exposure with an approximate north to south strike. Subsequent petrographic testing completed on hand specimens identified the rock to be a greenschist grade metamorphosed dolerite and gabbro. The highly weathered gabbro rock was

low to medium strength. These features are shown in Figure 5. Hand held radiometric equipment could have been utilised to help identify the location of the anomaly but was not considered necessary at this early stage of the project.



Figure 5: Reddish orange clay associated with weathering of igneous rock (left) and gabbro and concentric weathering and quartz vein (right)

6 TERRESTRIAL GEOPHYSICAL SURVEYS

Seismic refraction tomography surveys and subsequent Frequency Time Analysis (FTAN) of surface waves (Rayleigh and Love) was completed by the GHD geophysics team to provide both a P-wave and S-wave velocity profile (Natale et al, 2004). The geophysical surveys were completed predominantly at the location of dams in the upper and lower storage but also at the proposed powerhouse location. They allowed for identification of features possibly associated with differentially weathered bedding and/or geological structures such as bedding parallel faults. The orientation of the possible structure was checked against the regional geological and reconnaissance mapping and found to generally agree. An example of the geophysical survey results is presented in Figure 6.

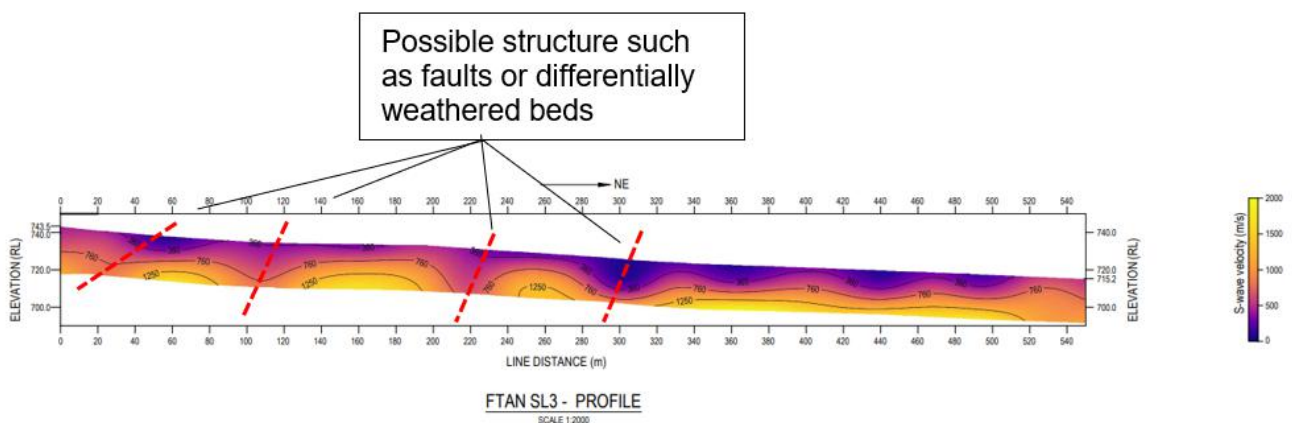


Figure 6: Geophysical survey results presented as FTAN

7 CONCEPTUAL GEOLOGICAL MODEL

Following the desktop study and geological reconnaissance mapping, an initial conceptual geological model was developed to identify potential hazards and opportunities related to the site's geology. This conceptual understanding

helped identify various engineering geological opportunities, uncertainties, and hazards, providing a framework for planning intrusive investigations.

7.1 ROCK (UNITS AND STRUCTURE)

The site is dominated by the folded metasedimentary rocks comprising a mixture of metasiltstone, phyllite and fine to medium grained sandstones. The folding of these rocks has imparted a strong axial planar cleavage in the rocks (particularly the argillaceous rocks) that strikes along the fold axes which is in a generally north to south direction. Two main anticlines and two main synclines plunging towards the south have been identified in the project footprint. A number of complex smaller folds and possible thrust faults have also been interpreted to be present from the interpretation of available lidar data.

The presence of bedding shears and other faulting associated with the folding was considered highly likely. Other faulting including thrust faulting associated with regional tectonic stresses were also considered to be present.

Orthogonal jointing patterns were noted in some of the metasedimentary rock units. The main defect sets are considered to comprise a relatively consistent cleavage set, with additional joint sets that are associated with the folding.

A previously unmapped area of fine to medium grained mafic igneous rock was encountered between the upper and lower reservoirs during the walkover.

Petrographic thin section analysis, completed on hand specimens collected during the walkover, identified these rock types as meta-dolerite and meta-gabbro. Petrographic analysis also identified the presence of actinolite which is a mineral common in altered basic volcanics across eastern Australia. However, this actinolite was noted to be in an acicular and prismatic habit but not in a fibrous or asbestiform habit.

Thick quartz veins were expected across the site aligned with the regional structure.

7.2 SOILS

Soil development across the site was minimal resulting in a generally thin layer (up to approximately 1 to 2 m thickness) of colluvium present on the slopes. This depth of soil is expected to increase towards the base of the valleys where it is reworked into alluvial deposits, but it is anticipated that the depth of soil will generally not exceed 5 m across the site. However, localised, deeper but relatively narrow zones of soil associated with deep weathering of beds or faults were also anticipated. The geophysical surveys indicated that discrete zones of possibly soil strength material could occur to depths of up to 20m below surface.

7.3 HYDROGEOLOGY

It was uncertain how the hydrogeological model and permeability of the rock mass may be impacted by shears and faults; it may be relatively high along these features; or these features may be of low permeability causing localised changes of groundwater conditions over short distances. As permeability of structural features represents a hazard to the project this will be investigated in future stages of geotechnical investigation.

7.4 SUMMARY

In summary, the initial conceptual geological model identified that the rock mass is relatively complex with numerous folds, faults, different lithological units and bedding parallel and bedding cross-cutting igneous intrusions and faults. There is a potential for high permeability along faults and shears. A 3D block model sketch was developed to illustrate the geological relationships and hazards. This sketch (presented as Figure 7) does not show all intrusions and faults or true dips of features and is for illustrative purposes only. Also omitted are lower angle thrust faults and overturned folds.

The ground conditions were identified as being potentially complex at the site, but risks associated with this complexity were deemed to be able to be managed by appropriate scoping of geotechnical and geological investigations and laboratory testing. Materials suitable for construction were identified to be available at the site.

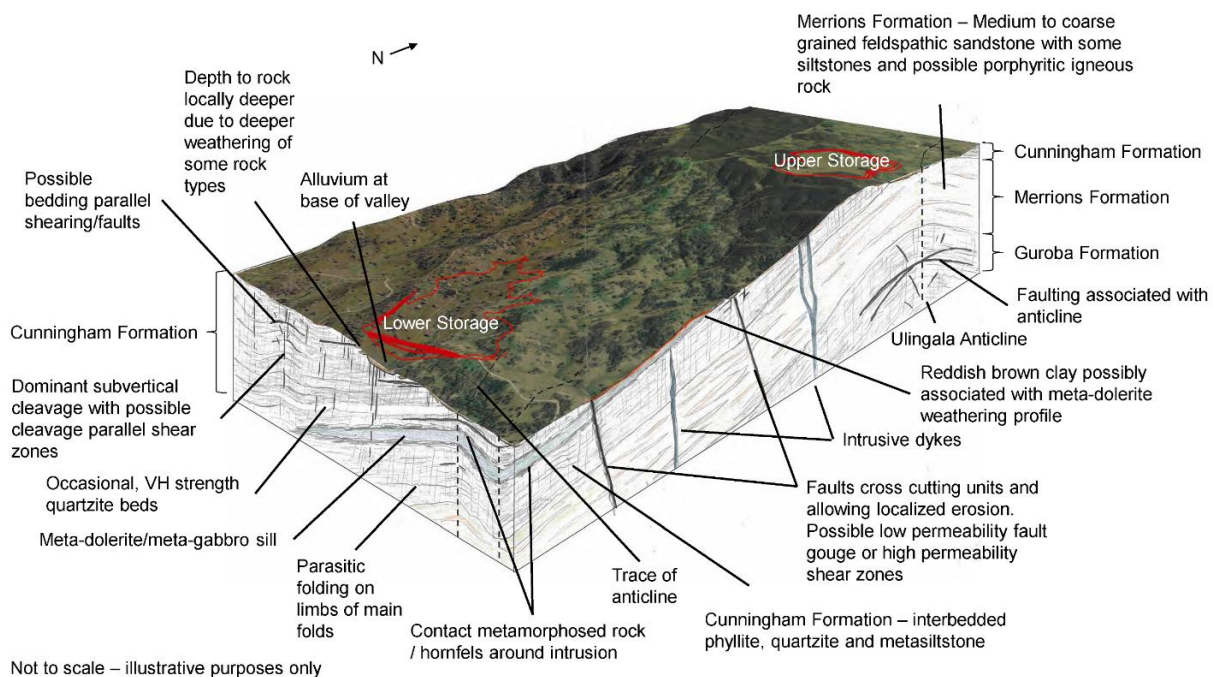


Figure 7: Illustration of conceptual geological model

8 GAP ASSESSMENT AND GEOTECHNICAL RISK REGISTER

Following the desktop study and site walkover and reconnaissance geological mapping, the developed conceptual geological model enabled identification of several hazards and opportunities for the project: It was identified that the geological and geotechnical conditions related to the metasedimentary rock would dominate the majority of the upper and lower dams as well as the bulk of the waterways if an underground option was chosen and that the igneous intrusion would potentially play an important role in design development for the project, depending upon the characteristics of this intrusion below surface. The geological conditions and resultant issues and opportunities are outlined in the table below.

Table 2 Geological Hazards and Opportunities

Geological Condition	Issues	Opportunity	Elements of project potentially impacted
Rock structure	Interbedded and folded and faulted sedimentary sequence leading to variable geotechnical properties such as rock mass strength and permeability (dam foundations) and differing support requirements in tunnels	Relatively predictable north-south striking folds and presence of possible “marker beds” means that major groups of rock units can be understood across the project area and allowed for in design and construction.	All
Phyllite/meta-siltstone rock with dominant cleavage	Excavated rock may be unsuitable for use as rockfill due to tabular nature of blocks. Tunnels and shafts will possibly require more support than in rocks with less structure. Potential instability controlled by rock structure in excavations.	The rock may be easier to excavate due to presence of cleavage. Tunnelling and shaft excavation in the weaker phyllite rock will require less excavation effort than harder rocks in area. Some dams (such as Kangaroo Creek) have effectively used	All

Geological Condition	Issues	Opportunity	Elements of project potentially impacted
	<p>Phyllite rock likely to be unsuitable for use as concrete aggregate due to shape and clay content.</p> <p>Possible durability issues and breakdown of rock once exposed as rockfill.</p>	<p>tabular rock as rockfill – lessons can be learned from such dams</p>	
<p>Vein quartz</p>	<p>Rock will require additional effort to excavate and will be highly abrasive to equipment. Silica dust generation may be high.</p>	<p>Vein quartz expected to have good geotechnical properties</p>	<p>Tunnel and shafts</p>
<p>Igneous meta-gabbro/meta-dolerite rock intrusion along waterway route</p>	<p>This rock may be more abrasive to tunnelling and could be more deeply weathered than the phyllite resulting in more complex anchoring of any surface penstocks.</p> <p>Petrographic analysis indicates presence of the mineral actinolite which elsewhere may take the form of asbestiform minerals with potential health impacts on construction workers.</p> <p>Excavation in the igneous rock may be slower due to more widely spaced joints and higher strength</p>	<p>This area may prove useful for development of quarries for rockfill, concrete aggregate and potentially sand.</p> <p>Better geomechanical conditions may be encountered in the igneous intrusion than in the surrounding metasedimentary rock leading to reduced ground support requirements.</p> <p>Petrographic testing currently indicates that the actinolite is not fibrous and presents a reduced risk to health (in line with other rock dust related illnesses). Additional appropriate testing will be completed to confirm this.</p>	<p>Waterway Rock Quarry Powerhouse</p>
<p>Contact between igneous intrusion and country rock (surrounding metasedimentary rock).</p>	<p>Thermally metamorphosed metasedimentary rock may be of very high strength and abrasive. Alteration may have also reduced strength of igneous rock/metasedimentary rock in vicinity of the contact. Possible brecciation along contact may increase permeability along contact.</p>	<p>Contact may be “tight” and have lower permeability than the shears and crushed seams expected in the metasedimentary rocks.</p> <p>Lower contact could be used as a stratigraphical marker to help constrain the geological interpretation.</p>	<p>Waterway Rock Quarry Powerhouse</p>
<p>Thin residual soil and alluvial/colluvial cover at lower and upper storage and escarpment slopes</p>	<p>Minimal soil available for earthfill Possible instability should seepage from upper storage occur.</p>	<p>Potential for shallow anchoring of surface penstock into competent rock</p> <p>Reduced excavation support required in upper section of shafts</p> <p>Ability to excavate steeper cut slope batters (foliation and bedding dependent due to potential reduced slope stability parallel and subparallel to bedding and foliation).</p> <p>Possibly shallow depth of preparation for rockfill or concrete faced rockfill dam foundations.</p>	<p>Waterway Upper dam Powerhouses</p>

Geological Condition	Issues	Opportunity	Elements of project potentially impacted
“Dip-slope” failures in vicinity of waterway route	Movement of slope could jeopardise waterway. Excavation into slope for access tracks could cause significant failure or requirement for stabilisation.	These areas are relatively easy to identify and can be avoided	Waterway
Pyrite and other sulphide minerals present in the less weathered metasedimentary rocks	Upon excavation, the sulphide minerals may oxidise causing a number of issues including volume expansion and degradation of cut slopes and tunnel walls and possible rockfill. Oxidation would result in release of sulphuric acid and sulfates with potential environmental affects and degradation of concrete structures/shotcrete. Spoil may need to be treated onsite or disposed of offsite.	Testing can be completed to assess this issue. Acid sulfate issues are known and managed at rock fill dams such as Corin Dam in the ACT.	Tunnels, shafts, powerhouses Rock quarries
Groundwater	Groundwater conditions are largely unknown and folded and faulted geological strata could allow for discrete zones of high permeability below dams or into underground excavations.	Minimal surface seepages were observed indicating possible deep groundwater. Faults and strata may also be relatively impermeable.	Upper and lower storage, tunnels and shafts, powerhouse.

9 GEOTECHNICAL INVESTIGATION SCOPING

Following on from the development of the conceptual geological model and identification of hazards and gaps in knowledge, GHD commenced scoping of a targeted phase of preliminary geotechnical investigations.

The investigation scope included:

- Detailed geological mapping across the storage areas and along the penstock routes and of the igneous geology identified in the previous stage to build on the preliminary mapping completed previously. This would provide more information on geological structure, slope instability and lithological variations across the project area. Potential quarry locations were also included in the mapping scope, particularly with respect to the presence of possible igneous rock.
- Excavation of test pits/trenches across the upper and lower storage areas, waterway and possible quarry and borrow areas to depths of between 3 and 4 m or refusal on rock. In possible borrow areas and dam foundations, test pits would be extended for up to 15m in length to allow mapping of the subsurface profile.
- Cored boreholes of varying depth at key locations at the upper storage dams, inlet, waterway, powerhouse and lower storage dam location. These boreholes were oriented as much as possible to maximise intersection of varying geology by inclining the opposite direction to the anticipated foliation/bedding dip direction
- In-situ testing including permeability testing and televiewer surveys were scoped to be completed in all boreholes to allow for an understanding of the depth of “destressing”, permeability and rock structure.
- Vibrating wire piezometer installation in six boreholes and dataloggers deployed to monitor seasonal variation of piezometric levels.
- Reverse circulation (RC) boreholes for installation of groundwater monitoring wells at select locations downstream of each embankment and between the two storages. The monitoring wells are to be used for long term water level monitoring and water sampling and were installed within vertical boreholes and constructed such that the invert of the screened interval is located approximated 10 m below first water strike.

Each monitoring well was equipped with water level sensors and dataloggers and sampled quarterly to characterise groundwater quality to provide information for the engineering design of the project and to enable development of

baseline hydrogeological conditions at the site and inform on potential impacts to the underlying aquifer and associated ecosystems.

Whilst downhole measurement of P-wave and S-wave velocity and flowmeter assessments of groundwater flow were not utilised at this stage of investigations they will be beneficial in future stages of investigation.

In the early stages of this project in-situ stress was assessed using a combination of desktop review of regional conditions combined with innovative laboratory testing techniques which will be the subject of a future paper. In-situ stress testing will be completed in future stages of geotechnical investigations now that a good understanding of the geological structure has been developed to assist in targeting of test locations and types.

The information gathered during the geological and geotechnical investigations, would be used to confirm the conceptual geological model or allow for revision.

10 INTRUSIVE INVESTIGATIONS AND RESULTS

The aim of the geological and geotechnical investigations was to characterise the general geological conditions and answer key gaps and provide information to assess the identified project risks and enhance understanding of the impact of these conditions on the various components of the project.

The intrusive investigations completed at the site included excavation of 45 no. test pits, some of which were extended to show a wider exposure of the geological materials, and a total of 15 no. geotechnical boreholes drilled to depths varying from 20 m to 340.6 m below surface. The shallower boreholes were drilled for the dams forming the upper and lower reservoir whilst the deeper holes were for collection of information for the underground waterways which had become the favoured design approach by the commencement of the investigations.

The intrusive investigations identified that the predominant lithology was a fine grained metapelite/metasedimentary rock with occasional beds of fine to medium grained quartzose sandstone that varied in thickness from laminations to medium beds. XRD testing of the sandstones identified that they are quartzose with some carbonate cement and pyrite mineralisation. The sandstone also appeared to be less subjected to metamorphism than the metapelite. Where possible, laboratory testing was targeted at either beds of metapelite or the sandstone to provide information on the range of possible geotechnical properties that could be encountered.

Two boreholes targeted the igneous rock with the results indicating that this was a folded intrusive sill. A zone of silicified hornfels was encountered at the contact between the dolerite sill and the country rock.

Photographs of core from the metasedimentary unit and the dolerite are presented in Figure 8 and Figure 9.



Figure 8: Typical interbedded metasilstone and sandstone (left) and dolerite (right)

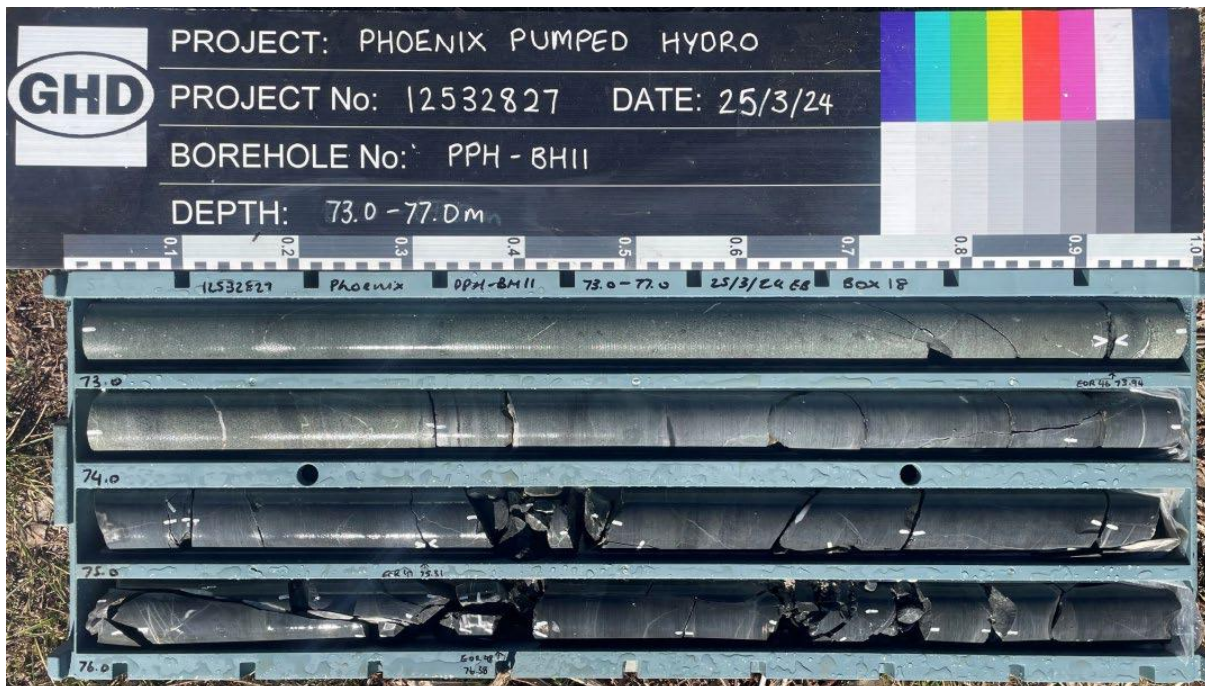


Figure 9: Core through base of sill at 73.95m

In-situ packer permeability testing was completed in each borehole with contiguous testing completed where possible. Generally low Lugeon values were encountered but there were some high takes associated with discrete seams within the rock mass at shallow depths.

A suite of laboratory testing was also completed to understand the variability of key geotechnical parameters and geochemical characteristics. This testing included:

- Unconfined compressive strength (UCS) testing
- Point load testing (PLT)
- Brazilian tensile strength testing
- Density testing
- Cerchar abrasivity testing
- Net acid production and net acid generation testing for assessment of acid sulfate rock
- Petrographic and quantitative x-ray diffraction of rock samples for a combined purpose of assessment of acid sulfate, asbestiform mineral habit screening and also calculation of Equivalent Quartz Content for use in assessment of Rock Abrasivity Index
- Direct shear testing of natural defects

It was identified prior to strength testing that premature failure of samples along foliation may result in a lower-than-expected estimation of strength in the metasedimentary rocks. A wide scatter in testing results was also observed in the results from testing of the dolerite with this possibly related to microscopic fracturing of the dolerite imparted during folding but which cannot be observed at hand specimen scale. Additionally, when compared with the estimated strength using an approximate relationship of Brazilian tensile strength testing to UCS as per Ribeiro et al (2015) ($UCS = \text{Brazilian tensile strength} \times 10$) a significantly lower strength was encountered with the UCS and PLT testing in the interbedded sedimentary rocks. This was attributed to failure upon foliation in the metasedimentary rock. The lower strengths did also not match with the field descriptions of strength (generally high to very high).

PLT results are presented in Figure 10 showing the large scatter of testing results in the dolerite, and overall lower strength results in the metasedimentary rock. In general, the metasiltsone was medium to high strength and the dolerite was very high to extremely high strength.

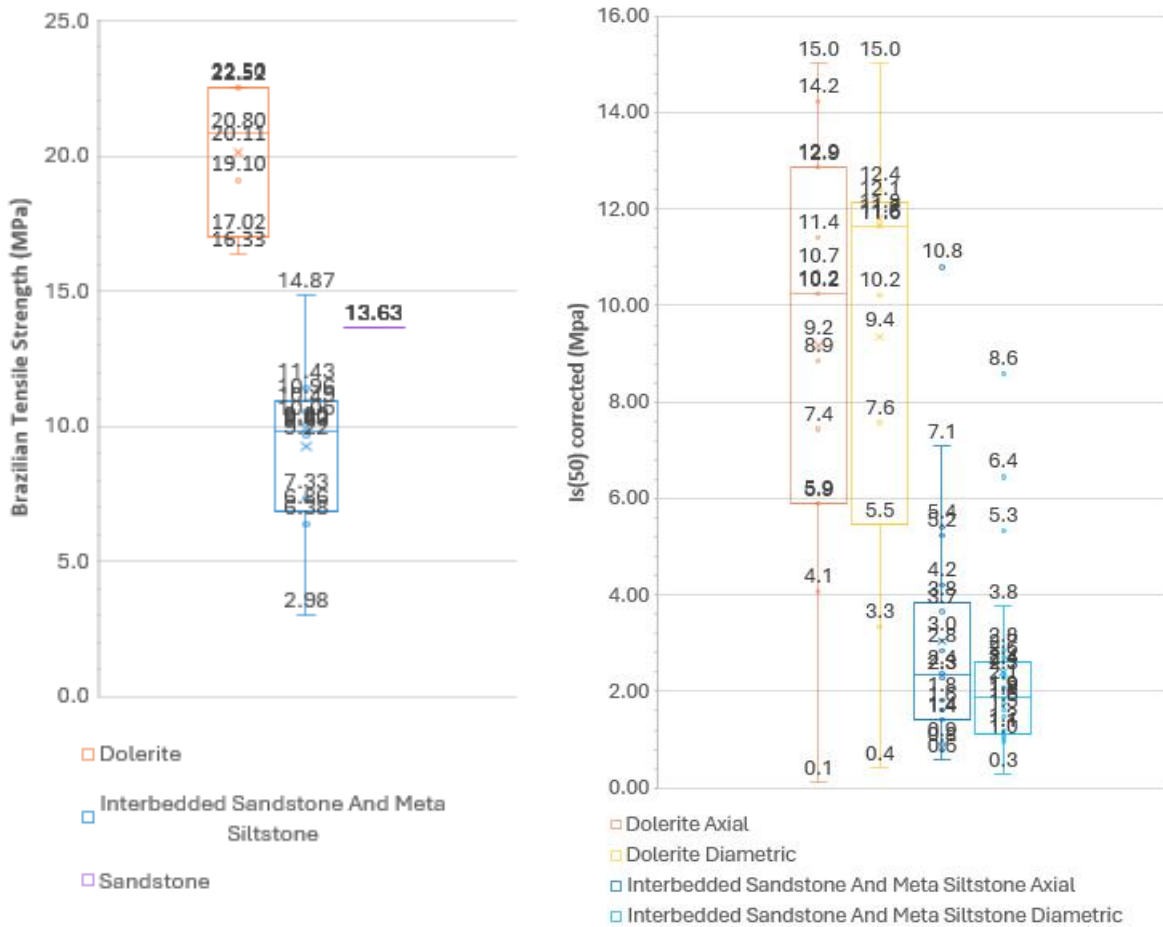


Figure 10: Brazilian tensile strength (left) and point load testing results (right)

Cerchar abrasivity testing was found to have a large scatter of results which likely relates to the relatively constrained test length (10 mm) which may not travel over the most abrasive mineral crystals or grains in the rock. The rock abrasivity index as outlined by Plinninger, 2010 appeared to provide much more consistent results related to the varying rock types present across the site with both the metasiltstone and dolerite being about the same abrasivity with the hornfels having the greatest abrasivity.

With all sedimentary rock derived from a deep ocean environment there is a potential for the presence of pyrite and other sulfides which can oxidise upon exposure to the atmosphere. This can have both environmental and engineering implications, with the potential for acidic water and sulfate damage to steel and concrete. As pyrite was frequently logged in the borehole core either as defect coatings, as nodules or disseminated through the rock substance, it was determined that testing was required to assess the hazard. A number of geochemical tests were completed with the results indicating that in most cases the rock has sufficient carbonate or other buffering minerals to neutralise the acid produced. Additional testing is required to confirm this at future stages of design.

Due to the presence of actinolite, an amphibole mineral resulting from alteration of pyroxenes, and the potential for these minerals to be asbestiform in habit, a preliminary screening exercise was completed using petrographic analysis methods. In addition, engineering geologists completing the mapping and logging were briefed on the potential presence of asbestiform minerals and its identification prior to the geotechnical investigations commencing. A naturally occurring asbestos management plan was also prepared to manage the health and safety risks if asbestiform minerals were encountered. To date no asbestiform actinolite has been encountered with the dominant crystal habit being acicular or prismatic.

The drilling investigations also confirmed the hydrogeological model with a fractured bedrock aquifer with sheared zone controls on increased permeability. The aquifer is in some locations semi-confined due to weathering and alluvium and colluvium cover.

11 DETAILED GEOLOGICAL MAPPING

Detailed geological mapping was completed at scale of 1:1000 over the project area primarily to gain information on the lithological variation across the site but also to collect structural geological data. The mapping was completed during the initial stages of the drilling investigations with the aim of allowing findings to influence the remaining scope of the intrusive investigations.

The mapping was able to determine the complex boundary of a mafic sill which has intruded into the metasedimentary rocks by a combination of a dominant brownish red soil colouration and hornfelsed zone that was found to be more resistant to weathering and erosion in the landscape. Once the structure of the sill was better understood, a review of high-resolution aerial photography revealed that the contrasting-coloured soils also gave an indication of the location of the sill, albeit affected in some locations by colluvial processes.

The detailed geological mapping was successful in confirming the geological structure away from the intrusive boreholes that had been drilled immediately prior to the mapping and provided almost immediate information to update the conceptual geological model and revise the drilling investigation scope to provide confirmation of the structure and geotechnical implications.

12 OPTIMISATION OF DESIGN DURING INVESTIGATIONS

A preliminary structural interpretation was completed immediately after completion of detailed geological mapping and this, along with the collected borehole data, supplemented the conceptual geological model which was assessed and then visualised in 3D space in Seequent's Leapfrog Works. The detailed surface geological mapping allowed for confirmation of the outcrop location and structural orientation and the boreholes provided information on the subsurface shape of the sill. Using this information, the sill was modelled in 3D and it was realised that the powerhouse silos could be repositioned and rotated to make better use of the dolerite and its more advantageous geotechnical characteristics (higher strength and wider joint spacing). Prior to the cessation of the drilling program, an additional borehole was designed and drilled to allow confirmation of the sill structure and the revised powerhouse location was confirmed. Figure 11 shows a geological section with the relocated powerhouse to be largely within the dolerite sill.

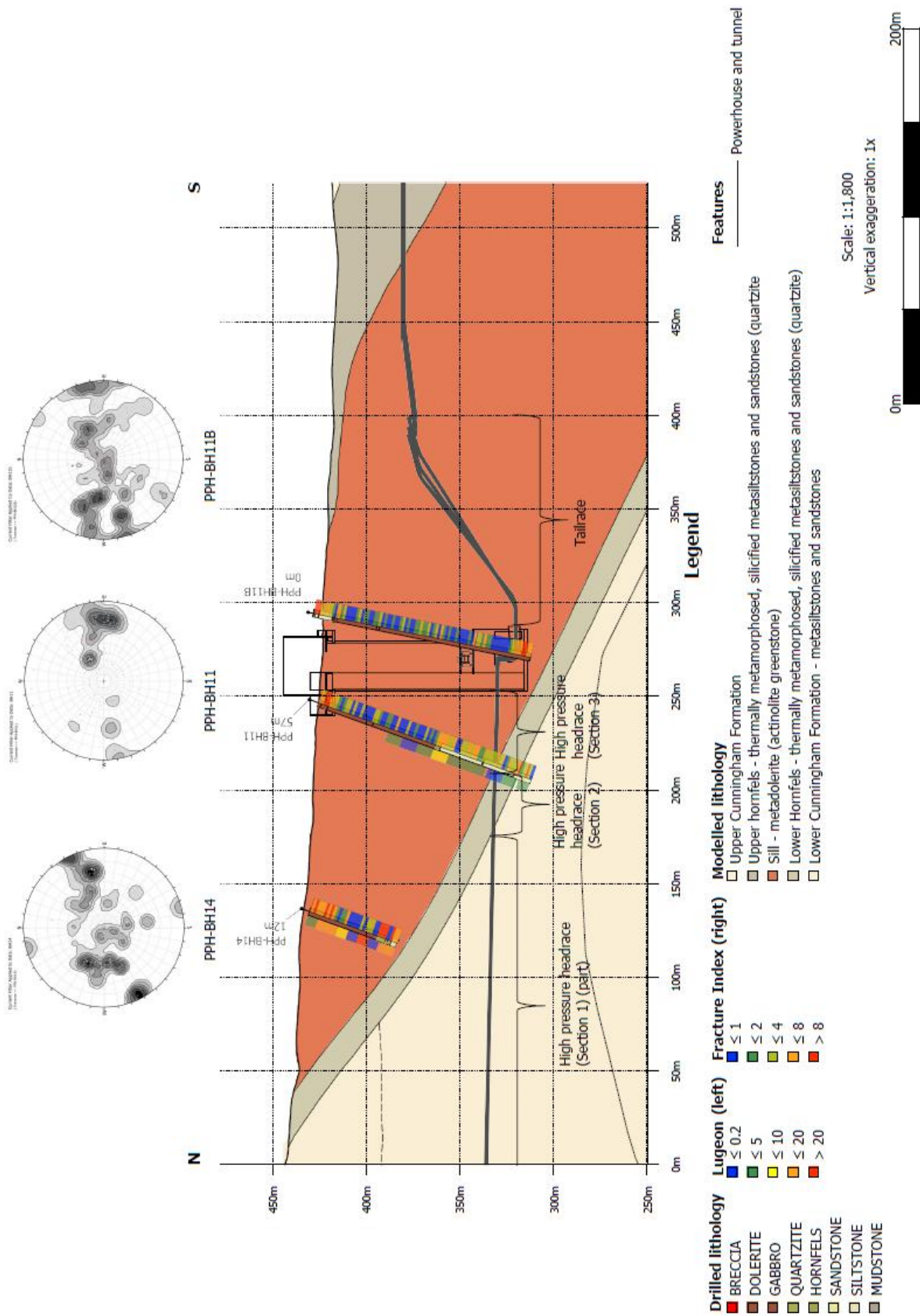


Figure 11: Geological section through powerhouse after relocation of structure

13 CONCLUSIONS

The use of “traditional” geological skills such as detailed surface geological mapping, understanding and application of structural geology concepts alongside the use of surface and aerial geophysical data, intrusive investigations, in-situ testing and laboratory testing in conjunction with 3D geological model visualisation allowed for the efficient and rigorous understanding of the engineering geology of the site.

The staged geotechnical investigation approach and iterative development of a conceptual geological model as part of the engineering geological model knowledge framework not only allowed for the effective delivery of a feasibility design for a complex pumped hydropower project but also allowed for agile and rapid optimisation of the project during design to better make use of more favourable geotechnical conditions. The engineering geological model development framework provides a methodical and technically rigorous approach to the understanding and management of ground hazards.

The rapid optimisation in the midst of the geotechnical investigations was only possible due to the effective transfer of data and verbally communicated information from site to the office and this information being used in the interpretation immediately. This approach was only viable as GHD was completing both the design and the investigations. This approach is recommended for all projects with compressed timeframes and the requirement for the use of ground investigation data in the design process in near real time of collection.

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